Vlaanderen
is landbouw & visserij

ILVO Mededeling 272

april 2021

TOWARDS CLIMATE-SMART SUSTAINABLE MANAGEMENT OF AGRICULTURAL SOILS IN FLANDERS

Part II: EJP SOIL survey on current research knowledge and stakeholder views on knowledge needs, barriers and opportunities for the knowledge system

ILVO
Instituut voor Landbouw-,
Visserij- en Voedingsonderzoek

www.ilvo.vlaanderen.be

Financiering

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Towards climate-smart sustainable management of agricultural soils in Flanders

Part II: EJP SOIL survey on current research knowledge and stakeholder views on knowledge needs, barriers and opportunities for the knowledge system

ILVO MEDEDELING 272
april 2021
ISSN 1784-3197
Wettelijk Depot: D/2021/10.970/272

Auteurs
Greet Ruysschaert
Maarten De Boever
Miro Jacob
Peter Maenhout
Tommy D'Hose

Acknowledgements

We would like to thank the EJP SOIL funding programme as part of the European Union's Horizon2020 research and innovation programme: Grant agreement N°862695. We sincerely would like to thank all persons who have shared their views and contributed with input to the stakeholder questionnaires, i.e. from BoerenBond/Innovatiesteunpunt/Groene Kring, Agrobeheercentrum, Bioforum, INAGRO, PCG, Praktijkpunt Vlaams-Brabant, OVAM, ANB, Department of Environment, VLM, Department of Agriculture and Fisheries, ILVO, INBO, the Soil Service of Belgium (BDB), Ghent University, Antwerp University, PIBO and BBL ('Bond Beter Leefmilieu'). We would like to thank Karoline D'Haene, Jeroen De Waegemaeker (ILVO), Katrien Oorts, Martine Swerts (Department of Environment - VPO/DOV), Hubert Hernalsteen and Lucas Van Dessel (Department of Agriculture and Fisheries) to provide extra information and feedback and to improve the quality of this report.

Abstract

EJP SOIL unites a broad European research consortium to enhance the contribution of agricultural soils to key societal challenges such as climate change adaptation and mitigation, sustainable agricultural production, ecosystem services provision, prevention and restoration of land and soil degradation and biodiversity maintenance. One of the objectives is to develop and deploy a roadmap for climate-smart sustainable agricultural soil management research. From this roadmap activities for the EJP SOIL work packages are defined and research topics for project calls selected. In order to develop this roadmap, in 2020 - the first year of EJP SOIL -, a number of inventories and stock take activities have been conducted, involving local stakeholders. This report, together with ILVO mededeling 271 (Ruysschaert and Jacob, 2021), summarizes the input provided for Flanders. In order to collect the information from a broad range of stakeholders including researchers, policy advisors and the farming sector, three questionnaires were developed, i.e. one focused on policy (see ILVO mededeling 271), one on practice and one on research. Nineteen organisations have contributed to one or more questionnaires. The results of both the 'research' and 'practice' questionnaires are part of this report. The 'research' questionnaire aimed to inventory (recent) research results and insights on the mapping, monitoring, modelling and prevalence of soil challenges, soil management and research gaps. The inputs of the consulted research stakeholders on the various topics, were supplemented with a literature search. The 'practice' questionnaire aimed to identify knowledge use and knowledge needs on sustainable soil management in Flanders from a practitioner's point of view and to identify barriers and opportunities for the knowledge system needed to foster sustainable soil management. In all three questionnaires, stakeholders were asked to prioritize soil challenges in Flanders for the upcoming decades. Maintaining/increasing soil organic carbon (SOC) was by far the most important soil challenge according to the stakeholders, followed by enhancing water storage capacity, enhancing soil biodiversity and enhancing soil nutrient retention/use efficiency. SOC is a well-studied soil challenge, but actual monitoring is lacking and research for soil management practices increasing SOC focused so far mainly on the addition of organic fertilisers/amendments and non-inversion tillage and less on the effect and potential of crops, cover crops, crop rotations and the impact of the water table. There are still many questions, including interactions with other soil challenges and how incentive schemes and associated monitoring and verification methods could be developed. Although water storage was the second priority for the stakeholders due to recent and projected drought spells, this topic was underrepresented in soil research until now. Stakeholders pointed out that an integrative soil vision is lacking in Flanders which is an overarching critical element for the knowledge system. Stakeholders also ask for a more structural multi-stakeholder soil network with clear roles and interactions between research, policy, advisory services and farmers. In addition, stakeholders pointed to the need of a centralized soil knowledge platform.

Table of Contents

1. Introduction

The main objective of the European Joint Programme **EJP SOIL** (2020-2024; www.ejpsoil.org) is to enhance the contribution of agricultural soils to key societal challenges such as climate change adaptation and mitigation, sustainable agricultural production, ecosystem services provision, prevention and restoration of land and soil degradation and biodiversity maintenance.
The EJP SOIL consortium unites a unique group of 26 European research institutes and universities in 24 countries. National research efforts are pooled in order to make better use of Europe's research and development resources. EJP SOIL activities closely interact with stakeholders of different categories, including policy stakeholders, farmers and farmer organisations, research communities, NGOs and agro-industry.

One of the objectives of EJP SOIL is to develop and deploy a **roadmap for climate-smart sustainable agricultural soil management research**. From this roadmap activities for the work packages are defined and research topics are selected for internal and external project calls. In order to develop this roadmap, in the first year of EJP SOIL, a number of inventories and stock takes activities have been conducted, i.e.:

- Task 2.1: Agricultural soil service aspirations at regional, national and European levels
- Task 2.2: Knowledge availability and use
    - Subtask 2.2.1: Knowledge availability
    - Subtask 2.2.2: Knowledge use
- Task 2.3: Identification of barriers and opportunities by scenario development
- Task 2.4: Reviews of key agricultural soil related issues for all members states in EJP SOIL, with 5 stock takes
    - Synthesis on the impacts of sustainable soil management practices;
    - Stocktaking on soil quality indicators and associated decision support tools, including ICT tools;
    - Stocktaking on estimates achievable soil carbon sequestration on agricultural land in the EU;
    - Inventory of the use of models for accounting and policy support (soil quality and soil carbon) in partner countries;
    - Stock take study and recommendations for harmonizing methodologies for fertilization guidelines across regions.

All partners were required to collect the necessary information for these inventories and stock takes for their countries or regions, involving a broad range of stakeholders and based on a methodology outlined by the respective task and stock take leaders. After, the information from the different countries was compiled in overall reports per task or stock take. These reports are publically available on www.ejpsoil.eu .

In this report (ILVO mededeling 272), the results for Flanders are compiled, except for task 2.1 which is reported in ILVO mededeling 271 (Ruysschaert and Jacob, 2021) and the stock take on fertilization guidelines.

The **aim of this report** is

i) to summarize **available research knowledge** and **research needs** (Chapter 3) on the prevalence, monitoring and modelling of the soil challenges defined in the EJP SOIL glossary (see ILVO mededeling 271 Annex I) and the soil management options to tackle these challenges, and

ii) to inventories **stakeholder views** (Chapter 4) on the prioritization of soil challenges that are expected to be relevant in Flanders in the upcoming decades, knowledge use and needs regarding sustainable soil management and barriers and opportunities for the knowledge system.

2. General approach and stakeholder involvement

In order to collect all necessary information in Flanders, **three questionnaires** were developed, i.e.:

- **Questionnaire 1: 'Toekomstvisie'** (Future vision), designed for collecting stakeholder opinions for EJP SOIL task 2.1 on the realization of current policy targets and assessment on how futureproof current policy targets on agricultural soils are. Stakeholders could also indicate what instruments and soil management practices would be most suitable for achieving aspirational goals for the different soil challenges. The results are reported in ILVO mededeling 271 (Ruysschaert and Jacob, 2021).
- **Questionnaire 2: 'Beleid en praktijk'** (Policy and practice), designed for collecting stakeholder opinions for EJP SOIL subtask 2.2.2 on knowledge use and needs and EJP SOIL task 2.3 on barriers and opportunities for knowledge development, sharing, organizing and application for sustainable soil management. This questionnaire was aimed for the wider stakeholder community. Results are summarized in Chapter 4, and the questionnaire can be found in Annex I.
- **Questionnaire 3: 'Onderzoek'** (Research), designed to capture the availability of knowledge and knowledge needs from a research perspective for EJP SOIL subtask 2.2.1 and the stock takes of EJP SOIL task 2.4. This questionnaire was mainly aimed for researchers and funding organisations and was supplemented with a literature research. The results are summarized in Chapter 3 and the questionnaire can be found in Annex II.

In all three questionnaires, stakeholders were asked to answer the following **prioritization question**:

"What do you expect that will be the main soil challenges that are most relevant for Flanders in the upcoming decades"?

For this question, they had to divide 100 points over a list of soil challenges. These soil challenges are: maintain/increase soil organic carbon (SOC), avoid N_2O/CH_4 emissions, avoid peat degradation, avoid soil erosion, avoid soil sealing, avoid salinisation, avoid acidification, avoid contamination, ensure optimal soil structure, enhance soil biodiversity, enhance soil nutrient retention/use efficiency and enhance water storage capacity. The result to this question is shown in Chapter 4 'Stakeholder views'.

On June 8th 2020, a **webinar** was organized to explain the purpose of EJP SOIL and the questionnaires. An invitation for this webinar was sent to 34 organisations, involving 115 persons, and the questionnaires were distributed via the e-mail list of the Soil Science Society of Belgium. In the invitations, it was suggested what questionnaire(s) seemed to be most appropriate for the organization to complete, but everyone was free to choose the questionnaire(s) of their own interest and expertise. Eventually, 49 persons have attended the webinar.

Table 1 provides an overview of the **19 organisations** who have contributed to one or more questionnaires. They were asked to what stakeholder group they identified themselves most. Some, ticked more than one category. The response of one organization often included the opinions of several individual members. The stakeholder organizations jointly represent a group of 30 experts for questionnaire 1, 30 stakeholders for questionnaire 2 and 25 experts for questionnaire 3. In most organizations the experts had an internal discussion that ended in a jointly completed questionnaire with consensus answers. In other organizations, the individual experts of the organization separately completed the questionnaire. In such case, and if the answers were divergent, we calculated the relative share of the organization vote for the different response categories. By doing this, we took into account the internal variability of the organization, while maintaining equal shares between the stakeholder organizations.

Table 1: *Overview of participating organisations, the stakeholder group they belong to and their contributions to one or more of three questionnaires*

Stakeholders	Research communities	Farmer schools	Farmers and demonstration farms	Advisors	Farmer organisations	Agro-industry	Laboratories	Industry	NGO	Middle and higher educational institutions	Research funders	National/regional policy	National European soil partnership	**Questionnaire 1**	**Questionnaire 2**	**Questionnaire 3**
Boerenbond-Innovatiesteunpunt-Groene kring				x	x									x	x	
Agrobeheercentrum					x									x	x	
Bioforum		x	x		x										x	
INAGRO	x			x											x	x
PCG	x			x			x							x	x	x
Praktijkpunt Vlaams Brabant	x		x	x											x	
OVAM				x							x	x		x	x	x
ANB				x							x					x
DepOMG-VPO	x										x	x	x	x	x	x
DepOMG (climate)												x		x		
VLM												x		x	x	
DepLV												x		x	x	
ILVO	x													x	x	x
INBO	x															x
BDB	x															x
UGENT	x									x						x
UA	x															x
PIBO			x											x	x	
BBL									x						x	
Number of organisations	9	1	3	6	3	0	1	0	1	1	3	5	1	10	13	10
Percentage (%)	26	3	9	18	9	0	3	0	3	3	9	15	3			
Number of persons participating per questionnaire														30	30	25

Based on the completed questionnaires, the information for the different EJP SOIL tasks and stock takes was compiled into the required format and submitted to the respective task and subtask leaders of EJP SOIL between September and November 2020. The reports, compiling all results of the different countries/regions is available on the EJP SOIL website (www.ejpsoil.eu), as well as the roadmap for agricultural soil research that is derived from these reports. This roadmap will get a yearly update based on the progress of and insights from different work packages of EJP SOIL and the internal and external research projects.

3. Knowledge availability and needs from a research perspective

3.1 Soil challenges: prevalence, monitoring and modelling

Soil organic carbon

<u>Carbon stocks and stock changes at the regional level</u>

In Belgium, the 3 regions (Flanders, Wallonia, Brussels) are responsible for their **greenhouse gas (GHG) emission inventories**, which are later compiled to produce the Belgian GHG inventory. Currently, Belgium (Flanders) is using the **Tier II approach to estimate GHG emissions from the LULUCF sector** (Land Use, Land Use Change and Forestry). This implies that emission and stock change factors are based on country- or region-specific data for the major land-use categories. However, the yearly emission factors used for each land use category are based on older studies (*see further*) and are thus not up to date. A **regional wide monitoring network** is designed (Sleutel et al., 2021) (but not yet installed) which would **enable to adopt a Tier III approach**, allowing for greater certainty.

The activity data used in the current LULUCF National Inventory Report are based on the **land-use change matrix** of Bauwens et al. (2010). This method uses a grid of points (1x1km) on which a diagnosis of land use is carried out. With this method land use was determined for the years 1989/90, 2009, 2012 and 2015 . Implementing a **land use map with finer resolution** (e.g. VITO-Ruimtemodel, 10x10m) could probably improve the area estimates of the different LULUCF land use categories and land use changes (Sleutel et al., 2021).

Current carbon stock estimates for different land use categories used in the **LULUCF inventory** are based on studies by Meersmans et al. (2011), Lettens et al. (2005b) and VMM et al. (2017) who all quantified changes in Belgian or Flemish SOC stocks for various time periods. The soil C stock values in mineral soils (0-30cm) for cropland and grassland have been updated in 2015 based on a study by Meersmans et al. (2011). They used a modelling approach, constructing a multiple linear regression model based on multicollinearity analysis predicting SOC as a function of land use, soil type, precipitation and agricultural management, to analyse the spatial patterns and temporal evolution (1960-2006) of **organic carbon in mineral soils under agricultural land use** in Belgium. For Flanders, SOC stocks (0-30 cm) between 1960 and 2006 decreased under cropland and grassland respectively from 54.6 to 53.9 ton C ha^{-1} and from 74.6 to 73.7 ton C ha^{-1} (Meersmans et al., 2011). This corresponds to a yearly decrease of 0.016 ton C ha^{-1} for cropland and 0.019 ton C ha^{-1} for grassland.
Lettens et al. (2005b) estimated the SOC stocks and changes in SOC stocks in Belgium (Flanders) between 1960, 1990 and 2000 for the land-use types cropland, arable land and forest in the 0-30cm soil layer. For **Flemish forest soils** (0-30cm) the SOC stock was estimated at 79 t C ha^{-1} in 2000 and the SOC increased between 1960 and 2000 with 0.425 t C ha^{-1}yr^{-1} (Lettens et al. 2005b). The **SOC of wetland** was estimated at 100 t C ha^{-1} by VMM et al. (2017). In absence of default values in the IPCC guidelines, average **soil carbon content under settlements** was estimated based on the SOC under cropland.

Besides the studies that were used for the emission inventory (*see above*), also some other studies attempted to quantify terrestrial carbon stocks and stock changes in Flanders or Belgium under forest, grassland and crops.

Sleutel et al. (2003) calculated the SOC loss on cropland in Flanders in the 1989-2000 period (i.e. 354 kton OC year^{-1}) and estimated that in order to restore the soil organic carbon content to the level of 1990, the **technical carbon sequestration potential** of Flemish cropland would be 300 kton CO_2 year^{-1} (82 kton OC year^{-1}) which would result in a 40-year restoration period. Tits et al. (2020) calculated, based on soil samples analysed by the Soil Service of Belgium in the 2016-2019 period, that 52% of permanent grasslands and 50% of arable field parcels have a soil carbon content below the target zone for soil fertility. If all arable (0-23 cm) and grassland (0-6 cm) field parcels would have a carbon content at the upper limit of the target zone for soil fertility, Tits et al. (2020) calculated that the potential for soil carbon sequestration would be 7.5 Mton C or 27.4 Mton CO_2. If this sequestration could be realised over a period of 20 years, we can calculate that 18% of the yearly greenhouse gas (GHG) emissions from agriculture (7.497 Mton CO_2-eq; milieurapport.be 2018) could be compensated. This would be 12% or 9% when calculated over a period of 30 or 40 years, respectively. D'Hose and Ruysschaert (2017) have calculated the **achievable carbon sequestration potential** of four management practices in Flanders, i.e., the area of permanent grassland remains (instead of decrease of 1% per year), the amount of certified compost used in agriculture doubles, the area of cover crops increases with 30% and the cereal straw incorporation increases from 30 to 60%. This would lead to a sequestration potential of 0.173 Mton CO_2 per year or 2% of the yearly emissions from agriculture (7.497 Mton CO_2-eq; milieurapport.be 2018). In later unpublished calculations, ILVO has refined this calculations. The calculations for permanent grassland and cover crops remained but for compost it was calculated how much farm compost could be made with underutilized woody biomass (430,000m³ - Viaene et al., 2017) from small landscape elements (gardens, parks, tree rows etc) in combination with green biomass (see also 3.2 'soil nutrient and organic matter management') and a scenario for agroforestry was added (from 110 ha to 900 ha). The scenario for straw incorporation was omitted because we assume that straw returns to the soil as farmyard manure when not incorporated. With these new calculations the yearly sequestration was 0.112 Mton CO_2 or 1.5% of emissions from agriculture.

Sleutel et al. (2007) also estimated the **carbon sequestration** by several management practices between 1990 and 2002 for **cropland** in Flanders based on **regional scaled input balances**. To assess and compare the ability of different management options for SOC sequestration the amount of 'effective OC' (OCeff) added to the soil was calculated, which is assumed to be the fraction (humification coefficient hc) of the incorporated OC that remains in the soil after one year under field conditions (Hénin and Dupuis 1945). Carbon inputs from green manuring, crop residue incorporation, temporary pastures, organic farming and compost application increased in 2002 compared to 1990 in Flanders, but was offset by a decreased input of carbon via straw incorporation or farmyard manure application and reduced slurry application. This resulted in a net decrease of effective organic carbon added to the soil. However, the shifts in total OC_{eff} input (-0.157 t OCeff ha^{-1} year^{-1}) between 1990 and 2000 could only explain one third of the observed decrease in SOC stock (-0.48 t OC ha^{-1} year^{-1}). Other causes of carbon stock loss could be increasing temperature and the long lasting effect of land use change, being a decrease in permanent pastures between 1970 and 1990 (Sleutel et al. 2007).

The **evolution of carbon stocks under grassland** has also been determined on a regional scale (Belgium, Flanders) in several studies and each reported a loss of carbon for Flanders under grassland. The extent of this loss depended on the method used and the chosen reference year. As mentioned above Meersmans et al. (2011) reported under grassland a loss of 0.019 ton C ha-1 year-1 (0-30 cm) for the 1960-2006 period. Mestdagh et al. (2009) and Lettens et al. (2005a,b) mainly used data from the Soil Service of Belgium (0-6 cm) and Mestdagh et al. (2009) used own measurements for calibrating depth functions to 1m using the Hillinski model. In contrast to Mestdagh et al. (2009), Lettens et al. (2005a,b) did not use agricultural censuses to estimate the area of grassland and arable land, but used so-called 'Landscape Units' (LSU) that link a specific land use (e.g. permanent grassland) and soil type (texture and drainage class). Mestdagh et al. (2009) and Lettens et al. (2005a,b) have calculated a loss of 0.83 and 0.70 t C ha-1 year-1 (0-30cm), respectively for the 1990-2000 period. The loss of carbon under grassland in Flanders was attributed to (i) a decrease of the total grassland area, (ii) the entry into force of the manure action plan in the 1990s (implementation of the Nitrates Directive) and the associated decrease of organic manure application on grassland and (iii) the increase of temporary grassland area to the detriment of permanent grassland.

Forest SOC stocks and the associated uncertainties were computed by averaging forest soil inventory data (De Vos 2009). Van Meirvenne et al. (2001) also collected **geostatistical knowledge** necessary for SOC stock computation of forest soils. The ForSite stocks have been used for the calibration and validation of **spatial SOC models** for the upper 100 cm of soils in natural open habitats in Flanders (Ottoy et al. 2017).

Flanders participated in the European EIONET 2010 data collection project to generate a soil organic carbon map in 2012. Estimates of SOC content on a grid of 1 km x 1 km cells were based on the model of Meersmans et al. (2011). For this model, 629 profiles across Belgium under cropland and grassland from the Aardewerk database were resampled during several field campaigns in the 2004-2008 period. For the **Global Soil Organic Carbon (GSOC) map** (dov.vlaanderen.be) for Flanders in 2017 a different approach was used for agricultural land compared to forest and the map was compiled at 10mx10m m spatial resolution (Poelmans, 2014) and after scaled up to the 40mx40m spatial resolution in accordance of the map of Wallonia. For agricultural soils an empirical SOC model was set up based on data of Meersmans et al. (2011) and Goidts et al. (2009) consisting of 352 profiles in Flanders sampled in the 2004-2008 period and for bulk density a pedotransfer function was used (Manrique and Jones, 1991). For forest soils, a relation between soil carbon stocks and texture-drainage class of the Belgian soil map was set up using 740 profiles in Flanders sampled in the 2004-2008 period.

Recent data on SOC stocks in Flanders and a **carbon monitoring network** are much needed. In preparation, a study (C-MON) was conducted, commissioned by the Policy Department of Environment, for the design, allocation of sampling points and measuring protocols (Sleutel et al., 2021). The C-Gar study collected more data on the expected variability of SOC stocks in public domain and private gardens to optimize the carbon monitoring in these land uses (Sleutel et al., 2020). Within the H2020 Envision project (started September 2020) and the EJP SOIL project STEROPES (started February 2021), ILVO is doing research on mapping soil carbon content of the top soil of bare arable land based on satellite images. In 2019, an analysis of **carbon hotspots in nature reserves** in Flanders was conducted with identification of their main threats and how to protect them in a sustainable way (Ottoy et al. 2020, Truyers et al. 2019, Van der Heyden et al. 2019).

Soil carbon models at the field scale

In the 2000s the advisory tool '**C-simulator'** was developed (Bodemkundige Dienst van België en Universiteit Gent Vakgroep Bodembeheer en bodemhygiëne, 2008) commissioned by the policy Department of Environment. The C-simulator was updated in the first half of the 2010s to the **Demeter-tool** (Demeter) for C, N and P management for Flemish and Dutch farmers (used by the Flemish Land Agency). The tool is based on the **Roth-C model** (using the amount of effective carbon (OCeff) added to the soil as input) and is parametrized for Flemish agriculture (with modified initial pool partitioning of added OM) to predict 0-30cm SOC concentration changes over 30 years in function of agricultural management.

Finke et al. (2015) developed a mechanistic **soil model SoilGen** that includes the carbon cycle for mineral soils (a refinement of the Roth-C model is part of SoilGen). As an integrated model, many feedbacks between SOC, soil hydraulic properties, soil mixing and leaching processes are modelled. It can handle various agricultural activities (ploughing, fertilizing, irrigation and crop management timing: germination, emergence, root and crop maturity, harvest).

Non CO_2-GHG emissions

In Flanders, research on non CO_2-GHG emissions from agricultural soils focused/focuses mainly on soil borne N_2O emissions from managed mineral soils. N_2O is not only a more relevant soil borne greenhouse gas (GHG) in Flanders than CH_4 but is also characterized by a stronger global warming potential. In addition, in Flanders mineral soils are most prevalent, in contrast to organic soils (e.g. peat/black soils).

Today the **GHG emission inventory of soil borne N_2O emissions** in Flanders still relies on a TIER I methodology for direct N_2O emissions and indirect N_2O emissions caused by leaching and runoff, which is based on statistics of N inputs to agricultural soils and the IPCC default emission factors. Indirect N_2O emissions caused by atmospheric deposition are calculated according to a Tier 2 methodology since region-specific emission factors are used.

At this moment, only a limited number of (older) scientifically sound **datasets** on soil borne N_2O emissions is available in Flanders and only a part of these datasets focusses on N_2O emission mitigation (Ameloot et al. 2016, Chaves et al. 2005, Nelissen et al. 2014) while others focused on the monitoring of these emissions from soils characterized by a variety of land uses (arable land, grassland, forest) (Goossens et al. 2001, Van Cleemput et al. 1994), different soil characteristics (e.g. pH) (De Groot et al. 1994) or tillage management (Beheydt et al. 2008, D'Haene et al, 2008). Many of these datasets were obtained via lab-based measurements of (undisturbed) soil cores and were often monitored very frequently but only for a (very) limited time period (Ameloot et al. 2016, Chaves et al. 2005, De Groot et al. 1994, D'Haene et al. 2008, Nelissen et al. 2014, Vermoesen et al. 1996). Field experiments (Beheydt et al. 2008, Goossens et al. 2001, Van Cleemput et al. 1994) were mostly monitored for a longer period (up to 1 or 2 years) but less frequent. In addition, as demonstrated by Goossens et al. (2001) 7% to 76% of total N_2O emissions may arise during winter (October-February).

When considering non-CO_2 greenhouse gas emission **modelling** in Flanders, focus is put on soil borne N_2O emissions from managed mineral soils. Estimates of regional N_2O emissions can be obtained via simulations. In Flanders, the **DNDC model** (process-based, requiring a high number of input parameters) was used for this purpose (Beheydt 2006). The simulated emission data were validated by a limited number of field measurements. Emissions from cropland were consequently overestimated. In addition, low similarities were obtained for N_2O emissions originating from (temporary) grassland, while in fact the highest measured emissions originated from temporary grassland. Consequently, for this application the DNDC model requires further optimization. Indeed, crop rotations, crop residues, permanent grassland, variation in spatial and temporal N application and WFPS (water filled pore space) depth gradients are not yet taken into account. However, the DNDC model could identify the following regions as most important contributors to total N_2O emission: the Sand Region, Sand-Loam Region, Campines and Polders.

Other (statistical) models were used by Roelandt et al. (2007) to simulate past and future temporal N_2O emissions trends at regional and national scale in Belgium. Despite reasonable agreement of simulations with historical data, a major factor limiting the reliability of their future projections were uncertainties in historical data. These uncertainties are caused by the limited number of (older) scientifically sound **datasets** on soil borne N_2O emissions that is available in Flanders. In addition, only a part of these datasets focusses on N_2O emission mitigation and many of these datasets were obtained via lab-based measurements on (undisturbed) soil cores for a (very) limited time period. Therefore, there is a general need for high-quality environmental datasets. Such datasets could contribute to the development of a better reporting to the IPCC according to a Tier III methodology.

In 2009, in Flanders, a model for the calculation of the NH_3 emissions for the agricultural sector was developed (Foqué and Demeyer 2009). This model called **EMAV (Emission Model Ammonia Flanders)** calculates the NH_3 emission in different emission stadia taking into account the manure flow throughout the farm (from stable over external manure storage to manure application on land and excretion by grazing animals). Direct soil NH_3 emissions from mineral fertilizer use and the application of manure are calculated using this EMAV model. Currently, in the *'Uitbreiding EMAV 2.1 niet-energetische emissies landbouw'* project commissioned by the Vlaamse Milieumaatschappij (VMM), this model is being extended by ILVO for N_2O and NO emissions and a new emission stadium accounting for emissions originating from (soil amended) crop residues will be introduced.

Studies that measured the impact of management practices on N_2O emissions focused on biochar (Ameloot et al. 2016, Nelissen et al. 2014), N-immobilizing materials to lower the impact of high-N crop residues (Chaves et al., 2005; Agneessens et al., 2014), cropland versus grasslands and grassland management (De Groot et al., 1994; Goossens et al., 2001, Van Cleemput et al. 1994) and reduced tillage (Beheydt et al. 2008; D'Haene et al., 2008). More information can be found in section 3.2 Soil management.

Soil erosion

Soil erosion is one of the major soil degradation processes in Flanders. Indeed, the **potential soil erosion** (by water) map of Flanders (Oorts et al. 2019a,b) shows that approximately 25% of agricultural soils could potentially be affected by soil erosion. These soils are especially situated in the southern regions, that are characterized by a hilly landscape and a sandy loam to loam soil texture. The potential soil (water) erosion map of Flanders (Oorts et al. 2019a,b) considers factors such as soil type (texture), slope and slope length, but not current crops and measures taken by farmers, and is yearly updated to reflect changes in field parcel borders. It estimates the mean annual total potential erosion per field parcel and subdivides the field parcels into different erosion risk classes. Water erosion is calculated according to the **RUSLE** formula (Renard et al, 1991) taking into account soil type, shape of the field parcel and rain erosivity. Topographic factors (slope and slope length) are calculated according to a modified 'stand-alone LS module' from the **WaTEM/SEDEM** model developed at KU Leuven (Oorts et al. 2019a,b; Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002). This model can also be used to estimate erosion by tillage (Notebaert et al., 2005), but currently, erosion by tillage is not taken into account in the potential soil erosion map.

In 2020, a **soil erosion risk indicator** (based on the RUSLE model) was introduced which is based on the modelled yearly risk of soil losses by water erosion. This indicator is currently available for the 2008-2019 period (Swerts et al. 2020). Unlike the potential soil erosion map, this indicator does take current crops and measures taken by farmers into account. It is not only used to obtain an indication of the evolution of the soil erosion risk but also allows to estimate the impact of policy measures (e.g. manure action plan). Since 2016 (when stricter legislation was introduced for soil erosion through CAP-cross compliance), the erosion risk is decreasing due to the use of less erosion sensitive crops and targeted erosion management strategies. In addition, a **sediment indicator** (based on WaTEM/SEDEM model) will be introduced in 2021 to estimate the risk of sediment transport to water courses.

Apart from soil erosion by water and tillage (Van Oost et al. 2000), erosion can also be attributed to **root and tuber crop harvesting** (e.g. potato and sugar beets). The latter was demonstrated both in Belgium and at European scale (Panagos et al. 2019, Ruysschaert 2005, Ruysschaert et al. 2005, 2006, 2007a, b). In Flanders, Ruysschaert et al. (2008) calculated that the net sediment export from cropland in 2002 was for 46% due to crop harvest and 54% due to sediment export by water erosion. Average soil losses due to crop harvest were calculated to be 1.7 ton ha^{-1} $year^{-1}$.

Two **wind erosion** risk maps were developed (Van Kerckhoven et al. 2009) based on the American Wind Erosion Equation Model (WEQ): a potential and an actual wind erosion risk map. In contrast to the first map, the latter does take a vegetation factor into account. However, the applied model has several limitations and therefore these maps can only be used to obtain an indication of the risk on wind erosion in a specific area.

A **landslide sensitivity map** was made by Van Den Eeckhaut et al. (2009) for the area west of Brussels in the south of the provinces of West Flanders, East Flanders and Flemish Brabant (www.geopunt.be). The map is based on a logistic regression model using a 10 by 10 m grid and predicts the probability of a landslide based on the slope gradient, the orientation of the slope (NW, W, ZW and Z), and the presence of certain lithostratigraphic units.

Several impacts of soil erosion on soil properties can be simulated via the **SoilGen model**, which also allows the simulation of soil degradation regarding acidification, clay leaching and fertility (Finke and Hutson 2008, Finke et al. 2015).

When studying the impact of erosion from agricultural soils on the global carbon cycle Van Oost et al. (2007) indicated that erosion can result in an increase of the **terrestrial C sink** for atmospheric CO_2.

Soil Compaction

In Flanders, both **soil compaction sensitivity and soil compaction risk maps** were developed (at soil pF values of 1.8 and 2.5) (Van De Vreken et al. 2009). Soil sensitivity maps are based on the pre-compression stress of soils which is a measure for structural strength of a soil or the maximal vertical pressure that can be supported by a soil without losing its elasticity. These values are estimated via pedotransferfunctions and are especially valid for soils that did not or only minimally suffered from soil compaction since only historical data were available for the estimation process. However, the maps can serve to indicate regions which are vulnerable to soil compaction. Soil compaction risk maps on their turn express the maximal wheel load at the recommended optimal tire pressure that can be applied to soils without risk on creating a vertical pressure that causes exceedance of the pre-compression stress at a certain soil pF value. The latter risk maps were developed for both a tire type typical for a tractor and one typical for a harvester (Van De Vreken et al. 2009). It is not known to what extent actual soil compaction is a problem in Flanders although we can assume that many field parcels are affected due to the use of heavy machinery and harvest under wet conditions late in autumn. Interviews conducted by the European project RAISOILCOMP pointed out that 34% of the Belgian farmers who participated are confronted with (deep) soil compaction. Further, 30% of those farmers indicated that they lack knowledge on effective remediation measures (Hack-ten Broeke, M., 2015).

The **Terranimomodel®** was adapted for soils in Flanders and allows farmers to simulate the impact of agricultural machinery, tyre pressure, tyre type, soil types and soil moisture conditions on the risk for soil compaction by field trafficking (Schjønning and Lamandé 2020). The tool primarily assesses whether stresses exceed the soil mechanical strength – hence likely inducing plastic/permanent deformation of the soil – for a specific traffic event. The vehicle-induced stress transmission in relation to soil compaction was also modelled by De Pue with the **discrete element method (DEM)** (De Pue and Cornelis 2019, De Pue et al. 2019, 2020a,b).

Furthermore, research in Flanders also concentrates on alternative indicators for soil compaction using UAV images for crop height indicators and EMI soil scans (Ren 2020) and on the evaluation and development of indicators for soil (physical) quality (Pulido Moncada et al. 2014a,b,2015a,b, 2018).

Nutrient retention and use efficiency

In Flanders, the soil fertility and nutrient status of soils is not monitored in an independent and statistically sound monitoring network but can be deducted from the soil analyses performed by the Soil Service of Belgium commissioned by farmers for the 2012-2015 period (Tits et al., 2016) and the 2016-2019 period (Tits et al., 2020).

Belgian agricultural soils are generally characterized by a high mean **plant available P** content. Indeed, in more than 78% of the arable fields and 57% of the grasslands this P content exceeds the optimal range (2012-2015 period). The Flemish VLM project "An economical and environmental friendly increased phosphorus use efficiency" (Amery et al. 2019), selected the best P-tests to assess both crop performance and P leaching risk and defined the optimal soil P-status for both crop growth and minimized leaching risks based on data of long-term field experiments in Europe, long-term pot trials and leaching experiments (Amery et al. 2019, Nawara et al. 2017).

The **pH-KCl** of 51% of the arable fields and 31% of the grasslands is lower than the optimal pH range. Within this group of arable fields, 16% was even characterized by a low to strongly acid pH (2016-2019 period) (Tits et al., 2020). Soil pH affects the nutrient use efficiency of both N and P. Low pH values increase the risk on N leaching due to a reduced N-uptake by plants and the coupled reduced plant growth. An optimal pH is also required for an efficient phosphorus use since crops require a higher soil P content for an optimal yield when the soil is characterized by a suboptimal (to low) soil pH.

Flanders is a **Nitrate Vulnerable Zone** according to the Nitrates Directive and the Manure Action Plan limits the amount of fertilizer that can be used. The amount of residual nitrate in the 0-90 cm soil layer is measured on field parcels between 1 October and 15 November reflecting the farmers fertilization activities and indicating the nitrate leaching risk during winter. In order to evaluate the residual soil nitrate limit value in the 0-90 cm soil layer and to differentiate this limit value according to soil texture and crop type, the **WAVE model** was used (N-(eco)^2 2002). The WAVE model (Water and Agrochemicals in the soil and the Vadose Environment) describes the transport of matter and energy in the soil, crop and vadose environment (Timmerman and Feyen 2003). The model consists of separate subroutines for water, solutes, nitrogen and heat transport as well as submodules for all N-transformation and uptake processes (Vanclooster et al. 1996). This model was also used in the ECOFERT project (2008-2012) about online monitoring and developing a model-based support system for just-on-time N fertilization in open field horticulture. For MAP6 (Manure Action Plan 2019-2022), the theoretical calculation of N losses during the winter period was based on model simulations using **EU-rotate-N**.

In Flanders, **P concentrations in surface and ground waters** are exceeding EU limits. Mabilde et al. (2017) used correlation analysis and **structural equation modeling (SEM)** to assess driving factors for groundwater orthophosphate concentrations in Flanders. On the other hand, Warrinnier et al. (2019) evaluated in their study the use of **surface complexation** modelling (SCM) to describe phosphate leaching from various soil columns and to better understand the involved mechanisms, including understanding effects of different fertilizer types on P mobility. They concluded that SCM can explain the leached P concentrations from unsaturated soil columns with contrasting properties. For predictions at a larger scale, they suggest that the parameter poor **Langmuir model**, which is based on Fe and Al oxyhydroxides in soil, is the preferred model for P leaching.

For Flanders, the **NEMO model** is used to provide insight into current and future water quality (VMM 2016, Van Opstal et al., 2014). The model calculates how nitrogen and phosphorus pass through soil and groundwater into watercourses in agricultural areas. As input for the NEMO model the amount of fertilizer (both mineral and organic) yearly applied to agricultural parcels is calculated using the **BAM model (fertilizer allocation model)**. For mineralization and immobilization of N and P, the Roth-C model is used describing C dynamics based on 5 pools in the 0-30 cm soil layer. As main input parameters for the Roth-C model meteorological data and amount and quality of applied exogenous organic matter (animal manure and crop residues) are needed. To describe the P-dynamics (P-retention and P-release) in the soil and possible drainage losses, the Langmuir adsorption isotherm for acidic sandy soils is used. As such, the P concentrations in ground and surface water can be better estimated.

Salinization

Until now, salinization was not regarded as an important soil challenge in Flanders. However, especially in coastal regions in Flanders, salinization is gaining more attention due the dry summers we have experienced in the past years and due to future expected impacts of climate change. It is currently not known to what extent soils in Flanders are affected by salinization. A first survey in 18 field parcels in the Flanders coastal region was conducted by the SALFAR Interreg-project (Ampe et al. 2019).

Soil ecosystem services

In Flanders, an ecosystem assessment was carried out in which soil fertility and in general the soil quality (soil biodiversity, soil nutrient retention, water storage capacity, soil structure) of agricultural soils in Flanders was evaluated based on literature (Cools and Van Gossum 2014, Nelissen et al. 2016, Stevens et al. 2015).

In the ECOPLAN project Antwerp University developed the **ECOPLAN toolbox** (Staes et al. 2016) to support policy and to evaluate ecosystem services such as those delivered by soil (water infiltration, water retention, carbon and nutrient storage, avoided erosion). The **QuickScan tool** for example reveals how many ecosystem services an area delivers (in biophysical units) and what values are associated with it (in monetary terms). The **simulation tool SE (scenario evaluator)** is a QGIS plugin for ecosystem services supply. This integrated model allows to calculate and to compare different scenarios which are often considered for spatial development projects. The analysis can help in the development of a more multi-functional project design and with the communication to the wider public.

3.2 Soil management

Grasslands and management

In Flanders almost 30% of the agricultural area is under permanent **grassland**. It is known that grassland can store more carbon than arable land. The high carbon storage potential combined with a significant area means that grassland can play an important role in the fight against climate change. In a long-term field experiment (duration of 10 years) initiated by Mestdagh (2005) on a sandy loam soil in Flanders the conversion from cropland to grassland resulted in an increase in soil organic carbon of

0.47 ton C ha^{-1} $year^{-1}$ in the 0-30 cm layer and 0.64 ton C ha^{-1} $year^{-1}$ in the 0-60 cm layer (D'Hose and Ruysschaert 2017b). This is in line with studies found in literature where carbon sequestration rates of 0.5 to 1.0 ton C ha^{-1}.$year^{-1}$ were found. The reverse effect, converting from grassland to arable land, results in an average loss of 1.0-2.0 ton C ha^{-1} $year^{-1}$ (D'Hose and Ruysschaert 2017b), but no exact numbers for Flanders exist.

The longer grassland remains on the same parcel, the more carbon is stored. Permanent grassland (maintained as grassland for at least five consecutive years) will therefore generally store more carbon than temporary grassland. More research is needed on the relationship between permanent grassland age, ground water table level and carbon stocks. This knowledge could serve as a basis to pay farmers for keeping grasslands longer at the same place. Farms managing temporary grassland, can also keep it for a longer period (e.g. 4 instead of 2 years) in order to increase the carbon stock in the soil. In this so-called **ley farming system** temporary grassland and arable crops alternate, leading to a sequence of carbon build-up and decomposition. In this context, a field trial for more than 30 years was established by Ghent University comparing three management systems: permanent grassland, ley farming and permanent arable land (Nevens en Reheul 2001, 2002,2003; van Eekeren et al., 2008).

Grassland management can also influence the build-up of carbon. The impact of grassland management, both based on national and international literature is summarised in D'Hose and Ruysschaert (2017b). For example, grazing can lead to a higher carbon build-up than mowing alone (Mestdagh et al. 2006). However, when considering grassland management, not only carbon sequestration should be considered but the total greenhouse gas balance, such as CH_4 and N_2O emissions and emissions caused by production of mineral fertilisers. The intensity of grassland exploitation plays a role in the carbon sequestration potential: both intensive and extensive grazing or mowing management leads to lower carbon stocks than intermediate management. However, more research should be conducted on the optimal exploitation intensity in function of carbon sequestration in the Flemish context, both for mowing and grazing. In order to maintain/increase the quality and production of grassland, grassland renewal (destroying and resowing) is an option. However, the effect of renewal on carbon build-up has so far been underexposed in Flemish research, as well as the effect of the introduction of other grass species (e.g. reed fescue grass) and butterfly-flowers. It is expected that their relevance will only increase in Flanders in view of the changing climate (e.g. reed fescue shows a higher drought resistance than English rye-grass) and the stimulation of the cultivation of leguminous plants (e.g., through CAP). Finally, fertilisation also plays its role. The application of livestock manure leads to a higher carbon build-up under grassland than when only mineral fertiliser is applied. The type of manure is important here. Cattle manure will add a larger amount of carbon to the soil than pig manure.

Apart from carbon sequestration or emissions, **land use** also affects **soil borne N_2O emissions**. Indeed, Goossens et al. (2001) measured N_2O emissions in three major agricultural areas in Belgium in both grassland and cropland. Intensively managed grassland (both mowing and grazing regime were studied) and mown temporary grassland were characterized by larger emissions (14-32 kg N ha^{-1} $year^{-1}$) as compared to cropped arable land (0.3-1.5 kg N ha^{-1} $year^{-1}$) and seemed to have larger N_2O-N losses per unit of fertilizer N applied. Important to note is the difference in fertilizer doses (up to 500 kg N ha^{-1} for grassland) that were applied according to the conventional agricultural practices at that time, and which may have contributed to observed differences. Likewise, Vermoesen et al. (1996) observed highest N_2O emissions in grazed permanent grassland (11.9 kg N ha^{-1} 435 $days^{-1}$) as compared to non-grazed temporary grassland (3.35 kg N ha^{-1} 312 $days^{-1}$) and a maize field (2.7 kg N ha^{-1} 312 $days^{-1}$). These higher emissions were attributed to a higher soil compaction, a high moisture content and a high nitrogen input.

Soil tillage and soil cover

Non-inversion/reduced tillage is quite well studied in Flanders since the early years 2000. In Flanders, non-inversion tillage is mostly conducted to ploughing depth or even deeper, since it has been shown that superficial conservation tillage may contribute to compaction (Van den Putte et al. 2012). This can be explained by late harvest under wet conditions and traffic by heavy slurry tanks causing compaction that needs to be lifted in order to avoid problems with crop growth and soil erosion (Vermang 2012). Therefore, results from international literature on reduced or even no-till cannot always be translated to the Flemish farming context. At first, in the early years 2000, most of the research on non-inversion tillage focused on water erosion, later also the effects on soil organic carbon and soil physical, chemical and biological properties were investigated. Research was conducted mostly on loamy or sand loamy soils both at farmers' fields (mostly strips with different tillage practices) and in longer term field experiments with multiple factors.

Through the implementation of non-inversion tillage (in combination with a cover crop before) sediment loss by water erosion (measured with rainfall simulations or gully volumes) can be reduced up to 85 %, having a positive impact on soil structure and reducing soil erosion (Leys 2008, Reubens et al. 2012, Valckx 2011, Van den Putte 2011, Ryken et al. 2018, Vanden Nest et al. 2019, Vermang 2012). The impact on carbon storage in the soil is less clear but in general non-inversion tillage, as implemented in Flanders, causes a redistribution of soil organic carbon with no proven increase in carbon stocks (D'Haene 2008, D'Hose et al. 2016, Vermang 2012, Willekens et al. 2014a). Kader et al. (2010) observed increased organic carbon contents in the 0-10 cm soil layer in 6 out of 7 silt loess soils, when non-inversion tillage was applied.

Due to the accumulation of organic matter in the top soil, mineral N, that is released from soil organic matter, is situated higher in the soil profile and might be better utilized by the crops (D'Hose et al. 2016, Willekens 2016, Willekens et al. 2014a, Willekens et al. 2014b). In addition, there is less risk of acidification and nutrients (mineral N and alkali elements) are less prone to leaching.

Non-inversion can have positive effects on soil organisms. The presence of beneficial soil fungi in the 0-10 cm top soil layer was shown to be favored (Willekens 2016). The impact of reduced tillage on the abundance of earthworms and their potential positive impact on soil erosion were investigated by Valckx (2011). The effects of compost, biochar and non-inversion tillage on soil biodiversity at molecular level are investigated more in depth in an on-going PhD-research at ILVO and UGent (Joos et al. 2020).

Besides this, reduced tillage might also have adverse effects as it may contribute to stimulated soil borne N_2O emissions due to higher soil moisture content (Beheydt et al. 2008). Indeed, minimal tilled soils (no ploughing, disking, etc.) cropped with maize and summer oat emitted significantly more N_2O-N (5.00 and 3.37 kg N_2O-N year^{-1}, respectively) over 1 year compared to a conventionally tilled (ploughing, disking) soil cropped with maize. Per kg of applied N, up to 0.04 kg N_2O-N was lost via N_2O emission in the minimum tilled soils, while this was only 0.001 kg N_2O-N for the conventional tilled field. In contrast to the conventional tilled soil, the minimum tilled soils were not drained, which probably contributed to a higher soil moisture content (60-65% compared to 43% Water Filled Pore Space (WFPS)). Soil texture could have affected the N_2O emissions as well, since the minimum tilled soils could be classified as silty clay loam while the conventional tilled soil was characterized by a silt loam texture. Furthermore, fertilizer management and residue management effects were not considered. Although application of a DNDC model allowed to obtain an rough estimate of the total N_2O emission, an appropriate simulation of the N_2O emission patterns could not be obtained. Despite D'Haene et al. (2008) also monitored higher N_2O emissions (10 days, laboratory conditions) when non-inversion tillage management was applied, further research is required to confirm these results.

Bijttebier et al. (2018) studied the barriers and drivers for non-inversion tillage for eight different farming type zones across four European countries. In Flanders drivers and barriers for non-inversion tillage were studied in 2013 for arable farms on loamy soils and dairy farms on sandy soils (Bijttebier and Ruysschaert, 2014). Adoption rates on at least one parcel were relatively low, i.e., 19% in dairy farms and 23% in arable farms despite the fact that the practice was encouraged, especially in the area of the arable farms, for erosion control. Barriers mentioned included higher risks on bad seedbed preparation, more weeds and crop diseases, no appropriate machinery available and already good results with ploughing. Less water erosion, less labour intensive and lower fuel use are examples of drivers that were mentioned by farmers in Flanders.

In order to prevent <u>on-site erosion</u> during maize and vegetable growing, non-inversion tillage techniques were further optimized, not only looking to the main tillage operation (ploughing vs non-inversion tillage) but also the combination with a.o. **seedbed preparation** (roughness) and **tillage depth** in autumn in the national GOMEROS project (2015-2019; VLAIO LA project). Besides non-inversion tillage, also other newer techniques were investigated in this project such as **strip tillage** and **broadcast sowing** (Vanden Nest et al. 2019). Other studies focused on off-site erosion control via the construction of e.g. **buffer collection systems** (Meert and Willems 2013).

Studies on the **reduction of <u>soil compaction</u>** have been started in Flanders since the second half of the years 2000. Several techniques reducing soil pressure (e.g. by low pressure tires) and the effect on crop productivity and soil quality have been tested both at farmers' fields and in field experiments (a.o., Elsen et al. 2014; Ren et al. 2019a). In the Interreg-project PROSENSOLS several techniques to avoid soil compaction are described (www.levendebodem.eu/Artikel/guid/4758). Adjusting tire pressure during slurry spreading demonstrated to have only limited effects on soil structure. In this case, the effect of soil moisture content was more pronounced (Ren et al. 2019a, D'Hose et al., 2017a). Favorable soil moisture conditions are thus an important factor to avoid wheel track compaction (Ryken et al. 2018).
Besides prevention, also several techniques for **remediating (sub)soil compaction** were investigated (e.g. deep tillage, deep rooting crops) in e.g. the PROSENSOLS project, but an integrated approach is still missing. Among deep rooting crops, white mustard roots were demonstrated to have an higher ability to penetrate compacted subsoil layers compared with winter rye (Ren et al. 2019b).
Currently, measures for soil compaction prevention (wheel load, tire inflation pressure, machine configuration, controlled traffic) and remediation (cover crops, crop type and rotation, tillage, soil improvers) are further tested in the 'Bodemverdichting (soil compaction)' project (VLAIO-LA; 2018-2022; ILVO, UGent, BDB, INAGRO) in close collaboration with farmers and other stakeholders. Focus is put on knowledge transfer and the continued expansion of the decision support tool Terranimo©.
In addition, vehicle-induced stress transmission in relation to soil compaction was modelled by De Pue (De Pue and Cornelis 2019, De Pue et al. 2019, De Pue et al. 2020a, De Pue et al. 2020b).

Crop and cropping system

Crop rotations are still quite understudied in Flanders. However, as legislative restrictions on the use of organic and mineral N and P fertilizers became more strict over the years (Manure Action Plan - Nitrate Directive) and due to a quest for sustainable farming systems, crop rotations are gaining more attention again. In Flanders, so far only few studies investigated the effects of crop rotations on soil quality and crop productivity (D'Hose 2015, Nevens and Reheul 2001, 2002, 2003, van Eekeren et al. 2008). The beneficial ability of crop rotations to increase crop production was demonstrated by Nevens and Reheul (2001, 2002) who compared different maize based cropping systems during a 14-year period in a field trial that was started in 1966 on a sandy loam soil in Melle. Forage maize in a ley-arable rotation and forage maize in a rotation with fodder beet and field bean, resulted in most cases in higher yields than maize monoculture on permanent arable plots. The rotation effect was mainly postulated as a N-contribution effect. Especially the inclusion of temporary grassland in the crop rotation (ley-farming) contributed to stimulated N mineralization in addition to an improved soil structure and quality (Nevens and Reheul 2002, van Eekeren et al. 2008). van Eekeren et al. (2008)

determined a wide array of chemical, physical and biological soil properties during a three-year period in the by then 36 year old field experiment. It was concluded that the ley-arable crop rotations were intermediate to permanent grassland and continuous arable land in terms of soil organic matter, soil structure and functioning of soil biota (e.g., N-mineralization). A similar experiment was studied by D'Hose (2015) on a sandy loam soil in Bottelare. After a period of 5 year no significant effects on overall soil quality or crop yields that could be ascribed to the introduction of a grass-ley or an extended crop rotation were revealed. This leads us to the conclusion that positive effects of crop rotations on the overall soil quality are only noticed after longer time periods.

The effects of a first generation **bioenergy crop** (maize) and three different second-generation bioenergy crops (willow short rotation coppice (SRC), *Miscanthus x giganteus*, switchgrass) on soil quality were investigated in a longer term field experiment in Melle at ILVO (2007-2016). While Miscanthus and switchgrass only had similar or worse effects on soil quality than maize, willow SRC did improve soil fertility and biodiversity in the upper soil layer when compared to maize. Schrama et al. (2016) found higher total organic carbon concentration in the upper (0-5 cm) soil layer for short rotation coppice with willows compared to *Miscanthus*, switchgrass, or maize. They also found that soil taken from these willow SRC field plots positively impacted the wheat production and disease suppresiveness in an coupled greenhouse experiment (Schrama et al. 2016).

In the study of Xu et al. (2019) the central question was whether collection of grain **maize** residues for energy production is detrimental for SOC. It appeared that above ground residues are not so important for SOC, but that the largest contribution is by roots and exudates. The root biomass of maize adds twice or even three times as much to the build-up of stable soil organic matter in the soil as the above-ground crop residues (maize straw) do. At the University of Antwerp, mesocosm experiments with maize were conducted investigating the role of nutrients (P addition) and mycorrhizal fungi on above- and belowground C fluxes (Ven et al. 2020, Ven et al. 2019).

Cover crops can enhance soil nutrient use efficiency by preventing N leaching (De Waele et al. 2014, Hermans et al. 2010). Cover crops also add carbon to the soil (De Waele et al. 2014). Sleutel et al. (2007) estimated that green manure adds 0.34 t EOC ha^{-1} $year^{-1}$ (effective organic carbon; i.e., carbon remaining in the soil after one year) to the soil and if it would be applied on the maximum cropland area of 93.000 ha in Flanders, an increase in EOC of 31.6 kton C $year^{-1}$ could be obtained. The effect on SOC will depend on the type of cover crop and the biomass yield: a short growth period or reduced growth due to late harvesting of the main crop or due to poor soil and weather conditions leads to a limited biomass yield and consequently a low amount of carbon added to the soil. There are no longer term field experiments in which cover crops are a separate factor in Flanders. Recently, ILVO reviewed literature for effective organic carbon by cover crops (De Boever et al., not published yet). All data available appeared to be for well-developed cover crops. Therefore, above and belowground biomass data from various field experiments and humification coefficients from several sources where compiled and correlations were made between sowing data and effective organic carbon for several cover crop types. These data could serve as input in carbon models such as Roth-C. A similar data collection was done for different energy crops such as rapeseed, grain and silage maize, SRC willow, sugar beet, winter wheat and spring barley (unpublished data ILVO).

Agroforestry and more specifically alley cropping systems (trees in or bordering arable fields) are gaining attention in Flanders. Due to a lack of mature arable alley cropping systems in Belgium, a set of arable fields bordered by a row of highpruned trees of moderate to older age (15-47 years) was selected as a proxy by Pardon et al. (2017). Significantly higher soil organic carbon (0-23 cm) and soil nutrient concentrations were observed in the vicinity of trees in field boundaries, most likely resulting from the input of tree litter and nutrient-enriched throughfall water (Pardon et al. 2019, Pardon et al. 2017). Observed increases were strongly related to the distance from the tree row, resulting in a

gradual change in soil conditions up to at least 30 m into the field. Significantly higher SOC concentrations in the plough layer resulted in an average increase in SOC stock of 5300 kg ha^{-1} within the field zone (i.e. between 2 and 30 m to the field edge with the threes). A carbon sequestration potential of 0.21 ton C ha^{-1} $year^{-1}$ was calculated. Moreover, the trees and the associated understory vegetation strip have been shown to contribute to the preservation of arthropod biodiversity and the enhancement of associated ecosystem services in both the tree rows and in the arable field zone.
Due to the short study period, no significant effects on soil characteristics were noticed in the young alley cropping systems but these fields are still being monitored in the framework of other agroforestry projects, in which also the impact of agroforestry on soil water management, biodiversity and soil fertility will be further investigated (www.agroforestryvlaanderen.be) .

The impact of **hedgerows** was studied by Van Vooren (2018). Compared to the plots at 30 m from the hedgerows, average soil organic carbon stock in the 0–20 cm soil layer was slightly higher in the plots at 1 m from the hedgerow (8% higher) (Van Vooren 2018). Crop yield was reduced and winter wheat thousand kernel weight was increased. Mineral nitrogen content was not affected in this study. Activity-density of spiders was increased while of carabids appeared not to be affected (Van Vooren et al. 2018).

Van Vooren (2018) also investigated the conversion of arable land into **grass strips** at field boundaries. Compared to an average SOC stock (0-20 cm) of 27.17 ton ha^{-1} in the adjacent parcel, conversion of arable land into a **grass strip** has resulted in a yearly SOC stock increase of 1.60 ton ha^{-1} $year^{-1}$ (based on the average age of the sampled grass strips and the average SOC stock in the adjacent parcels).

Short rotation coppice with **willows** (SRCW) in a free range area for chickens had no significant effect on soil organic carbon in a plantation of max 4 years old compared to adjacent grassland (Stadig 2017). In an follow-up study a slight trend of increasing SOC was observed in the top 30 cm soil layer as compared to the adjacent grassland. Total mineral N (Nmin) was affected by interactions between vegetation type, location, and soil depth; it was generally higher in SRCW than in grassland and in areas close to the chicken houses (Stadig 2017). Nmin did not appear to accumulate in the soil over the years, but there were strong indications for higher risk of N leaching to deeper soil layers and possibly to groundwater close to the chicken houses and in short rotation coppice with willows.

Soil nutrient and organic matter management

The effects of the **use of organic fertilizers** is quite well studied in Flanders. Effects of repeated use of **(farm)compost** applications on soil quality and crop productivity have been extensively investigated (Arthur et al. 2011a, Arthur et al. 2011b, Cougnon et al. 2008, D'Hose et al. 2012a,b, D'Hose et al. 2014, D’Hose et al. 2016, De Clercq et al. 2013, Elsen et al. 2011, Gybels et al. 2013, Tits et al. 2014, Willekens 2016, Willekens et al. 2014a). Combining the results of different Flemish long term field trials revealed that applying 1 ton carbon by means of compost results in a longer term carbon sequestration of 0.26 ton C (D'Hose and Ruysschaert 2017b). Beneficial yield effects of repeated farm compost application at non-N-limiting circumstances are not consistent. While D'Hose et al. (2012b) demonstrated significant yield effects after four years of repeated compost application, significant effects on crop dry matter yields were lacking in a study by D’Hose et al. (2016), despite the observed soil quality improvements and the increased nutrient levels following repeated compost application. Long term applications of compost may enhance soil available potassium, extractable phosphorus and may result in increased N availability and improved physical soil fertility. Repeated compost amendment was also identified as a successful management practice to increase soil water content at saturation in the 0-10 cm soil layer in a loamy sand soil (Arthur et al. 2011b). In a sandy loam soil, significant higher water contents at especially low pF values were observed after two years of repeated compost application in the 0-10 cm and 10-30 cm soil layer, while after for years of repeated compost application similar

significant effects were found in the 10-30 cm soil layer (D'Hose et al. 2016). However, as was the case for its effects on reduced soil bulk density (Arthur et al. 2011b, D'Hose et al. 2016) and increased soil macroporosity, the significance of these effects on the long term could not be demonstrated yet (Arthur et al. 2011b). On the other hand, soil biological properties were significantly improved by long term compost treatments. This was demonstrated by an increased microbial biomass-C, microbial activity, improved disease suppressiveness, increased number of earthworms, and a stimulation of several other specific groups of organisms (D'Hose 2015, D'Hose et al. 2014, D'Hose et al. 2016, Moeskops et al. 2012, Steel et al. 2012, Verbruggen et al. 2010, Willekens 2016, Willekens et al. 2014a). The effects of compost, biochar and non-inversion tillage on soil biodiversity at molecular level are investigated more in depth in an on-going PhD-research at ILVO and UGent (Joos et al. 2020). Through field experiments, the influence of mycorrhiza on soil C storage (Verbruggen et al. 2015, Verbruggen et al. 2017), and agricultural management (organic farming) on mycorrhiza was also investigated (Verbruggen et al. 2010, 2012, 2014).
Adoption of compost application in Flemish agriculture is still rather low. In 2016, only 13% of the VGF and green compost certified by Vlaco was used in agriculture, but this number has increased in recent years to ca. 20% (VLACO, 2020). Viaene et al. (2016) studied the barriers for compost use and on-farm composting in Flanders. For compost application barriers include the surplus of animal manure, complex regulations, availability and quality of the compost. The shortage of woody biomass, strict regulation, considerable financial and time investment, and lack of experience and knowledge are the main barriers hindering on-farm composting. The current Manure Action Plan (MAP6) and the upcoming Action Plan for food loss and biomass (waste) streams (2021-2025) (*Actieplan voedselverlies en biomassa (rest)stromen circulaire*) try to overcome some of these barriers by for example facilitating the collaboration between farmers and also between farmers and nature area managers to recycle biomass residues in on-farm compost to be used on arable fields. ILVO (unpublished) calculated that the local closing of cycles with farm composting could correspond to a potential soil carbon storage of 5.6 kton C year^{-1} when woody biomass (430,000m^3 - Viaene et al., 2017) from small landscape elements (gardens, parks, tree rows etc) would be used in combination with green biomass.

By combining data from Flemish and international field trials, D'Hose and Ruysschaert (2017b) recorded that per tonne of added carbon in the form of **farmyard manure** 0.20 ton C is stored in the soil in the longer term. Compared to compost, increasing the SOC content via **farmyard manure** results in a higher P availability at similar doses of P addition, but also increases the P leaching risk (Vanden Nest 2015, Vanden Nest et al. 2014, 2016).

Animal slurry contains less stable organic matter compared to compost and farmyard manure. Experimental field data of repeated application of a common dose of cattle slurry indicated that slurry sequesters approximately half the rate of farmyard manure when applying the same carbon dose (Vanden Nest et al. 2014). As indicated by D'Hose et al. 2016 the type of animal slurry also influences the carbon sequestration potential. After a period of 5 years (i.e.2010-2014) the repeated application of cattle slurry significantly increased SOC content (+0.07%-point) while similar effects were lacking in the plots with pig slurry (+0.01%-point).

Besides animal slurry, also the carbon sequestration potential of different types of **digestates** was tested in multi-year field trials in Melle (commissioned by VLACO) by Vanden Nest et al. (2015). The study period was too short to detect significant differences in soil organic carbon content but experiments are still running.

Biochar application to soils has gained interest as a climate change mitigation strategy, since it could act as a long-term carbon sink. Since 2011, a long term field trial was established at ILVO (Merelbeke) with **biochar** (2 types) and **biochar-compost** (Interreg project 'Biochar: climate saving soils', EU FP7 project 'Fertiplus'). It was demonstrated that the effect of pure biochar on soil quality, apart from SOC

increase, is limited because of its stability (Nelissen 2013, Nelissen et al. 2015). A single application of biochar, compost and biochar-blended compost (biochar added during the composting process to reduce GHG emissions and N loss) increased the C content of the top soil in the long term, but only compost and biochar-blended compost had a lasting effect on pH and the K content. However, the difference in soil pH, potassium availability and levels of N release between compost and biochar-compost were not significantly different. Soil physical and microbiological parameter were not positively impacted in the first four years after a single application (D'Hose et al. 2020).
In lab scale experiments, amendment of biochar to natural and reconstructed soil samples resulted in a decreased (50-90%) N_2O emission when nitrate fertilizer (KNO_3) was applied (Ameloot et al. 2016, Nelissen et al. 2014). Likewise, N_2O emissions were reduced when urea fertilizer was applied in biochar-amended reconstructed soil cores. In contrast, no effect of biochar amendment on N_2O emissions was observed after ammonia fertilization (Nelissen et al. 2014). The N_2O emission reduction effect was impacted by the presence of an assimilable C-source (e.g. particulate organic matter). Furthermore, when using newly produced biochar, a stronger emission reduction was observed if higher pyrolysis temperatures were applied during biochar production (Ameloot et al. 2016, Nelissen et al. 2014). However, after 7 months field incubation this effect was no longer observed (Ameloot et al. 2016).

The effect of **crop residues** from horticulture on the soil nutrient status and how to enhance the nutrient retention by means of crop rotations and cover crops was well studied by Agneessens et al. (2014). Another strategy investigated in Flanders is the simultaneous mixing of organic biological waste (straw, green waste compost, saw dust, tannic acid, paper sludge), functioning as **N-immobilizing materials**, with high-N crop residues (celery) when incorporated in soil (Chaves et al. 2005). High-N crop residues are typical for the horticultural croplands in Flanders and can stimulate N_2O emission upon incorporation in soil. In lab incubations, simultaneous application of straw, green waste compost, saw dust and tannic acid effectuated a N_2O emission reduction of 60%, 55%, 53% and 39%, respectively. In contrast, paper sludge stimulated N_2O emissions, probably due to its low C:N ratio (Chaves et al. 2005). Homogeneous mixing of both the crop residue and the N-immobilizing material in combination with sufficiently high soil temperatures was required to obtain optimal results (Agneessens et al. 2014). Long-term field experiments are required to fully unravel the potential emission reduction effect of these and other N-immobilizing materials.
The location of crop residues (incorporated in soil or surface application) was also found to impact soil water dynamics in an experiment with repacked soil columns that were subjected to dry-wet cycles (Coppens et al. 2006).

Research on **precision fertilization** is ongoing in Flanders. NIR-sensors and soil scans are used to predict the availability of mineral N from pig and cattle slurry for the crop in a more reliable way (VLAIO-LA project 'Precisiemest'). For more efficient 'just-on-time' fertilization in horticulture, research was conducted using on-line monitoring and a model-based advisory system (IWT project 'EcoFERT'). More efficient fertilization in leek by using precision farming tools is investigated in the VLAIO-LA project Wikileeks.

When studying the N_2O emissions from four Belgian soils, De Groot et al. (1994) monitored higher N_2O emissions when **NH_4^+-N fertilizer** was applied as compared to NO_3^--N. In contrast to soils with a pH of 8, a pH of 6 caused a N_2O emission delay when ammonium-N was applied, which finally resulted in a lower N_2O emission. The lower pH may have induced a lag-period of nitrification.

Water management

Research on water management and especially efficient **irrigation** management only recently gained attention in Flanders. Indeed, in the ERA-NET project POTENTIAL the potential of variable rate irrigation and fertigation in potato are investigated (Garré et al. 2020). Via the VLAIO-LA project 'Irrigatie 2.0' research is performed on how well-founded irrigation can be applied in several crops. This project also takes into account the potential limited availability of natural water resources in the near future by screening the appropriateness of water of alternative origin (e.g. recycled house-hold water, water from legume processing industry). Since periods of drought become more frequent and intense, the role of **capillary rise of groundwater** on microbial activity and soil carbon cycling are also investigated. Finally, also the impact of soil compaction on water transport in soil was investigated by van der Bolt et al. 2016.
In the Interreg project 'Carbon Connects' (2018-2021) the effect of **rewetting** agricultural land on soil carbon stocks and GHG emissions is monitored on pilot sites 'De Blankaart' and 'Kwetshage' by ILVO and VLM. In addition, on-farm composting of the biomass of rewetted land and using the compost for increasing C-stock levels in agricultural land is a possibility which is tested. Flanders has been plagued by drought for several years now and is struggling with a serious water shortage.The Flemish government is responding to this and recently announced the 'Blue Deal'. Flanders must maximize it effort to retain and store water in situ. Accordingly, **wet agriculture** (paludiculture) and **level-controlled drainage** of agricultural land are gaining interest.

3.3 Knowledge gaps

In general there is a strong need for more statistically sound **monitoring** in Flanders**,** on e.g. soil organic carbon, greenhouse gas emissions, pH and compaction since most basic data are outdated. Those data are all needed to fulfill (inter)national obligations and to obtain insight in the current soil status.

Soil organic carbon

The **behaviour of carbon input to soil** (degradation, mineralisation, humification, etc.) needs to be further investigated. How does organic matter in soil respond to management (crop rotation, manure amendment, tillage practices)? To what extent information gathered from physical fractionation aids in predicting decomposition of native SOC? Can we develop a user friendly (quick and cheap) soil analysis predicting the stability of (certain fractions) of soil organic carbon? What is the impact of soil texture on carbon mineralization? What is the influence of soil sealing and desealing on soil organic carbon stocks? What is the role of soil biodiversity? Do we need to distinguish between the microbial community in the rhizosphere versus the community in litter layer (or bulk soil)? And how are results of natural ecosystems applicable to agricultural systems and vice versa?

Though alternative (to the current) soil management practices and cropping systems are often acclaimed to show a better resilience to climate change (with longer and more intense drier periods, and periods with more rains with higher rain intensities), evidence is, particularly in Flanders, still lacking. **Ecosystem services** provided by soil organic carbon such as increase in water holding capacity, improved soil structure, reduction in soil erosion should be quantified. What is the relationship between soil organic carbon content and plant-available water? Is there a difference in water holding capacity between the different carbon fractions?

Carbon stocks under different **land use types and land management practices**, their changes over time and **effects of land-use change** need to be quantified. What is the carbon sequestration potential in arable and grassland soils in Flanders and their relation to pedo-climatic conditions? Which soils are saturated? As soils can only store a limited amount of carbon it would be interesting to estimate their **maximum carbon storage potential**. Sampling a number of Flemish grassland plots (that have been under grass for decades) could provide an estimate of the maximum carbon storage potential under grassland depending on soil type and drainage condition. What are the optimal carbon stocks for land use types such as grassland, cropland, gardens, forests? In order to optimize crop performance and minimize environmental problems, should we aim at an optimization of the soil metabolism and related carbon dynamics rather than at maximizing carbon storage? Recent data about SOC stocks in Flanders are lacking. These data are crucial to monitor **changes and dynamics in SOC**, as input for SOC models, improved contribution to (global) potential SOC sequestration maps and LULUCF accounting. Soil carbon research should move towards **enabling integrated modelling of the cycles of C, N and P** including accounting for biomass production and the soil water status as a function of climate and water management.

More **regionally differentiated research** and state-of-the-art reviews are needed about **effective soil management strategies**. What is the effect of **grassland** renewal on carbon stocks? What is the effect of intensity of grassland management (number of cuts, grazing intensity) and species composition on the carbon sequestration potential? Finding a good balance between agricultural production and carbon sequestration through rewetting on agricultural land is needed. What is the relationship between permanent grassland age, ground water table level and carbon stocks? What is the role of CH_4 and N_2O when increasing the water table under permanent grassland? What is the impact of nutrient influx on the decay of carbon rich peatlands?

The **influence of soil tillage and soil nutrient management** on soil carbon stocks needs to be further investigated. What is the effect of direct application of woodchips to the soil? What is the potential of enhanced weathering of silicate sources such as basalt, grinder bricks/concrete, steel slags mine tailings to sequester carbon in agricultural soils? What is the potential when combined with other negative emission technologies (such as biochar)? More knowledge and practical decision tools are needed **to choose the best strategies for organic material and other waste streams** that can be returned to the soil based on a life cycle assessment-like approach avoiding negative trade-off effects. Thus, understanding the **trade-off** between GHG and SOC between different processing techniques, taking into consideration the entire cycle from harvesting biomass, over storage, over processing and application to soils is much needed.

We should focus more on the **contribution of crops (above and below ground), crop combinations and the impact of water management**. We need to further explore why and how much below-ground C inputs contribute more than above-ground C inputs to carbon stocks. More research into the possibilities of different crop types to store extra carbon is needed. What is the impact of climate change and new varieties on biomass production? The impact of perennial crops, improved cover crops with deep and abundant rooting, changes in crop rotation (intercropping, winter cereals, ley farming) as well as long term impact of mixed cropping systems such as agroforestry and other small landscape features on carbon stocks should be investigated. What is the impact of water management practices that optimize the balance between drainage and water conservation? Where do we need to prioritize water storage, where agricultural production? But maybe above all: what is the effect of combined measures on soil carbon stocks?

Finally, more research is needed on how to create an **enabling context for increasing soil carbon stocks**. In other words, we need to research how we can stimulate effective and efficient soil care by farmers. How can we stimulate the production (availability of raw materials) and application of (farm) compost. How can we stimulate the implementation of deep rooting crops which may improve SOC sequestration in Flemish agriculture? The stimuli are diverse such as financial (i.e. public subsidies or private payments), educational, etc. In order to motivate farmers to become carbon farmers there is much need for developing **accurate and cost-effective systems for carbon accounting** at the farm level and regional scale (including more quick and non-invasive soil sampling methods, remote sensing, modelling and regional calibration) to be used in carbon credit systems or for CAP payments. Moreover we should use new techniques to **quantify the benefits of SOC** for crop growth by relating SOC variability to other spatial and temporal data such as crop growth, weather conditions and soil texture. By accessing more data on a higher spatial and temporal resolution, the (economic) impact of SOC might become clearer, which can motivate farmers to become a carbon farmer.

Non CO_2-GHG emissions

At the moment the **GHG emission inventory of soil borne N_2O emissions** in Flanders still relies on a TIER I methodology for direct N_2O emissions and indirect N_2O emissions caused by leaching and runoff. Indirect N_2O emissions caused by atmospheric deposition are already calculated according to a Tier 2 methodology since region-specific emission factors are available. Therefore, the **soil N_2O emission factors** for GHG accounting should be further fine-tuned to region-specific emission factors depending on soil management practices and tailored to the local farming situation. Local GHG emission data on several crops and land management strategies are required. Further research focusing on soil borne greenhouse gas (GHG) mitigation strategies should include long-term (cover all seasons, long-term effect of management strategies) **field experiments** and ensure a very frequent monitoring of especially N_2O. The monitoring should take account of weather events and agricultural practices since these can strongly influence N_2O emissions. Indeed, more insight is needed in the impact of environmental circumstances during agricultural practices and the impact of temperature and moisture conditions in order to simulate seasonal environmental conditions (including winter period) and effects of climate change. Finally, these datasets can facilitate the development of accurate models which may allow better prediction of (regional) N_2O emissions.

More information on the (long-term) impact on N_2O/CH_4 emissions is required for:

- Slurry/farmyard manure/digestate/compost: application method, feedstock composition, timing of application/environmental circumstances, amount, frequency of application;
- (Reduced) tillage;
- Specific crop rotations / catch crops and crop residue management;
- N immobilization via addition of organic biological waste and crop residues: type of organic biological waste, application method, environmental circumstances, dose, etc.;
- Temporary and permanent grassland and grazing vs mowing;
- Peaty permanent grasslands in the Polder area and its soil and water management;
- Land use change (including conversion of grassland to arable land).

In addition, also off-site GHG balances of organic amendments (compost, digestate, manure) need to be taken into account. Therefore, the trade-off between GHG and SOC between different processing techniques, taking into consideration the entire **life cycle** from harvesting biomass, over storage, over processing and application to soils needs to be considered. This will also point out if there should be opted for other or adapted processing techniques. Likewise, also the potential increase or decrease of mineral N fertilizers (causing changes in N_2O-emissions and energy consumption) by changing management should be considered.

Soil compaction and soil sealing

There is a general need to alleviate **soil compaction** via a holistic approach. Which combination of tillage practices, crop selections and/or soil improvers, fertilizer types and timing of application yields the best results? In addition, more research on the impact of soil compaction on crop yield and quality is needed. For this, **high detailed mapping of soil compaction** could be related with crop performance indicators (e.g. UAV based), demonstrating the (economic) impact of soil compaction. Improved methods to quickly assess and monitor soil structure are also required. The usefulness of remote sensing techniques (based on e.g. crop parameters, standing water, SOC), soil scanning, yield maps and tractor engine parameters for detecting (the variability in) soil compaction on a field scale should be further investigated.

In addition, more attention should be paid to which soils that are preferentially not to be sealed and on the impact on soil quality after desealing. At this moment 14% of Flemish soils is sealed (Strategische visie Beleidsplan Ruimte Vlaanderen).

Soil biodiversity

The soil food web and **soil biodiversity** are both highly important for enhancing soil quality. However, there is an urgent need for standardized, scientifically based indicators and target zones, preferably per land use type and/or soil type. Parameters for a healthy soil metabolism that result in a healthy crop should be defined. More knowledge is required on how this soil metabolism can be favored. What is the impact of soil management on soil biodiversity and what is the impact of soil biodiversity on plant growth, crop yield and quality (functional agrobiodiversity in the soil) and soil ecosystem services? When investigating the role of soil organisms in soil functioning, researchers should distinguish between the microbial community in the rhizosphere versus the community in litter layer (or bulk soil). Finally, the role of microbiology on soil structure needs to be further explored while there is also a need for better insight on the impact of soil texture on microbial functioning and its impact on C-cycling.

Soil water retention and dynamics

Enhancement of the water holding capacity in soils is one of the major (future) challenges in Flanders. Therefore, a sensitivity analysis of factors determining **water holding capacity** is required. A soil moisture monitoring framework should be constructed, with links to (remotely assessed) crop data. Many questions still need to be answered. Which water management practices optimize the balance between drainage and water conservation, for the purpose of optimal crop response, minimal leaching and minimal loss of organic matter? As precipitation is expected to be episodic in summer and droughts will occur more often, **water conservation** will become more important. How can soils be made more resilient to drought? Where will drought most likely impact agricultural production and what will be the impact on microbial activity in topsoil?
Better insight in **soil crust** formation and its remediation and the development of methods to quantify their hydraulic properties need to be developed. In addition, modelling of **nutrient dynamics** related to groundwater dynamics, especially for phosphates is still a rather grey area. For this, also more in-depth knowledge on the feedback mechanisms between water management, land management and the N, P, C nutrient cycles are required. This information could then be integrated in mechanisms in process-based model(s).

Soil management

Strategies to speed up soil quality amelioration need to be explored and more research is required on how minimal inputs can generate optimal and sustainable outputs. The effects of **alternative soil management** practices and cropping systems on soil quality, crop production and the resilience of soils to climate change need to be further explored. Though alternative (to the current) soil management practices and cropping systems are often acclaimed to show a better resilience to climate change, evidence is most often lacking. Management systems that follow **agro-ecological principles** need to be further tested. Optimization of non-inversion tillage is also required. Systems that have shown promising results, even in the Global South, should be considered and it should be investigated how these systems could be adapted to the local (farming) conditions. When considering soil management practices there should also be more focus on the **contribution of crops** (above and below ground), crop combinations and the impact of water management. Effects of alternative crops (main + cover crops) in ameliorating soil quality and crop production need to be tested. Improved crop rotations with crops that cover soil for longer periods (intercropping, winter cereals, ley farming) should also be investigated. More long-term field trials should be organized in order to investigate and evaluate the effects of such (new) management techniques.

When studying management techniques the **feasibility and cost-effectiveness** to put those techniques in practice should be taken into account. Today, we are confronted with the question on how the implementation in Flemish agriculture can be stimulated. How can farmers be stimulated to **imply an effective and efficient soil care**. The stimuli could be diverse: from financial (i.e. public subsidies or private payments) to educational methods. While most strategies improve soil quality and reduce environmental risks, increases in crop yield are not always described, which also hinders their adoption by farmers. Furthermore, more attention needs to be paid to **knowledge sharing** with and among farmers. We broadly know which measures increase soil quality, however they always come at a short-term cost to farmers, so we need better quantitative long-term data, and a change in policy to better incorporate and calculate environmental costs.

In Flanders, an evaluation is needed for the combined (interacting) effects of different nutrients in fertilizers to enhance plant growth. Another important research theme is how to reduce N- and P-leaching losses leading to eutrophication. For this, tailoring studies to **optimize fertilization** can contribute to the solution. An important challenge for both farmer and policy to increase the soil's inherent fertility is the **carbon-phosphorus contradiction**. How can the organic carbon content of agricultural soils be optimized without increasing P-stocks and without increasing the risk for P-leaching? The use of compost could result in an increased SOC content while minimizing the risk on N and P-leaching. However, an important issue here is how the production (availability of raw materials) and the use of (farm) compost application can be stimulated?
Decades of excess **acidifying and eutrophicating deposition** have certainly leached parts of natural mineral contents of soil (especially sandy and loamy soils). To which degree this has happened, is still largely unknown (experiments have been started). How to correct the leaching processes of acidified soils in Flanders, is also still a grey area.

3.4 General conclusions from the research perspective

Soil organic carbon, soil erosion, nutrient retention/leaching and soil compaction are the most studied soil challenges for agricultural soils in Flanders in terms of developing models, estimating the current status and developing management practices to increase soil organic carbon, avoid soil erosion, decrease nutrient losses and avoid and remediate soil compaction. Although research for non CO_2-GHG emissions is mostly older, quite a number of research gaps have been formulated, especially to improve the GHG emission inventory.

Maps were produced for SOC and potential soil water erosion and sensitivity/risk maps for soil compaction, risk maps for actual and potential wind erosion and sensitivity maps for landslides were developed. These are all based on older data and/or models but not on actual monitoring. In Flanders, no regional statistically sound soil monitoring is on-going at the moment. There is an urgent need for recent soil data (as most basic data are outdated by at least 50 years). Furthermore, harmonisation and centralisation of existing data is also needed as basis for soil policy, research and reporting as well as the production of new maps based on new techniques such as remote sensing.

Non-inversion tillage and the application of organic fertilisers or amendments are the most studied soil management practices. Although the importance of crops and crop rotations for soil quality and tackling soil challenges is obvious, crop rotations are understudied and there are no long term field experiments that investigate the impact of cover crops as a research factor. Despite the considerable area of grassland in Flanders and its importance for climate change mitigation and adaptation and biodiversity, evidence of the effect of grassland management on soil quality and soil challenges is largely missing.

Flanders has been plagued by drought for several years now and is struggling with a serious water shortage. Accordingly, methods to retain and store water in situ, wet agriculture (paludiculture) and level-controlled drainage of agricultural land are gaining interest, but were so far understudied.

Although studies on soil biodiversity are certainly not complete in this report, research is ongoing, also with new DNA-based techniques. However, knowledge gaps are still large and there is a need for standardized, scientifically based indicators and target zones and for understanding the roil of the soil food web in delivering soil ecosystem services.

4. Stakeholder views on soil challenges and sustainable soil management

4.1 Approach

This chapter compiles the perspective of key stakeholders in Flanders on soil challenges and sustainable soil management, subdivided over three themes:

(1) prioritization of soil challenges;
(2) identifying knowledge use and knowledge needs on sustainable soil management in Flanders;
(3) identifying barriers and opportunities for knowledge development, sharing, organizing and application on sustainable soil management in Flanders.

For theme 1, stakeholders were asked to prioritize soil challenges. The same prioritization question was asked in all three questionnaires (see Chapter 2).

For the other two themes, the report is based on the results of Questionnaire 2 (Annex I), completed by in total 13 key stakeholder organizations, of which policy organizations, farmer advice organizations and farmer organizations are most highly represented (see Chapter 2). The high representation of these actors is important, because they are key stakeholders for knowledge use and production.

For theme 2, the questionnaire consists primarily of closed questions. For these questions, the stakeholders were asked to indicate their answer on a predefined likert scale with five question-specific categories. For each question, an argumentation box was foreseen to draft a short explanation. Additionally, after each set of closed questions, there were also a range of open ended questions that allowed the stakeholders to reflect on the general topic. The results of theme 2 are summarized in paragraph 4.3 ‘Knowledge availability and use’.

For theme 3, the questionnaire consists of a set of pre-listed barriers or opportunities. This allowed each stakeholder to tick the answer-categories that fitted the question. The pre-listed stakeholder votes were used to identify the most important barriers and opportunities. For all answers the stakeholders were stimulated to explain their choice. In addition to the pre-listed answers, every question also has the option “other”. In this box the stakeholders were invited, if appropriate, to define a specific answer that is not included in the pre-defined list. The results of theme 3 are summarized in paragraph 4.4 ‘Barriers and opportunities of knowledge development and use’.

4.2 Prioritization

The stakeholders had to prioritize the key soil challenges in Flanders for the upcoming decades. This prioritization exercise was completed by all stakeholders who participated in one or more of the three questionnaires that were launched at the same time (see Chapter 2). A total of 19 organisations have done the scoring and the combined results are shown in Figure 1.

Maintaining/increasing soil organic carbon (SOC) was by far the most important soil challenge for the upcoming decades according to the stakeholders. This was followed by enhancing water storage capacity, enhancing soil biodiversity and enhancing soil nutrient retention/use efficiency. Avoiding soil erosion and ensuring an optimal soil structure were priorities five and six. Together these six soil challenges got 82 points out of 100.

Water storage is an emerging topic the past years due to longer drought spells that were experienced and the expectations that drought problems might even increase in the future due to climate change. No clear differences between stakeholder groups were detected.

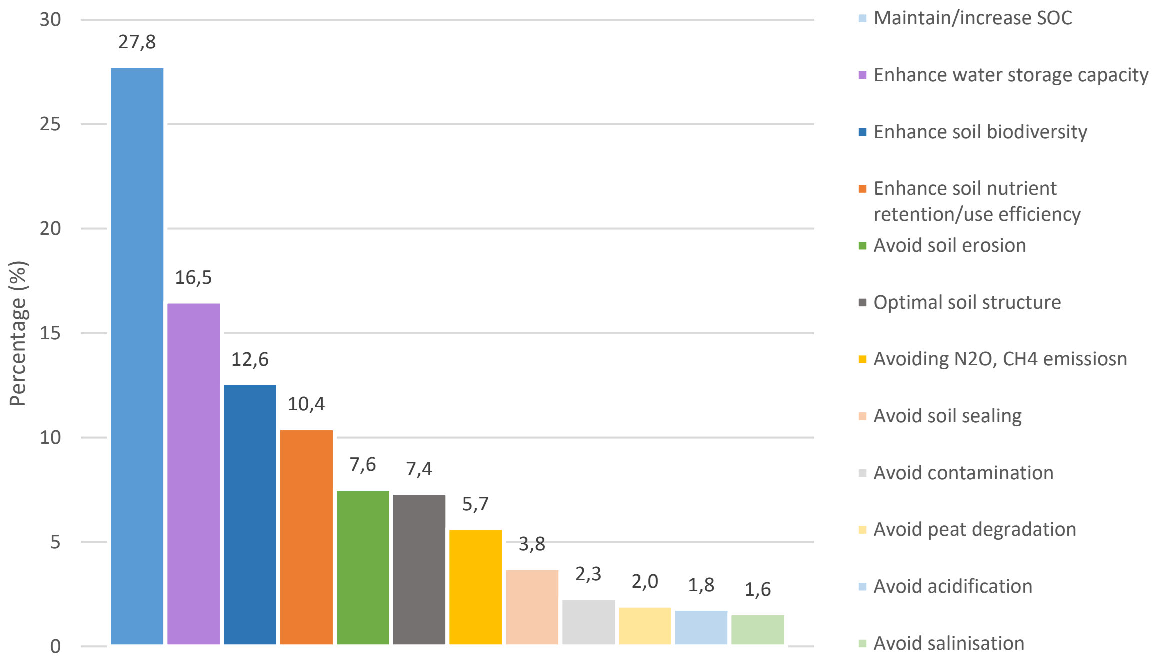


Figure 1: *Prioritization of soil challenges by stakeholders for Flanders, who answered the question 'What do you expect that will be the main soil challenges that are most relevant for Flanders in the upcoming decades' (scored by 19 organisations)*

4.3 Knowledge availability and use

In this paragraph, the overarching conclusions that could be drawn from the stakeholders views on knowledge availability and use is discussed first. After the general overview, the answers to the specific questions are presented one by one.

Overarching stakeholder views

Overall, a set of three general recommendations are repeatedly listed by the stakeholders across different questions and throughout the different parts of the questionnaire on the coordination and strength of the knowledge system and on knowledge needs in Flanders.

Integrative soil vision

The stakeholders argue that soil policy in Flanders is too dispersed and that we lack a comprehensive soil vision. Yet, an integrative soil vision is especially important, as soil quality requires a continuous attention and is affected by many actors and actions.

Structural multi-stakeholder soil network

At the basis of a systemic vision, and abundantly emphasised by the stakeholders, is the need for a strong scientists-advisor-farmers-policy network that enables structural collaboration.

Centralized knowledge platform

The stakeholders, repeatedly mentioned the need for a centralized and harmonized platform, openly accessible by all actors. Such a platform should not only contain knowledge from Flemish research, but should also put international knowledge in the Flemish perspective.

(1) The stakeholders argue that soil policy in Flanders is too dispersed and that we lack a comprehensive soil vision. Yet, an integrative soil vision is especially important, as soil quality requires continuous attention and is affected by many actors and actions. ***[integrative soil vision]***

(2) At the basis of a systemic vision, and abundantly emphasised by the stakeholders, is the need to for a strong scientists-advisor-farmers-policy network that enables structural collaboration. ***[structural multi-stakeholder soil network]***

(3) The stakeholders, repeatedly mentioned the need for a centralized and harmonized knowledge platform, openly accessible by all actors. Although there is a lot of communication (especially through printed media and electronic newsletters), not all actors are reached and not all information is (equally) shared. Such a platform should not only contain knowledge from Flemish research, but should also put international knowledge in the Flemish perspective (examples of such platforms already exist for pigs, cows etc**.**). There is also an urgent need for soil monitoring in Flanders, most basic data are outdated by at least 50 years. Monitoring is needed not only to fulfill (inter-)national obligations, but also to get insight in the current soil quality status. For soil biodiversity in particular, more scientific knowledge is needed, but research needs are also high for the carbon sequestration potential and the water storage capacity of soils. Soil knowledge should get a higher priority in farm schools to prepare the next generation of farmers. ***[centralized knowledge platform]***

Specific stakeholder views

The specific stakeholder views are structured around the knowledge system, the strength of the knowledge system and the knowledge needs in Flanders. The questions and the likert scale for each question can be found in the questionnaire in Annex I.

Coordination of the knowledge system

The first set of questions is on the coordination of the knowledge system, which refers to the nature of the formal links between stakeholders and coordination of soil knowledge production and dissemination. The results are displayed in Figure 2.

How well is farmers' access to relevant knowledge about sustainable soil management? (1.1)

There is no agreement between the stakeholders. The answer ranges from good (42%) to somewhat deficient (33%). Farmers organizations and advisors rate the farmers access to knowledge higher than policy and research stakeholders. There is agreement that there is a lot of information available and accessible in field demonstrations, communication in agricultural press and seminars and workshops. Yet, the transition of knowledge to the individual farmers could be enhanced. Some stakeholders argue that only part of the farmers are reached and that independent on-farm advice is to a large extent lacking. Access to knowledge for individual farmers is also argued to be largely dependent on specific conditions of the farmer: socio-economic situation, educational level, willingness to adapt. More in general, the stakeholders advise to strengthen the scientists-advisors-farmers network.

How well are young farmers prepared for sustainable soil management in farm schools? (1.2)

More than half of the stakeholders indicate that young farmers are somewhat poorly (28%) to very poorly prepared (25%) for sustainable soil management in farm schools, 30% are neutral; 17% belief that they are well prepared. The stakeholders agree that, although young farmers are aware of the importance of soil quality, this topic should get a higher priority in farm schools.

How well is the advisory service prepared to promote knowledge on sustainable soil management to farmers? (1.3)

Half of the stakeholder indicate that advisory services are very well (8%) to well (42%) prepared to share knowledge on sustainable soil management with farmers. One-fourth of the stakeholder organisations does not have an opinion (neutral; n=12) and one-fourth thinks they are somewhat poorly prepared. The stakeholders point out that it is important to make a difference between public advising services and non-public (commercial) advisors. Whereas the first group has good knowledge on sustainable farming, the others providing commercial advice do not always have access to such knowledge and are often driven by short-term profitability. The stakeholders that indicated "somewhat poorly prepared" (25%) raise the importance to continue to raise awareness for slower long-term effects by soil management. They state that soil quality is a continuous work of many years. These stakeholders emphasise the importance to structurally strengthen individual on-farm advice through a strong scientists-advisor-farmers network.

How well is the overall coordination of knowledge transfer on sustainable soil management? (1.4)

The majority of the stakeholders (53%) indicated that knowledge transfer on sustainable soil management is somewhat poorly coordinated, 30% even indicates that the transfer is uncoordinated, the rest is neutral. The stakeholders agree that cooperation between the stakeholders is increasing, but they emphasize the lack of coordination. A better coordination is needed to foster knowledge transfer between fundamental research, applied research, advisors and farmers. It is suggested that a network of advisors specialized in sustainable soil management should be created with good access to the latest research insights. This would enable a transition from ad hoc project based knowledge transfer to a central contact point and databank.

How well are research activities in relation to sustainable soil management coordinated by policy-makers? (1.5)

Nearly half of the stakeholders (45%) indicates that policy-makers somewhat poorly coordinate research activities in relation to sustainable soil management, 18% even indicates that there is no coordination. There is agreement that soil policy is too dispersed and that we lack a comprehensive soil vision and research agenda. Due to this absence, there is little to no interaction between funding agencies. The program 'GRONDZAKEN' is listed as a recent program that tries to overcome the lack of interaction by linking all government agencies that are dealing with soils in order to improve interaction, knowledge exchange and to create a more coherent soil policy.

Other reflections regarding the coordination of knowledge use and knowledge exchange between stakeholders

Overall, building on the previously mentioned elements, three general reflections are raised by the stakeholders:

- The knowledge system lacks a holistic overview. For example, the economic effects are often not considered.
- The knowledge system lacks policy coordination; soil policy is subdivided between sectoral divisions within the government. Soil management in agricultural land is both the responsibility of the policy department of Agriculture and Fisheries and the policy department of Environment, both even under a different minister. In addition, responsibilities are also divided between different policy agencies (e.g. 'mestbank' at VLM). There is much work to be done to get these policy actors communicating, but things are in motion (see 'Grondzaken' program in the previous and next question).
- There is a discrepancy between short term (economic) incentives and long term impact of sustainable soil management practices.

How can the coordination of knowledge production and use regarding sustainable soil management be improved?

The stakeholders listed a set of key elements that should be solved, to improve knowledge production and use:

- More coordination between policy, research, advisory services is necessary because knowledge is scattered and for the moment poorly coordinated. There are linkages between all actors, but most are ad-hoc and project-based rather than systematic. There is need for a systemic integrative long-term vision on agricultural soils. A potential step forward is recently initiated by the "Grondzaken" program. Grondzaken aims at more interaction and a systematic collaboration between different governmental policy and research organizations. This program is key to come to a more coherent soil policy and knowledge base. For Grondzaken to succeed it is important that a clear mandate is given to employees of different institutes and departments to work together in an open culture.

- A better connection, collaboration and coordination between fundamental research, applied research and advisory services is needed in order to create a better knowledge flow from research to farmer and farmer to researcher.
- Soil knowledge should be centralized and be accessible for all stakeholders.
- A network of advisors that are specialized in soil management and can provide individual farm support should be established. This network should be well connected with research to transfer new knowledge to farmers. It would probably help if the role of different organizations would be better defined and a formal collaboration that is a win-win for all could be established in an open knowledge exchange culture and based on trust. This is often hindered by competitions for the same funding.
- Reward innovative farmers for their knowledge transfer. A strong partnership with incentives for knowledge sharing would enable pioneer farmers to transfer their experience and farmer knowledge to researchers. A possible approach would be to create a cost-free monitoring system for pioneers.

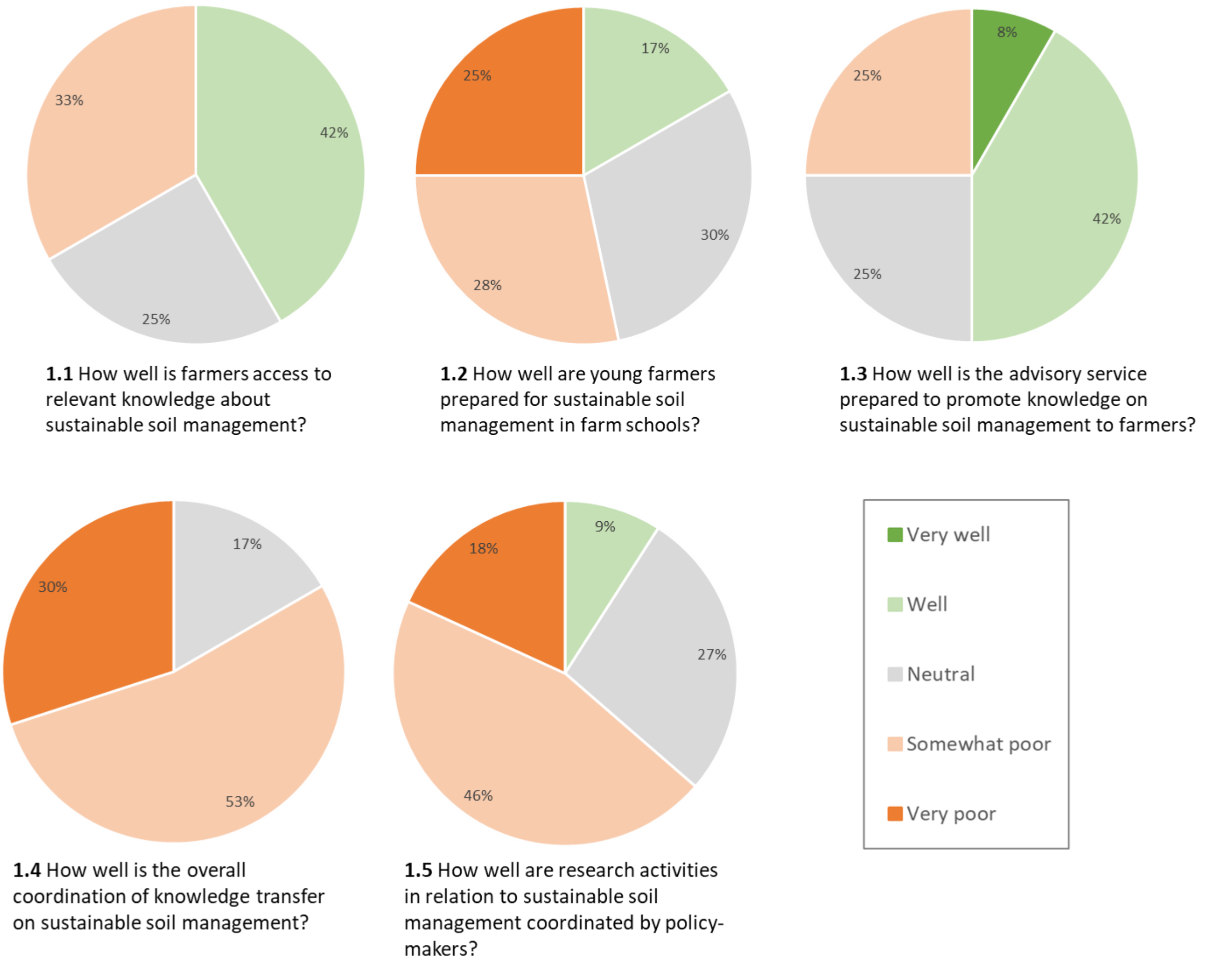


Figure 2. *Variability of stakeholder inputs on closed questions about the coordination of the knowledge system. (total number of responses per question: 1.1 N=12; 1.2 N=12; 1.3 N=12; 1.4 N=12; 1.5 N=11).*

Strength of the knowledge system

The second set of questions is on the strength of the knowledge system, which depends on the focus of resource allocations, public investments and engagement; for instance in advisory service, knowledge production and knowledge exchange. In a strong knowledge system the farmers should benefit from these activities. The results are summarised in Figure 3.

To which extent is the current knowledge system effective in communicating knowledge on sustainable soil management to farmers? (2.1)

There is no agreement between the stakeholders on the effectiveness of knowledge communication. The answers range from effective (50%) over somewhat effective (23%) to not effective at all (8%). Farmers organizations and advisors rate the communication efficiency higher than policy and research stakeholders. The stakeholders agree that there exists a lot of communication on diverse channels. Yet, some argue that the group of farmers reached through the different channels is similar. This means that it is difficult to reach all farmers. Others argue that the information is often topic-specific and dispersed, which causes farmers to struggle with the overall implementation.

To which extent are different platforms used to disseminate knowledge on sustainable soil management to farmers? (2.2)

The different platforms used for the dissemination of knowledge on sustainable soil management, in order from most used to less used, are:

- Printed media and electronic newsletters are highly used to used. They remain a very important source of information.
- Peer-to-peer groups and farmer interest groups are used. They remain important for the dissemination of knowledge, but lack a structural character.
- Advisory service and technical reports are used to 'neutrally' used. Yet, systematic advisory support on soil management at individual farm level remains limited.
- Webpages and blogs are used to somewhat used. Mostly on project basis or by younger farmers.
- Social media is somewhat used by younger farmers.
- Scientific literature is not used to somewhat used.

In addition, also farm demonstrations are listed as important for the dissemination of knowledge.

To which extent are resources available for the dissemination of knowledge on sustainable soil management? (2.3)

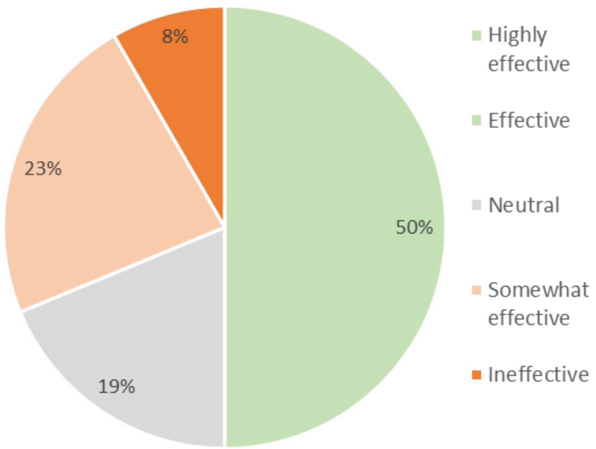
Most stakeholders indicate that to some extent (64%) resources are available for the dissemination of knowledge on sustainable soil management. However some stakeholders point out that scientific literature is not always accessible, when not open access. And more in general that, although information can be available, this doesn't mean that there is a coordinated action towards enhancing sustainable soil management.

To which extent are financial resources available for the production of knowledge on sustainable soil management? (2.4)

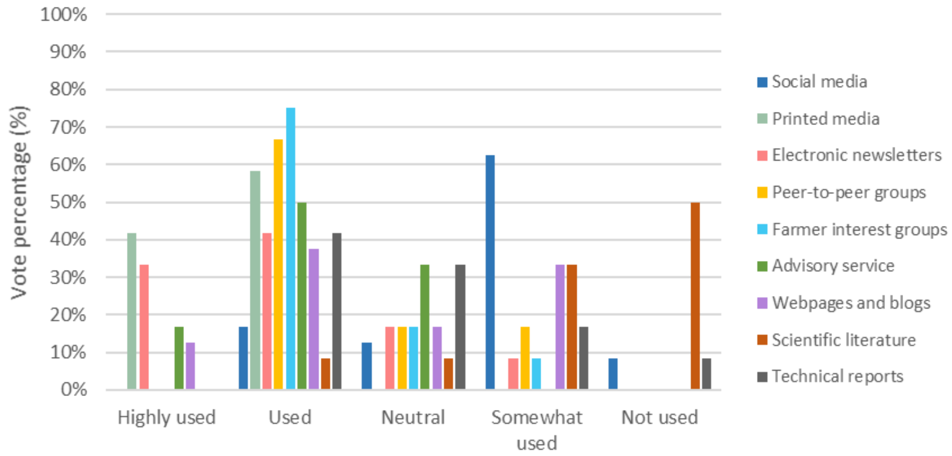
There seems to be an equal division between the stakeholders, with 42% indicating to some extent and 42% indicating to a small extent. Although the opinions of the stakeholders is divided, overall the stakeholders agree that there is too little continuity due to project dependency. In high level European projects there is sufficient budget available for the production of knowledge, but these mostly larger projects are not accessible for all stakeholders. In smaller projects the budget for knowledge production is mostly too limited. Moreover, since soil research requires long term investigations there is a structural need of co-financing, which is not possible for all stakeholders.

Reflections regarding the dissemination of knowledge on sustainable soil management and ideas to improve knowledge availability and transfer?

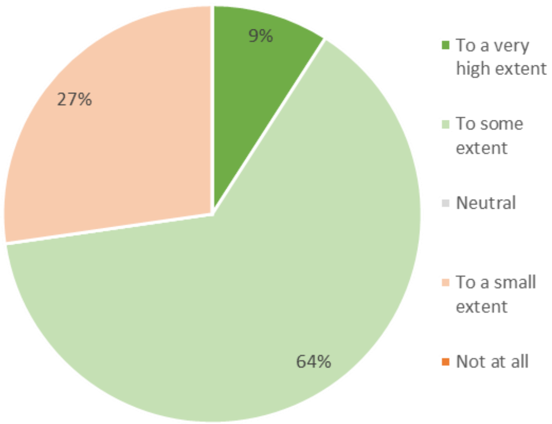
Knowledge on sustainable soil management is fragmented and policy regulations are sometimes even opposing each other. This makes it difficult for farmers to put knowledge into practice. There is a need for an integral vision and associated communication and management strategies, and enhanced collaboration. Communication on all levels is highly necessary and urgent. Several stakeholders also raise the need of a central (single point) communication platform to share knowledge and practical guidelines. Such a platform should not only contain knowledge from Flemish research, but should also put international knowledge in the Flemish perspective (examples of such platforms already exist for pigs, cows etc.).



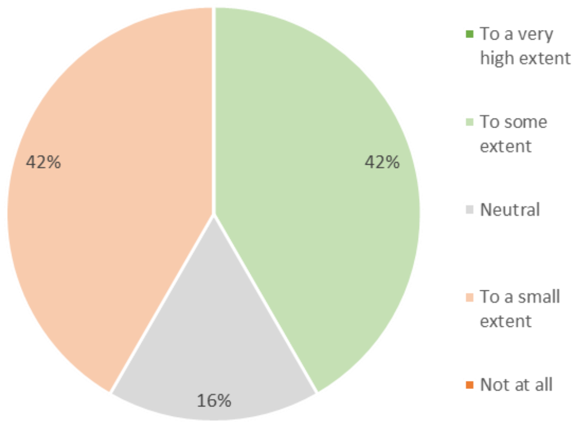
2.1 To which extent is the current knowledge system effective in communicating knowledge on sustainable soil management to farmers?



2.2 To which extent are different platforms used to disseminate knowledge on sustainable soil management to farmers?



2.3 To which extent are resources available for the dissemination of knowledge on sustainable soil management?



2.4 To which extent are financial resources available for the production of knowledge on sustainable soil management?

Figure 3. *Variability of stakeholder inputs on closed questions about the strength of the knowledge system (total number of responses per question: 2.1 N=12; 2.2 N=12; 2.3 N=11; 2.4 N=12).*

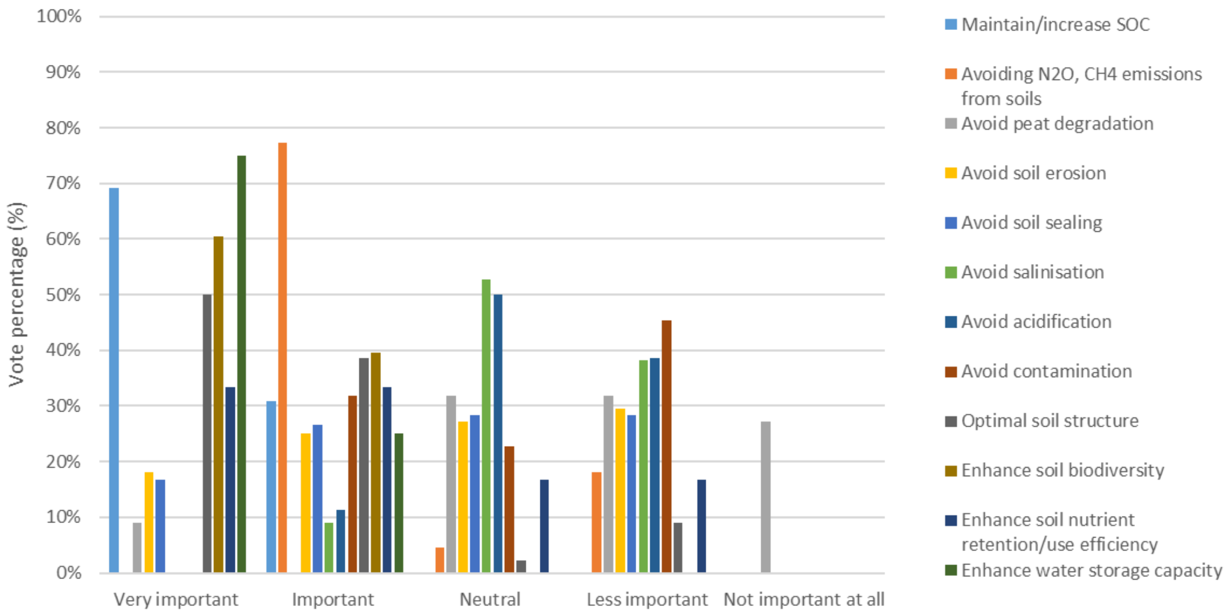
Knowledge needs in Flanders

The third set of questions is on the stakeholders assessment of the knowledge needs in Flanders.

How important are research needs for the following soil challenges in Flanders? (3.2)

Based on the stakeholders' inputs, the research needs for the soil challenges, in order from most important to less important are (Figure 4):

- Enhance water storage capacity and maintain/increase SOC: very important
- Enhance soil biodiversity, optimal soil structure, enhance soil nutrient retention/use efficiency: very important to important
- Avoiding N_2O and CH_4 emissions from soils: important
- Avoiding soil erosion, avoiding soil sealing: range between very important and less important
- Avoiding salinization, avoiding acidification: neutral to less important
- Avoiding contamination: less important to important
- Avoiding peat degradation: neutral to not important



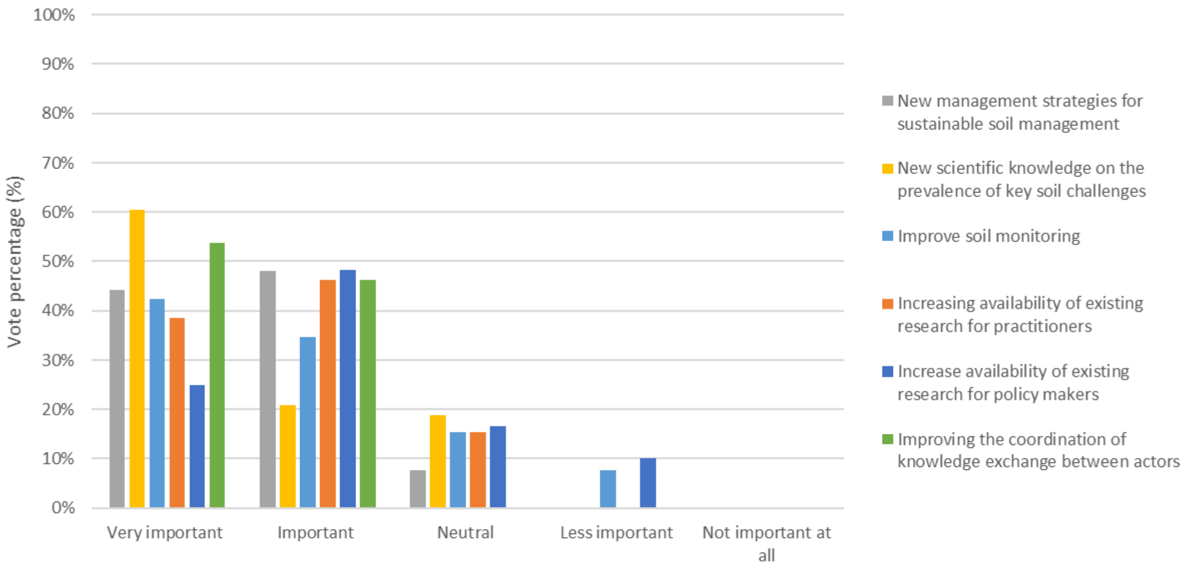
3.2 How important are research needs for the following soil challenges in Flanders?

Figure 4. *Variability of stakeholder inputs on the closed question how important are research needs for the soil challenges in Flanders.*

How important are the following tasks to improve soil knowledge in Flanders? (3.3)

All tasks listed in the questionnaire are considered important by the stakeholders to improve soil knowledge. Most important is the input of new scientific knowledge on the prevalence of key soil challenges and improving the coordination of knowledge exchange between actors. For most soil challenges we have information on the potential prevalence based on modelling, but we lack actual insights from monitoring networks. For soil biodiversity in particular more in scientific knowledge is needed. Other important tasks are (in order of importance based on the stakeholder ratings, figure 5):

- New management strategies. Farmers are aware of the importance of sustainable soil management and need (continuous) knowledge on (new) sustainable management practices and on the impact of existing strategies. Sustainable soil management implies a holistic approach, it is the coordinated action of different aspects that leads to sustainable soil management;
- Availability of research for active farmers;
- Improving soil monitoring;
- Availability of research for policy makers. Important, but in Flanders research results are already accessible throughout different channels. However, there is need for more practical information. Besides providing information, there is also a need for exchange platforms on the latest knowledge.



3.3 How important are the following tasks to improve soil knowledge in Flanders?

Figure 5. *Variability of stakeholder inputs on the closed question how important are the tasks listed to improve soil knowledge in Flanders.*

What are the most important scientific research gaps in Flanders?

The stakeholders agree that the most important research gaps are on soil life and biodiversity, carbon sequestration potential and water storage capacity. In more detail the following elements are raised:

- There remain plenty unanswered questions on the carbon sequestration potential. Some examples are: What is the potential of different (new) crops, cover crops and the extent to which roots are contributing to SOC (eg. Root:shoot ratios)? What is the relationship between soil organic carbon content and plant-available water. How much water is being stored? What is the relevance for crop growth? What is the difference in water holding capacity between different carbon fractions? What is the potential of increasing soil organic carbon content by means of organic amendments and what is the risk for increasing nutrient leaching. What is the carbon sequestration potential in arable and grassland soils in Flanders? What is the effect of grassland management (i.e. reseeding, rotation) on carbon sequestration? How much carbon can be stored? Which soils are saturated?
- There is a knowledge gap on the potential of new technologies (soil scans, drones, satellite images, sensors, tractor data) and how they can be combined with other data (e.g. crop growth models, weather data) to map variations in soil quality and to increase crop yield potential.

- There is a knowledge gap on soil biodiversity, how it impacts soil functioning and what are bench mark values. What is the effect of a.o. crop rotation, soil cultivation, pesticides and climate on soil biology.
- There is a knowledge gap on N_2O emissions and its variability.
- There is a knowledge gap on the effect of minerals, micro nutrients on soil health (plant health).

What are the most important gaps in current soil monitoring in Flanders?

Soil monitoring needs are very high in Flanders, most basic data are outdated by at least 50 years. Yet, monitoring is needed to fulfill (inter-)national obligations and to get insight in the current soil status. For carbon stocks a monitoring network is designed and monitoring will start soon, but for all other soil challenges there is no scientific sound monitoring. The SOC monitoring network should be extended to also measure other soil properties. Additionally, the stakeholders indicate that monitoring data should also be comparable and stored in a central and accessible database. Some stakeholders also mention the need to investigate how satellite or other remote sensing data could be used to map soil challenges.

How can knowledge on sustainable soil management be made more relevant for policy-makers in Flanders? What are knowledge needs from the policy perspective?

The stakeholders formulate a need for more practice oriented and feasible policy with stimulating instead of controlling regulations. Specific needs discussed are:

- Need for CAP payments research focused towards farm or field parcel monitoring.
- Need for result-based payments as incentive for sustainable farming practices. An accurate and cost effective method for carbon accounting should be established and certified by the government.
- Need for a long-term perspective and an holistic approach.
- Need for harmonized holistic non-opposing policies.
- Need for indicators and benchmarks in soil policy to monitor soil quality in light of the soil challenges.

What are the most important gaps in availability of knowledge on sustainable soil management in Flanders? What are knowledge needs from the farmer perspective?

Farmers need tailor-made advice, providing an answer to the key question: which sustainable management practices are most (cost) effective and are most suitable for a specific farm type and what are the benefits and preconditions? To answer this, a systemic vision including all farming aspects is needed. Specific questions listed are:

- Need for knowledge on soil biodiversity, e. g. what is the impact of crop rotation on soil biodiversity (and the extensive effects this has on e.g water availability, plant health).
- What is the effect of green manure and water availability for the next crop?
- What is the effect of no-till and weed management?
- How to enhance soil organic matter (in sandy soil)?

How can the use of knowledge on sustainable soil management by farmers be promoted in Flanders?

Several ideas are listed to promote the use of knowledge, most stress the need for more communication and participation between the different stakeholders. Specific ideas listed to improve the use of knowledge on sustainable soil management are:

- Individual farm advice by advisors that are well connected to research and have the latest research insights;
- A closer collaboration with all actors in the value chain;
- A stimulating consistent policy;
- A two-way communication and cross-sharing between farmers and policy makers;
- Knowledge is one aspect, but also an holistic approach (as provided by the green deal) is needed for effective knowledge application;
- Maybe a “soil license” (similar to the phyto-license) could be introduced?

4.4 Barriers and opportunities of knowledge development and use

This section includes, the potential barriers and opportunities of knowledge development and use in Flanders as perceived by the key stakeholders. The barriers and opportunities are subdivided between general and specific elements. General elements refer to sustainable soil management as a whole, while specific elements refer to barriers and opportunities identified for a specific soil challenge such as decline of soil organic matter or soil erosion.

In case the stakeholders did not specify a specific soil challenge when completing the specific barriers and opportunities table, the answers they provided have been moved and clustered in the general barriers and opportunities list. Only when the stakeholder referred to a specific soil challenge, it was possible to keep the answer in a separate list for the specific challenges.

The section starts with the overarching conclusions that could be drawn from the stakeholders views on the barriers and opportunities of knowledge development and use. After this general overview, the answers to the specific questions are discussed one by one.

Overarching stakeholder views on barriers and opportunities of knowledge development and use

Below is a summary matrix of the key elements listed by the stakeholders as barriers and opportunities for knowledge development, sharing and transfer, harmonization, storage and application (Figure 6). The matrix has two columns (barrier and opportunity) and four rows with the four knowledge development and use categories.

For each knowledge development and use category, a set of general recommendations was extracted based on the barriers and opportunities identified by the stakeholders.

<table>
<tr><th></th><th></th><th>Barrier</th><th>Opportunity</th></tr>
<tr><td rowspan="2">Knowledge development</td><td>General</td><td>Economic constraints
Lack of training for advisors and farmers
Lack of (centralized) (geospatial) soil data
Lack of multi-actor collaboration (in the value chain)
Lack of application of new technologies and the necessary competences to apply them
High average age of farmers</td><td>Multi-actor and trans-disciplinary research
Activating and valorizing funds
Reinforce the trainings for farmers, advisors and other actors
Soil sustainable management indicators
Detailed (centralized) (geospatial) soil data
Development and validation of bio-physical models</td></tr>
<tr><td>Specific</td><td>Not specified</td><td>Evaluating the connection between land use and soil challenges [Soil biodiversity; SOC; Nutrient retention/efficiency; Soil structure]</td></tr>
<tr><td colspan="2">General recommendations</td><td colspan="2">The stakeholders recommendations to enhance knowledge development can be summarized in two paths.<ol type="i">
To enable collaboration and training, by activating and valorizing funds for multi-actor and transdisciplinary research and by reinforcing trainings for farmers and all other actors.
To strengthen data availability and understanding, by gathering detailed centralized and geospatial soil data, by defining sustainable management indicators and by creating and validating bio-physical models.</td></tr>
<tr><td rowspan="2">Knowledge sharing and transfer</td><td>General</td><td>Lack of dissemination and communication between all actors and all farmers
Lack of strong networks with methods to support an effective sharing of knowledge
No proper access to (practically usable) knowledge advice
A lack of trainings for farmers and advisors</td><td>Supporting multi-actor approaches
Demonstration farms and peer-to-peer learning
Training program for farmers and advisors
Permanent national networks with all stakeholders</td></tr>
<tr><td>Specific</td><td>The knowledge is not available for all farmers [SOC]
There is an urgent need for communication among all stakeholders [soil biodiversity]</td><td>Not specified</td></tr>
<tr><td colspan="2">General recommendations</td><td colspan="2">The stakeholders recommendations to enhance knowledge sharing and transfer can be summarized in two paths.
- Improving stakeholder participation, by actively building on multi-actor approaches and by enabling demonstration farms and peer-to-peer learning.
- Improving dissemination, through interaction in a permanent national stakeholder network and by high level training programs for farmers and farmer advisors.</td></tr>
</table>

<table>
<tr><td rowspan="2">Harmonization, organization and storage of information</td><td>General</td><td>Lack of an up-to-date soil monitoring network
Lack of harmonized, centralized and standardized data
Need for improved understanding of the effects of different soil management techniques
Need for soil reference values</td><td>Application of standardized and harmonized methodologies
A national soil data platform.
Potential of new technologies
Important to use international standards
Sound soil monitoring data is important for climate policy
Big data on soils and soil management to draw lessons and to valorize efforts</td></tr>
<tr><td>Specific</td><td>Lack of harmonized and standardized data [Soil biodiversity; SOC; Soil nutrients; Soil structure]</td><td>Harmonized and standardized methodologies [Soil biodiversity; SOC; Soil nutrients; Soil structure]
Specific regulations, agro-environmental measures at national and regional level, national or regional incentives [Soil biodiversity; SOC; Soil nutrients; Soil structure]</td></tr>
<tr><td colspan="2">General recommendations</td><td colspan="2">The stakeholders recommendations to enhance knowledge harmonization, organization and storage can be summarized in three paths.
- Application of standardized and harmonized methodologies based on international standards
- A centralized soil data platform with sound soil monitoring data that can be used to valorize efforts by farmers
- Big data on soils and soil management, including data access based on the application of new technologies</td></tr>
<tr><td rowspan="2">Knowledge application</td><td>General</td><td>Economic barriers
Coherent policy (without institutional and legal obstacles)
The lack of knowledge and knowledge exchange among farmers and researchers
The lack of an individual (farm specific) approach.
Loss of certainty</td><td>Good policy with incentives to stimulate effective policy measures
Science-policy-advisors-farmers interface
Valorizing soils
Development of region specific soil management strategies
Certification principles for tools and advisory services
Tailor-made advice
(market-based) Rewarding of farmers efforts
Ready-to-use technologies
Long term studies</td></tr>
<tr><td>Specific</td><td>Lack of technology [Soil biodiversity; SOC; Soil nutrients; Soil structure]
Farmer loss of yield and profit [Soil biodiversity; SOC; Soil nutrients; Soil structure]</td><td>Good interface between science and policy [Soil biodiversity; SOC; Soil nutrients; Soil structure]
Improving access to long-term field sites and development of specific advice [Soil biodiversity; SOC; Soil nutrients; Soil structure]</td></tr>
</table>

General recommendations	The stakeholders recommendations to enhance knowledge application can be summarized in three paths. - Improved **interaction** between science-advisors-farmers and policy. - **Incentives** to valorize soil quality, rewarding farmer efforts and stimulating effective policy measures - **Tailor-made advice** and region specific soil management strategies based on ready-to-use technologies and long **term field studies**.

Figure 6*. Summary matrix of barriers and opportunities of knowledge development and use*

Specific stakeholder views of the barriers and opportunities identified by the stakeholders.

The specific stakeholder views are discussed for knowledge development, sharing and transfer, harmonization, storage and application. Based on the argumentation provided in the questionnaire and the stakeholder ranking, the shared barriers and opportunities are discussed in more detail. In addition, if applicable, the ideas brought forward in the category "other" are also discussed.

Knowledge development

Barriers

Most important barriers for knowledge development are the lack of training for advisors and farmers on soil related issues and the lack of financial resources. It is not easy to find the required co-funding for soil research and financing for long term soil research. Important barriers are also the fragmentation of soil research and the lack of relations among research, advisory services and farmers (including their associations), as well as, the lack of links between soil management, farming systems and soil quality. In general, stakeholders mention the lack of holistic trans-disciplinary soil research in Flanders. Also a national database on soils and the lack of spatially explicit soil data are listed as important barriers by the stakeholders. Other barriers listed are the high average age of farmers and the lack of public-private partnerships, since soils are a common good. In addition the stakeholders listed the following barriers not included in the predefined categories:

- At institutional level, there is a need to develop the right competences and to facilitate collaboration. New techniques are arising that can be of use for soil science and soil management (GIS, remote sensing, large databases), but many soil scientists lack the competences to integrate these opportunities in their work. While, others that are familiar with these new technologies often lack good knowledge of soils and soil management.
- The lack of soil responsibility by the different actors and as a consequence the lack of a sense of urgency for soil action, both in the society and in policy.
- The need for economic incentives to work on soil quality and the need to also involve actors of the value chain.
- The large variability and the different scales, make soil quality a difficult topic. Some problems are local (erosion, salinization), while others are more global (climate change).

Opportunities

A key opportunity for knowledge development lies in the support of multi-actor and trans-disciplinary research. Through the involvement of farmers and advisors (as valuable partners) in the early stage of project definition or in living labs; and by activating and valorizing funds, in particular for long term experiments. Another highly ranked opportunity lies in the development and application of soil sustainable management indicators, associated with detailed measuring data at local level. Soil measurements and indicators would generate understanding in the soil potential and would enable to support policy decisions, while at the same time generating big data on soils. Opportunities are also found in the development and validation of relevant bio-physical models for predicting long term dynamics of soil phenomena. The stakeholders also indicate that it is important to reinforce the trainings for farmers, advisors and other actors in developing soil related knowledge. In addition the following opportunities were listed by individual stakeholders:

- KRATOS financing could be used as co-funding for soil related research projects, so that a group of individual farmers can work together with researchers on a soil related topic.
- the EU Green Deal and carbon accounting schemes provide opportunities to strengthen knowledge development.

Specifically: for biodiversity, SOC, nutrients and soil structure important opportunities are found in the evaluation of the connection between land use and these soil challenges.

Knowledge sharing and transfer

Barriers

The main barriers in knowledge sharing and transfer are communication between researchers and (all) farmers and the lack of strong networks (science-science, science-farmers, science-advisors, science-society, science-policy). It is important that networks are more formalized and collaborations should be encouraged and facilitated at the higher level. By doing so, researchers, advisors, farmers and policy makers can bridge the gaps between them. At the same time it is also important to involve all actors (part of the actors are not involved) and to reach out to all farmers (part of the farmers is not reached). The stakeholders also stress that knowledge should be usable in practice and that the benefits for farmers should be identified to be able to reach farmers. The dissemination of knowledge in its current form is specified to be inadequate. There is knowledge, but the knowledge is not available for all actors dealing with soil. The stakeholders mention the need for appropriate methods to support an effective sharing among researchers and farmers. The access to proper knowledge advice for farmers is difficult and there is a lack of advisors specialized in sustainable farm management that can support individual farms. Including in schools, there is a lack of trainings for farmers and advisors that in a systemic approach show the complexity and interlinkages of soil related aspects. Some stakeholders define the need for course material on soils for advisors, farmers, policy, and even the need for

specialized soil advisers. In addition, some farmer advice organizations ask to be more involved in fundamental research, for example in field experiments.

Specifically: for soil biodiversity there is a need for communication among all stakeholders and for soil organic carbon (SOC) there is a need to better spread the importance of SOC to all farmers.

Opportunities

The stakeholders agree that there are three overarching opportunities:

- Stakeholder participation; setting-up operational groups and taking stock from farmers already working on soil-related themes. By doing so farmers based knowledge is taken into account. Supporting multi-actor approaches is defined by the stakeholders to be the most important opportunity to strengthen knowledge sharing and transfer. Overall, demonstration farms and peer-to-peer learning are considered key to share and transfer knowledge. The

farmer advice organizations and living labs are identified as good examples to strengthen such collaboration in the future.
- Improving training programs for farmers and advisors.
- Establishing a network of advisors specialized in sustainable soil management that can give individual and collective support on soil management. This network should have a formal connection to research in order to transfer research insights effectively and the other way around, sharing knowledge needs of farmers with researchers. Such feedback loops should also integrate and support farmer advisers. The establishment of permanent national networks with all stakeholders is also listed as an opportunity for sharing and transferring knowledge.

The 'Grondzaken' network is identified by one of the stakeholders as an example of collaboration between several governmental departments and research institutes that deal with soils. Such a systematic collaboration should be further enhanced in order to get a more coherent soil policy and knowledge base.

Additional opportunities mentioned by stakeholders are:

- To make it more attractive for farmers to participate in research (for example by introducing financial incentives).
- To establish a soil advisory service (linked to the farmer advice organization) with a holistic view on soil chemistry, physics, biology and others.
- Support for farmers in the transition to 'new farming'.

<u>Harmonization, organization and storage of information</u>

Barriers

The stakeholders indicate the lack of an up-to-date soil monitoring network as most important barrier for soil information. At present, soil maps date back to the '60-'70s, while more recent data is only gathered on a project basis and therefore spatially scattered. Beside scattered, there is also a need for centralized, harmonized and standardized soil sampling, soil analysis and mapping, or more in general a common data policy. Such a policy should also, more efficiently, align policy and practice. The stakeholders also mention the need for reference values to understand what a measurement means (what is a good value) and the need for improved understanding of the effects of different soil management techniques. In addition, farmers have a lot of soil analyses (as a requirement of different soil policies), but these analyses are often not used for soil improvement. The LPIS (Land Parcel Identification System) could be a possible platform to registers soil quality and could be used to monitor parcel specific soil quality changes. Positive changes in soil quality could potentially be used as incentive for sustainable soil management.

Specifically: for soil biodiversity, soil organic carbon, soil nutrients and soil structure there is a lack of harmonized and standardized data.

Opportunities

The biggest opportunities to enhance soil information in Flanders lie within the promotion of harmonized and standardized methodologies based on international standards to gather soil data and the storage of data in a national soil data platform. In Flanders a soil passport is being developed by the policy department of agriculture and ILVO. The aim is that all soil related information (both public and private data such as soil analysis data) becomes available for a field parcel and that the data can be easily accessed and shared. This soil passport could be used by advisory services or could be linked to web-based decision support tools. Other opportunities are given by the potential of new technologies such as geographic information systems, statistics and modelling. These different sources of data can be used to get better insight in spatial variability of soil quality, the type of soil quality problems and how to improve crop production potential. Sound soil monitoring data is also important for climate policy and could, for example, be used as a basis for result based CAP (or other) payments. Overall, it is important to use international standards. In Flanders a web based platform for storage of soil data has been developed (Databank ondergrond Vlaanderen) and recently within the 'Grondzaken' platform a working group on soil data and data sharing has been established. Using international standards will also enhance the potential exchange of knowledge and methodologies with different countries. More and detailed knowledge, based on standardized methodologies, is indicated to be an important opportunity. Big data on soils allows to draw lessons on the effect of soil management techniques and be used to valorize efforts. In addition, one stakeholder points out that, within this process, it will be important to safeguard individual data privacy.

Specifically, for soil biodiversity, soil organic carbon, soil nutrients and soil structure there is need for harmonized and standardized methodologies and specific regulations, agro-environmental measures and national or regional incentives.

Knowledge application

Barriers

Three types of barriers were indicated by the stakeholders: financial aspects, policy and the lack of knowledge.

- Firstly, the main barrier for knowledge application is economical. Economic barriers can, for example, be the costs and lags in return from changing land management practices or the lack of appropriate incentives. Return on investment of soil improving practices are often not clear. To prevent unexpected outcomes, it is important to collaborate with different actors, including farmer organizations and farmers. Stakeholders also refer to the discrepancy in long term benefits and short term investments.
- Secondly, coherent policy without institutional and legal obstacles is very important. Institutional and legal barriers can be land tenure and access, lack of good policies and incentives, lack of scientific support to policy makers and/or vice versa. In particular land in seasonal lease is, repeatedly, stated to hamper sustainable soil management.
- Thirdly, good and permanent communication, including a strong exchange among farmers and researchers. The lack of tools that facilitate positive exchanges among farmers and researchers, or among farmers (peer-to peer) represents an important barrier to applying knowledge already developed and tested. The stakeholders mention a need for a more structured exchange between farm advisors and research and a knowledge platform for potential soil management activities.

In addition, stakeholders also mention the lack of an individual (farm specific) approach. In the farmers' decision, also the parental influence can play a role. Soil treatments are often practices inherited from father to son, and can therefore be difficult to adapt. Changing soil management habits needs courage, because it means the loss of certainty. And on top of this, there is also the impact of the value chain on the farmers' decision.

Specifically, for soil biodiversity, soil organic carbon, soil nutrients and soil structure there is a lack of (new) technology application and farmers loss of yield and profit.

Opportunities

There are several opportunities to improve soil knowledge application. Good coherent soil policy with incentives to stimulate effective soil management measures, valorizing soils for example through integration in the circular economy or in the bio economy, mechanisms to support farmers in applying knowledge, or development of region-specific soil management strategies. A (market-based) rewarding system could compensate for the efforts made by the farmer and could boost the economical return of good soil management. It is import to scan the potential of new ready-to-use technologies, such as remote sensing and crop yield maps from harvesters, which could help to quantify the impact of good soil management and a good soil condition on achieving maximum crop yield potential. Also, a strong interface between science, policy, advisors and farmers, including tailor-made advice, could stimulate sustainable soil management. Finally, a knowledge desk could be initiated, where all latest insights on sustainable soil management are gathered with (over time) access to long term field studies.

Specifically, for soil biodiversity, soil organic carbon, soil nutrients and soil structure there is need for a good interface between science and policy and for access to long term field sites and the development of specific advice.

4.5 General conclusions from the stakeholder views

The key lessons learned from knowledge availability and use, have been summarized in three pillars: (i) integrative soil vision, (ii) a structural multi-stakeholder soil network and (iii) a centralized knowledge platform. Building on these three pillars is important for soil knowledge availability and use in Flanders. From the barriers and opportunities, focus points and actions have been identified to actively strengthen these pillars in Flanders (Figure 7).

Pillar 1 consists of an integrative soil vision and could be seen as an overarching critical element for soil knowledge development, sharing and application. This is especially important, because soil quality requires continuous attention and is affected by many actors and actions.

Pillar 2 consists of a structural multi-stakeholder soil network, with clear roles and interactions between research, policy, advisory services and farmers. From 4.4, we learn that such a network should stimulate stakeholder participation, improve dissemination of knowledge, offer high level training for farmers and advisors, reward farmer efforts and provide incentives to valorize soil quality and provide tailor made advice with ready to used practical knowledge, preferably building upon long term field studies.

Pillar 3 consists of a centralized soil knowledge platform. From 4.4, we learn that this platform could strengthen data availability and understanding. The platform should be based on standardized and harmonized methodologies with international standards, contain big data on soils and soil management, including data provided by application of new technologies and a sound soil monitoring system. Soil monitoring is not only important in the short time, but will also provide long term datasets over time.

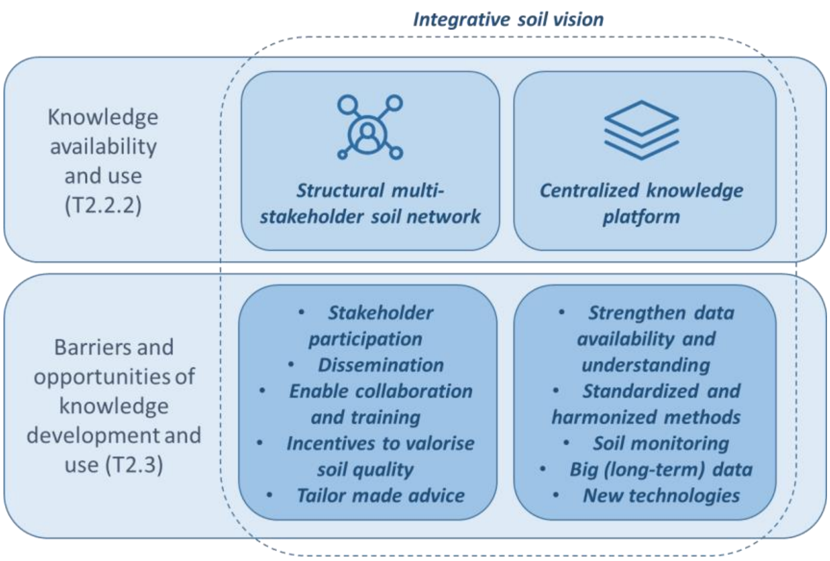


***Figure 7**: Main conclusions derived from stakeholder views on sustainable soil management and the knowledge system in Flanders*

References

Agneessens L, Vandecasteele B, Van De Sande T, Goovaerts E, Crappé S, Elsen A, De Neve S. 2014. Onderzoek naar het beheer van oogstresten bij vollegrondsgroenten en mogelijkheden van vanggewassen en teeltrotaties met het oog op de waterkwaliteitsdoelstellingen van het Actieprogramma 2011-2014 (MAP4): Deel 1. Alternatieve beheeropties van oogstresten van groenten. Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij (VLM), Brussel.

Ameloot N, Maenhout P, De Neve S, Sleutel S. 2016. Biochar-induced N_2O emission reductions after field incorporation in a loam soil. Geoderma 267:10-16.

Amery F, Vandecasteele B, Odeurs W, Elsen A, Vandendriessche H, Nawara S, Smolders E. 2019. Eindrapport "Milieukundig en economisch verantwoord fosforgebruik". Studie APLM/2014/3 in opdracht van VLM. 387p.

Ampe C, Goethals E, Vycnkier C, De Bie J, Ruysschaert G. 2019. Soil salinity in the Flanders coasta area. The perception of farmers compared to field measurements. Poster presented at the Saline Futures conference in Leeuwarden.

Arthur E, Cornelis W, Vermang J, De Rocker E. 2011a. Effect of compost on erodibility of loamy sand under simulated rainfall. Catena 85:67-72.

Arthur E, Cornelis WM, Vermang J, De Rocker E. 2011b. Amending a loamy sand with three compost types: impact on soil quality. Soil Use and Management 27:116-123.

Bauwens S, Mengalejeune P, Hébert J. 2010. Inventaire sur l'affectation des terres et du changement d'affectation des terres et la foresterie (LULUCF) de la Belgique. Gembloux Agro-Bio Tech, Université de Liège.

Beheydt D. 2006. Nitrous oxide emission from agricultural soils : experimental approach and simulation. PhD dissertation, Ghent University, 177 p.

Beheydt D, Boeckx P, Ahmed HP, Van Cleemput O. 2008. N_2O emission from conventional and minimum-tilled soils. Biology and Fertility of Soils 44:863-873.

Bijttebier J, Ruysschaert G. 2014. Farm survey country report: Belgium. Catch-C project. 344 p.

Bijttebier J, Ruysschaert G, Hijbeek R, Werner M, Pronk AA, Zavatarro L, Bechini L, Grignani C, ten Berge H, Marchand F, Wauters E. 2018. Adoption of non-inversion tillage across Europe: use of a behavioral approach in understanding decision making of farmers. Land Use Policy 78: 460-471.

Bodemkundige Dienst van België, Universiteit Gent Vakgroep Bodembeheer en bodemhygiëne. 2008. Ontwikkelen van een expertsysteem voor het adviseren van het koolstofbeheer in de landbouwbodems. LA BOD/STUD 2006 01 04. Studie in opdracht van Vlaamse Overheid, Departement Leefmilieu, Natuur en Energie & ALBON, Dienst Land- en Bodembescherming, 155 p.

Chaves B, De Neve S, del Carmen Lillo Cabrera M, Boeckx P, Van Cleemput O, Hofman G. 2005. The effect of mixing organic biological waste materials and high-N crop residues on the short-time N_2O emission from horticultural soil in model experiments. Biology and Fertility of Soils 41:411-418.

Cools N, Van Gossum P. 2014. Hoofdstuk 18 - Ecosysteemdienst behoud van de bodemvruchtbaarheid. (INBO.R.2014.1988205). In Stevens, M et al. (eds.), Natuurrapport - Toestand en trend van ecosystemen en ecosysteemdiensten in Vlaanderen. Technisch rapport. Mededelingen van het Instituut voor Natuur- en Bosonderzoek, INBO.M.2014.1988582, Brussel.

Coppens F, Garnier P, De Gryze S, Merckx R, Recous S. 2006. Soil moisture, carbon and nitrogen dynamics following incorporation and surface application of labelled crop residues in soil columns. European Journal of Soil Science 57:894-905.

Cougnon M, D'Hose T, Reheul D. 2008. Gebruik en werking van GFT-compost in de teelt van maïs. Onderzoeksproject in opdracht van VLACO. 28 p.

D'Haene K. 2008. The potential of reduced tillage in Flanders. PhD dissertation, Ghent University, 199 p.

D'Haene K, Van den Bossche A, Vandenbruwane J, De Neve S, Gabriels D, Hofman G. 2008. The effect of reduced tillage on nitrous oxide emissions of silt loam soils. Biology and Fertility of Soils 45:213-217.

D'Hose T. 2015. The effect of farm compost application and crop rotation on chemical, physical and biological soil quality and crop yields. PhD dissertation,Ghent University. 165p.

D'Hose T, Cougnon M, De Vliegher A, Van Bockstaele E, Reheul D. 2012a. Influence of farm compost on soil quality and crop yields. Archives of Agronomy and Soil Science 58:S71-S75.

D'Hose T, Cougnon M, De Vliegher A, Vandecasteele B, Viaene N, Cornelis W, Van Bockstaele E, Reheul D. 2014. The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. Applied Soil Ecology 75:189-198.

D'Hose T, Cougnon M, De Vliegher A, Willekens K, Van Bockstaele E, Reheul D. 2012b. Farm compost application: Effects on crop performance. Compost Science & Utilization 20:49-56.

D'Hose T, Debode J, Ruysschaert G, De Tender C, Vandecasteele B. 2020. Has compost with biochar applied during the process added value over biochar or compost for increasing soil quality in an arable cropping system? Applied Soil Ecology 156, 103706.

D'Hose, T., Ren, L., Cornelis, W., Ruysschaert, G., 2017a. Effect van bandenspanning en bodemvochtgehalte op bodemverdichting en gewasgroei. ILVO Mededeling 230. 47p.

D'Hose T, Ruysschaert G. 2017b. Mogelijkheden voor koolstofopslag onder gras- en akkerland in Vlaanderen. ILVO Mededeling 231. 76p.

D'Hose T, Ruysschaert G, Viaene N, Debode J, Nest TV, Van Vaerenbergh J, Cornelis W, Willekens K, Vandecasteele B. 2016. Farm compost amendment and non-inversion tillage improve soil quality without increasing the risk for N and P leaching. Agriculture, Ecosystems & Environment 225:126-139.

De Boever M, D'Hose T, Ruysschaert G. Unpublished. Literatuurstudie effectieve organische stof.

De Clercq T, Elsen A, Bries J. 2013. Onderzoek naar de bemestings-en bodemverbeterende waarde van GFT-compost via een meerjarige proef op akkerland. Verslag wintertarwe –resultaten 2012. 41 p.

De Groot C-J, Vermoesen A, Van Cleemput O. 1994. Laboratory study of the emission of NO and N_2O from some Belgian soils. Environmental monitoring and assessment 31:183-189.

De Pue J, Cornelis WM. 2019. DEM simulation of stress transmission under agricultural traffic Part 1: Comparison with continuum model and parametric study. Soil and Tillage Research 195:104408.

De Pue J, Di Emidio G, Flores RDV, Bezuijen A, Cornelis WM. 2019. Calibration of DEM material parameters to simulate stress-strain behaviour of unsaturated soils during uniaxial compression. Soil and Tillage Research 194:104303.

De Pue J, Lamandé M, Cornelis W. 2020a. DEM simulation of stress transmission under agricultural traffic Part 2: Shear stress at the tyre-soil interface. Soil and Tillage Research 203:104660.

De Pue J, Lamandé M, Schjønning P, Cornelis WM. 2020b. DEM simulation of stress transmission under agricultural traffic Part 3: Evaluation with field experiment. Soil and Tillage Research 200:104606.

De Vos B. 2009. Uncertainties of forest soil carbon stock assessment in Flanders. PhD dissertation, KU Leuven. 318p.

De Waele J, De Vliegher A, Vandecasteele B, Odeurs W, Elsen A, Haesaert G, Derycke V, Verlinden G, Bries J, Wittouck D. 2014. Beste landbouwpraktijken van teelten in combinatie met nateelten/vanggewassen. Literatuurstudie. Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij door de Vakgroep Bodembeheer van de Universiteit Gent, de Vakgroep Plantaardige Productie van de Hogeschool Gent, ILVO, de Bodemkundige Dienst van België en Inagro. 91p.

Elsen A, Tits M, Vandendriessche H. 2011. How can VFG-compost applications contribute to carbon sequestration in agricultural land: a model approach validated by long term field trial measurements. International Symposium on Soil Organic Matter, 2011/07/11-2011/07/14, Leuven, Belgium.

Elsen F, Beckers V, Diels J, Van Orshoven J, Wauters S, Huybrechts M. 2014. Praktijkonderzoek naar de toepassing van preventieve en remediërende maatregelen tegen bodemaantasting door bodemverdichting. Studie uitgevoerd in opdracht van de Vlaamse Overheid, Dep. Leefmilieu, Natuur en Energie, Afd. Land en Bodembescherming, Ondergrond, Natuurlijke Rijkdommen, door de Bodemkundige Dienst van België, het Departement Aard- en Omgevingswetenschappen (KU Leuven) en Thomas More (KU Leuven Associatie). 314 pp.

Finke P, Hutson J. 2008. Modelling soil genesis in calcareous loess. Geoderma 145:462-479.

Finke P, Samouelian A, Suarez-Bonnet M, Laroche B, Cornu S. 2015. Assessing the usage potential of SoilGen2 to predict clay translocation under forest and agricultural land uses. European Journal of Soil Science 66:194-205.

Foqué D, Demeyer P. 2009. Optimalisering en actualisering van de emissie-inventaris ammoniak landbouw. ILVO Mededeling 69. 152p.

Garré S, Janssens P, Reynaert S, Dumont G, Von Hebel C, Piccard I, Pauly K, Neumann Andersen M, Manevski K, Peng J, Kørup K, 2020. Variable rate irrigation and nitrogen fertilization in patato; engage the spatial variation (potential). Background document – with guidelines for variable rate application of water and nitrogen in potato. Soil Service of Belgium, 90 p.

Goidts E, Van Wesemael B, Crucifix M. 2009. Magnitude and sources of uncertainties in soil organic carbon (SOC) stock assessments at various scales. European Journal of Soil Science 60(5): 723-739.

Goossens A, De Visscher A, Boeckx P, Van Cleemput O. 2001. Two-year field study on the emission of N_2O from coarse and middle-textured Belgian soils with different land use. Nutrient Cycling in Agroecosystems 60:23-34.

Gybels R, Viaene J, Vandervelden J, Reubens B, Vandecasteele B. 2013. Biomassa als bodemverbeteraar: onderzoek naar de toepassing van beheerresten als bodemverbeteraar. Agentschap Natuur en Bos, Inverde & ILVO.

Hack-ten Broeke M. 2015. RAI-SOILCOMP: Raising Awareness on the Impact of subSOIL COMPaction. Project No. SN04-03. Final report, 71p.

Hénin S, Dupuis M. 1945. Essai de bilan de la matière organique du sol. Annales Agronomiques 15:17–29.

Hermans I, Elsen A, Bries J. 2010. Groenbemesters en nitraatresidu. Bodemkundige Dienst van België vzw.

Joos L, Beirinckx S, Haegeman A, Debode J, Vandecasteele B, Baeyen S, Goormachtig S, Clement L, De Tender C, 2020. Daring to be differential: metabarcoding analysis of soil and plant related microbial communities using amplicon sequence variants and operational taxonomical units. BMC Genomics 21, 733.

Kader MA, Sleutel S, D’Haene K, De Neve S. 2010. Limited influence of tillage management on organic matter fractions in the surface layer of silt soils under cereal–root crop rotations. Soil Research 48:16-26.

Lettens S, Van Orshoven J, Van Wesemael B, De Vos B, Muys B. 2005a. Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. Geoderma 127:11-23.

Lettens S, Van Orshoven J, Van Wesemael B, Muys B, Perrin D. 2005b. Soil organic carbon changes in landscape units of Belgium between 1960 and 2000 with reference to 1990. Global Change Biology 11:2128-2140.

Leys A. 2008. Hydrological and erosion aspects of conservation agriculture. PhD dissertation, KU Leuven.

Mabilde L, De Neve S, Sleutel S. 2017. Regional analysis of groundwater phosphate concentrations under acidic sandy soils: Edaphic factors and water table strongly mediate the soil P-groundwater P relation. Journal of environmental management 203:429-438.

Manrique LA, Jones CA. 1991. Bulk-density of soils in relation to soil physical and chemical-propoerties. Soil Sci. Soc. Am. J. 55: 476-481.

Meersmans J, van Wesemael B, Goidts E, Van Molle M, De Baets S, De Ridder F. 2011. Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960–2006. Global Change Biology 17:466-479.

Meert P, Willems P. 2013. Evaluatie van berekeningsmethoden voor het bepalen van de benodigde buffercapaciteit van kleinschalige opvangsystemen in het kader van erosiebestrijding. Studie in opdracht van Vlaamse Overheid – Departement LNE – Afdeling Land en Bodembeschering, Ondergrond, Natuurlijke Rijkdommen. 246p.

Mestdagh I. 2005. Carbon sequestration in different Flemish grassland ecosystems. PhD dissertation, Ghent University. 201 p.

Mestdagh I, Lootens P, Van Cleemput O, Carlier L. 2006. Variation in organic-carbon concentration and bulk density in Flemish grassland soils. Journal of plant nutrition and soil science 169:616-622.

Mestdagh I, Sleutel S, Lootens P, Van Cleemput O, Beheydt D, Boeckx P, De Neve S, Hofman G, Van Camp N, Vande Walle I. 2009. Soil organic carbon–stock changes in Flemish grassland soils from 1990 to 2000. Journal of plant nutrition and soil science 172:24-31.

Moeskops B, Buchan D, Van Beneden S, Fievez V, Sleutel S, Gasper M, D'Hose T, De Neve S. 2012. The impact of exogenous organic matter on SOM contents and microbial soil quality. Pedobiologia 55:175-184.

Nawara S, Van Dael T, Merckx R, Amery F, Elsen A, Odeurs W, Vandendriessche H, McGrath S, Roisin C, Jouany C, Pellerin S. 2017. A comparison of soil tests for available phosphorus in long-term field experiments in Europe. European Journal of Soil Science 68:873-885.

N-(eco)^2. 2002. Bepaling van de hoeveelheid minerale stikstof in de bodem als beleidsinstrument. Eindrapport Deel 4: Scenarioanalyses, Afleiding van de normen, Aanbevelingen aan de landbouwers. Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij door het consortium Bodemkundige Dienst van België, Instituut voor Land- en Waterbeheer (K.U.Leuven), Laboratorium voor Bodemvruchtbaarheid en –biologie (K.U.Leuven), Bodemkunde en Fertiliteit (R.U.Gent) en SADL (K.U.Leuven). Besteknummer 2000/1. 271 pp.

Nelissen V. 2013. Effects of biochar on soil processes, soil functions and crop growth. PhD dissertation, Ghent University.

Nelissen V, Ruysschaert G, Manka'Abusi D, D'Hose T, De Beuf K, Al-Barri B, Cornelis W, Boeckx P. 2015. Impact of a woody biochar on properties of a sandy loam soil and spring barley during a two-year field experiment. European Journal of Agronomy 62:65-78.

Nelissen V, Saha BK, Ruysschaert G, Boeckx P. 2014. Effect of different biochar and fertilizer types on N_2O and NO emissions. Soil Biology and Biochemistry 70:244-255.

Nelissen V, Van Gossum P, Reubens B, Ruysschaert G, D'Hose T, Pardon P, Van Vooren L. 2016. Hoofdstuk 7 - Maatregelen om het ESD-aanbod van landbouw te verhogen (INBO.R.2016.12342977). In Van Gossum. et al. (eds.), Natuurrapport - Aan de slag met ecosysteemdiensten. Technisch rapport. Mededelingen van het Instituut voor Natuur- en Bosonderzoek, INBO.M.2016.12342456, Brussel.

Nevens F, Reheul D. 2001. Crop rotation versus monoculture; yield, N yield and ear fraction of silage maize at different levels of mineral N fertilization. NJAS-Wageningen Journal of Life Sciences 49:405-425.

Nevens F, Reheul D. 2002. The nitrogen-and non-nitrogen-contribution effect of ploughed grass leys on the following arable forage crops: determination and optimum use. European Journal of Agronomy 16:57-74.

Nevens F, Reheul D. 2003. Permanent grassland and 3-year leys alternating with 3 years of arable land: 31 years of comparison.

Notebaert B, Govers G, Verstraeten G, Van Oost K, Ruysschaert G, Poesen J, Van Rompaey A. 2005. Verfijnde erosiekaart Vlaanderen: eindrapport. K.U. Leuven, Onderzoeksgroep Fysische en Regionale Geografie, 53 p.

Oorts K, Buyle S, Deproost P, Swerts M. 2019a. Eindrapport potentiële bodemerosiekaart per perceel (2018). Departement Omgeving, Brussel.

Oorts, K, Buyle S, Van de Wauw J. 2019b. Berekening van de potentiële erosiekaart per perceel in SAGA-GIS. Departement Omgeving, Brussel.

Ottoy S, Truyers E, De Block M, Lettens S, De Vos B, Swinnen W, Hendrix R, Verstraeten G, Vancampenhout K. 2020. Vijftig tinten grijs: het belang van natuur(beheer) in de strijd tegen klimaatverandering: koolstof-hotsports in Vlaamse natuurgebieden. Bodem: tijdschrift over duurzaam bodembeheer. blz. 12-14.

Ottoy S, Van Meerbeek K, Sindayihebura A, Hermy M, Van Orshoven J. 2017. Assessing top-and subsoil organic carbon stocks of Low-Input High-Diversity systems using soil and vegetation characteristics. Science of The Total Environment 589:153-164.

Panagos P, Borrelli P, Poesen J. 2019. Soil loss due to crop harvesting in the European Union: A first estimation of an underrated geomorphic process. Science of the Total Environment 664:487-498.

Pardon P, Mertens J, Reubens B, Reheul D, Coussement T, Elsen A, Nelissen V, Verheyen K. 2019. Juglans regia (walnut) in temperate arable agroforestry systems: effects on soil characteristics, arthropod diversity and crop yield. Renewable Agriculture and Food Systems:1-17.

Pardon P, Reubens B, Reheul D, Mertens J, De Frenne P, Coussement T, Janssens P, Verheyen K. 2017. Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems. Agriculture, Ecosystems & Environment 247:98-111.

Poelmans L, Van Daele T. 2014. Landgebruikskaart NARA-T 2014. VITO in opdracht van het Instituut voor Natuur en Bosonderzoek 2014/RMA /R /45. 55p.

Pulido Moncada M, Ball BC, Gabriels D, Lobo D, Cornelis WM. 2015a. Evaluation of soil physical quality index S for some tropical and temperate medium-textured soils. Soil Science Society of America Journal 79:9-19.

Pulido Moncada M, Gabriels D, Cornelis WM. 2014a. Data-driven analysis of soil quality indicators using limited data. Geoderma 235:271-278.

Pulido Moncada M, Gabriels D, Cornelis W, Lobo D. 2015b. Comparing aggregate stability tests for soil physical quality indicators. Land Degradation & Development 26:843-852.

Pulido Moncada M, Lozano Z, Delgado M, Dumon M, Van Ranst E, Lobo D, Gabriels D, Cornelis WM. 2018. Using soil organic matter fractions as indicators of soil physical quality. Soil Use and Management 34:187-196.

Pulido Moncada M, Penning LH, Timm LC, Gabriels D, Cornelis WM. 2014b. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil & Tillage Research 140:20-28.

Ren L. 2020. Evaluation of soil compaction: effects, prevention, alleviation and detection. PhD dissertation, Ghent University.

Ren LD, D'Hose T, Ruysschaert G, De Pue J, Meftah R, Cnudde V, Cornelis WM. 2019a. Effects of soil wetness and tyre pressure on soil physical quality and maize growth by a slurry spreader system. Soil & Tillage Research 195 (art. 104344):12.

Ren L, Vanden Nest T, Ruysschaert G, D'Hose T, Cornelis WM. 2019b. Short-term effects of cover crops and tillage methods on soil physical properties and maize growth in a sandy loam soil. Soil and Tillage Research 192:76-86.

Renard KG, Foster GR, Weesies GA, Porter JP. 1991. RUSLE: revised universal soil loss equation. Journal of Soil and Water Conservation 46 (1): 30-33.

Reubens B, Ruysschaert G, D'Hose T, D'Haene K. 2012. Eindrapport BodemBreed Interreg: overzicht van resultaten, inzichten en aanbevelingen. Instituut voor Landbouw-en Visserijonderzoek (ILVO), Merelbeke, België.

Roelandt C, Dendoncker N, Rounsevell M, Perrin D, Van Wesemael B. 2007. Projecting future N_2O emissions from agricultural soils in Belgium. Global Change Biology 13:18-27.

Ruysschaert G. 2005. Spatial and temporal variability of soil losses due to crop harvesting. PhD dissertation, KU Leuven. 281 p.

Ruysschaert G, Jacob M. 2021. Towards climate-smart sustainable management of agricultural soils in Flanders. Part I: EJP SOIL survey on current policy ambitions and future aspirational goals. ILVO mededeling 271.

Ruysschaert G, Poesen J, Auerswald K, Verstraeten G, Govers G. 2007a. Soil losses due to potato harvesting at the regional scale in Belgium. Soil Use and Management 23:156-161.

Ruysschaert G, Poesen J, Notebaert B, Verstraeten G, Govers G. 2008. Spatial and long-term variability of soil loss due to crop harvesting and the importance relative to water erosion: A case study from Belgium. Agriculture, Ecosystems and Environment 126: 217-228.

Ruysschaert G, Poesen J, Verstraeten G, Govers G. 2005. Interannual variation of soil losses due to sugar beet harvesting in West Europe. Agriculture Ecosystems & Environment 107:317-329.

Ruysschaert G, Poesen J, Verstraeten G, Govers G. 2006. Soil losses due to mechanized potato harvesting. Soil & Tillage Research 86:52-72.

Ruysschaert G, Poesen J, Wauters A, Govers G, Verstraeten G. 2007b. Factors controlling soil loss during sugar beet harvesting at the field plot scale in Belgium. European Journal of Soil Science 58:1400-1409.

Ryken N, Vanden Nest T, Al-Barri B, Blake W, Taylor A, Bode S, Ruysschaert G, Boeckx P, Verdoodt A. 2018. Soil erosion rates under different tillage practices in central Belgium: New perspectives from a combined approach of rainfall simulations and Be-7 measurements. Soil & Tillage Research 179:29-37.

Schjønning P, Lamandé M. 2020. An introduction to Terranimo®(www. terranimo. dk). Unpublished note, Aarhus University, Dept. Agroecology: Agroecology.

Schrama M, Vandecasteele B, Carvalho S, Muylle H, van der Putten WH. 2016. Effects of first- and second-generation bioenergy crops on soil processes and legacy effects on a subsequent crop. GCB Bioenergy 8:136-147.

Sleutel S, D'Hose T, Lettens S, Ruysschaert G, De Vos B. 2020. MONITORING VAN HET ORGANISCHE KOOLSTOFGEHALTE IN VLAAMSE BODEMS IN OPENBAAR DOMEIN EN PARTICULIERE TUINEN (opdracht VPO-OMG_VPO_2018_15-F02) – Eindrapport. Vlaams Planbureau voor Omgeving, Brussel.

Sleutel S, D'Hose T, Lettens S, Ruysschaert G, De Vos B. 2021. ACTUALISATIE EN VERFIJNING VAN DE ONDERBOUWING VAN EEN METHODIEK VOOR DE SYSTEMATISCHE MONITORING VAN KOOLSTOFVOORRADEN IN DE BODEM (opdracht OMG/VPO/BODEM/TWOL/2017/1) – Eindrapport. Vlaams Planbureau voor Omgeving, Brussel.

Sleutel S, De Neve S, Hofman G. 2007. Assessing causes of recent organic carbon losses from cropland soils by means of regional-scaled input balances for the case of Flanders (Belgium). Nutrient Cycling in Agroecosystems 78:265-278.

Sleutel S, De Neve S, Hofman G, Boeckx P, Beheydt D, Van Cleemput O, Mestdagh I, Lootens P, Carlier L, Van Camp N. 2003. Carbon stock changes and carbon sequestration potential of Flemish cropland soils. Global Change Biology 9:1193-1203.

Stadig L. 2017. Gimme shelter. Combining free-range broiler chickens with production of short rotation coppice. PhD dissertation, Ghent University.

Staes J, Vrebos D, Marsboom C, Van der Biest K, Boerema A, Broekx S, Liekens I, de Nocker L, Van De Kerchove R, Delalieux S, Bennetsen E, Landuyt D, Verheyden W, De Meyer R, Mortelmans D, Keune H, Jacobs S, Tirry D, Jacxsens P, Ottoy S, Gariels K, Dangol A. 2016. Planning for Ecosystem Services: the ECOPLAN toolbox.

Steel H, Vandecasteele B, Willekens K, Sabbe K, Moens T, Bert W. 2012. Nematode communities and macronutrients in composts and compost-amended soils as affected by feedstock composition. Applied Soil Ecology 61:100-112.

Stevens, M., Demolder, H., Jacobs, S., Michels, H., Schneiders, A., Simoens, I., Spanhove, T., Van Gossum, P., Van Reeth, W., Peymen, J. (Eds.) 2015. Flanders Regional Ecosystem Assessment: State and trends of ecosystems and their services in Flanders. Synthesis. Communications of the Research Institute for Nature and Forest, INBO.M.2015.7842756, Brussels

Swerts M, Broekaert S, Deproost P, Renders D, Oorts K. 2020. Bodemerosierisico-indicator Vlaanderen (2008-2019). Departement Omgeving, Brussel.

Timmerman A, Feyen J. 2003. The WAVE model and its application; Simulation of the substances water and agrochemicals in the soil, crop and vadose environment. Ciencia y Tecnología Agropecuaria 4:36-41.

Tits M, Elsen A, Bries J, Vandendriessche H. 2014. Short-term and long-term effects of vegetable, fruit and garden waste compost applications in an arable crop rotation in Flanders. Plant and soil 376:43-59.

Tits M, Elsen A, Deckers S, Boon W, Bries J, Vandendriessche H. 2016. Bodemvruchtbaarheid van de Akkerbouw- en Weilandpercelen in België en Noordelijk Frankrijk (2012-2015). Publicatie van de Bodemkundige Dienst van België.

Tits M, Elsen A, Deckers S, Bries J, Vandendriessche H. 2020. Bodemvruchtbaarheid van de Akkerbouw- en Weilandpercelen in België en Noordelijk Frankrijk (2016-2019). Publicatie van de Bodemkundige Dienst van België. 235 pp.

Truyers E, Ottoy S, Lettens S, De Vos B, Swinnen W, Hendrix R, Verstraeten G, Vancampenhout K. 2019. Analyse van koolstof-hotspots in Vlaamse natuurgebieden en het beperken van koolstoflekken door natuurbeheer. Perceel 1: Analyse van koolstof-hotspots op ANB terreinen. Studie uitgevoerd in opdracht van het Agentschap voor Natuur en Bos van de Vlaamse overheid. (ANB/klim/18-001). Eindrapport.

Valckx J. 2011. Ecosystem engineering by earthworms in temperate agroecosystems on loamy soils. PhD dissertation, KU Leuven.

Van Cleemput O, Vermoesen A, de Groot C J, van Ryckeghem K. 1994. Nitrous oxide emission out of grassland. Environmental monitoring and assessment, 31(1), 145-152.

Van De Vreken P, Van Holm L, Diels J, Van Orshoven J. 2009. Bodemverdichting in Vlaanderen en afbakening van risicogebieden voor bodemverdichting. Eindrapport van een verkennende studie in opdracht van Vlaamse Overheid, Departement Leefmilieu, Natuur, Energie, Afdeling Land en Bodembescherming, Ondergrond, Natuurlijke Rijkdommen. BOD/STUD/2007/01. 133p.

Van Den Eeckhaut M, Poesen J. 2009. Uitbreiding (fase 3) van de gevoeligheidskaart voor grondverschuivingen in Vlaanderen. Rapport in opdracht van Vlaamse Overheid, Departement Leefmilieu, Natuur en Energie, Afdeling Land en Bodembescherming, Ondergrond, Natuurlijke Rijkdommen, p.169.

Van den Putte A. 2011. Application of conservation tillage in European cultivated landscapes: possibilities and limitations. PhD dissertation, KU Leuven, 178 p.

Van den Putte A, Govers G, Diels J, Langhans C, Clymans W, Vanuytrecht E, Merckx R, Raes D. 2012. Soil functioning and conservation tillage in the Belgian Loam Belt. Soil & Tillage Research 122:1-11.

van der Bolt F, Cornelis W, de Pue J, Hendriks R, van den Akker J, Massop H, Joris I, Dams J, Vos J. 2016. Bodemverdichting in Vlaanderen: Gevolgen van bodemverdichting op het watertransport door een bodem. Wageningen Environmental Research. Report no. 1566-7197.

Van der Heyden D, Heyvaert J, Truyers E, Lettens S, De Vos B, De Somviele B, Vancampenhout K. 2019. Analyse van koolstof-hotspots in Vlaamse natuurgebieden en het beperken van koolstoflekken door natuurbeheer. Perceel 2: Voorkomen van koolstoflekken door natuurbeheer – het ontwikkelen van een beoordelingskader. Studie uitgevoerd in opdracht van het Agentschap voor Natuur en Bos van de Vlaamse overheid. (ANB/klim/18-001). Eindrapport.

van Eekeren N, Bommelé L, Bloem J, Schouten T, Rutgers M, de Goede R, Reheul D, Brussaard L. 2008. Soil biological quality after 36 years of ley-arable cropping, permanent grassland and permanent arable cropping. Applied Soil Ecology 40:432-446.

Van Kerckhoven S, Riksen M, Cornelis W. 2009. Afbakening van gebieden gevoelig aan winderosie in Vlaanderen. Eindrapport, Universiteit Gent, Vakgroep Bodembeheer. Studie in opdracht van Vlaamse Overheid, Departement Leefmilieu, Natuur en Energie, Afdeling Land en Bodembescherming, Ondergrond, Natuurlijke rijkdommen. BOD/STUD/2007/02. 79 p.

Van Meirvenne M, Vanoverbeke M, Willems K, Capieau A, De Vos B, Buysse C, Mencke E, Verhelst A, De Rop A. 2001. Voorspellende kwaliteit en bruikbaarheid van de bodemkaart en historische bosbodemprofielgegevens voor de opmaak van signaalkaarten: eindverslag. Instituut voor Bosbouw en Wildbeheer.

Van Oost K, Govers G, Desmet P. 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape ecology 15:577-589.

Van Oost K, Quine T, Govers G, De Gryze S, Six J, Harden J, Ritchie J, McCarty G, Heckrath G, Kosmas C. 2007. The impact of agricultural soil erosion on the global carbon cycle. Science 318:626-629.

Van Opstal M, Tits M, Beckers V, Elsen A, Van Overtveld K, Batelaan O, Van Orshoven J, Bries, J, Vandendriessche H, Diels J. 2014. Vernieuwde kwantificering van de verliezen van N en P vanuit de landbouw naar het oppervlaktewater. Eindrapport, mei 2014. Studie uitgevoerd in opdracht van de Vlaamse Milieumaatschappij door het Departement Aard- en Omgevingswetenschappen (KU Leuven) en de Bodemkundige Dienst van België.

Van Rompaey A, Verstraeten G, Van Oost K, Govers G, Poesen J. 2001. Modelling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms 26 (11), 1221-1236.

Van Vooren L. 2018. Multifunctionality in agriculture: impact of hedgerows, grass strips and extensive grassland management on crops, regulating ecosystem services and biodiversity. PhD dissertation, Ghent University.

Van Vooren L, Reubens B, Ampoorter E, Broekx S, Pardon P, Van Waes C, Verheyen K. 2018. Monitoring the impact of hedgerows and grass strips on the performance of multiple ecosystem service indicators. Environmental management 62:241-259.

Vanclooster M, Viaene P, Christiaens K, Ducheyne S. 1996. WAVE, a mathematical model for simulating water and agrochemicals in the soil and the vadose environment. Reference and user's manual (Release 2.1). Technical Report. Institute for Land and Water Management, KULeuven.

Vanden Nest T. 2015. Long term use of different organic fertilizer types and impact on phosphorus leaching. PhD dissertation, KU Leuven, 260 p.

Vanden Nest T, Ruysschaert G, Vandecasteele B, Cougnon M, Merckx R, Reheul D. 2015. P availability and P leaching after reducing the mineral P fertilization and the use of digestate products as new organic fertilizers in a 4-year field trial with high P status. Agriculture, Ecosystems & Environment 202:56-67.

Vanden Nest T, Ruysschaert G, Vandecasteele B, Houot S, Baken S, Smolders E, Cougnon M, Reheul D, Merckx R. 2016. The long term use of farmyard manure and compost: Effects on P availability, orthophosphate sorption strength and P leaching. Agriculture Ecosystems & Environment, 216: 23-33.

Vanden Nest T, Vandecasteele B, Ruysschaert G, Cougnon M, Merckx R, Reheul D. 2014. Effect of organic and mineral fertilizers on soil P and C levels, crop yield and P leaching in a long term trial on a silt loam soil. Agriculture, Ecosystems & Environment 197:309-317.

Vanden Nest T, Van de Sande T, De Boever M, Dekeyser D, Ruysschaert G. 2019. Brongerichte erosiebestrijdingstechnieken bij groenten en maïs. Eindrapport van het GOMEROS-project. ILVO Mededeling 257.

Ven A, Verlinden MS, Fransen E, Olsson PA, Verbruggen E, Wallander H, Vicca S. 2020. Phosphorus addition increased carbon partitioning to autotrophic respiration but not to biomass production in an experiment with Zea mays. Plant, Cell & Environment 43(9): 2054-2065.

Ven A, Verlinden MS, Verbruggen E, Vicca S. 2019. Experimental evidence that phosphorus fertilization and arbuscular mycorrhizal symbiosis can reduce the carbon cost of phosphorus uptake. Functional Ecology 33:2215-2225.

Verbruggen E, Jansa J, Hammer EC, Rillig MC. 2015. Do arbuscular mycorrhizal fungi stabilize litter-derived carbon in soil? Journal of Ecology 104:261-269.

Verbruggen E, Pena R, Fernandez CW, Soong JL. 2017. Chapter 24: Mycorrhizal interactions with saprotrophs and impact on soil carbon storage. Mycorrhizal Mediation of Soil, Fertility, Structure and Carbon Storage: 441-460.

Verbruggen E, Rillig MC, Wehner J, Hegglin D, Wittwer R, van der Heijden MG. 2014. Sebacinales, but not total root associated fungal communities, are affected by land-use intensity. New Phytologist 203:1036-1040.

Verbruggen E, Röling WFM, Gamper HA, Kowalchuk GA, Verhoef HA, van der Heijden MGA. 2010. Positive effects of organic farming on below-ground mutualists: large-scale comparison of mycorrhizal fungal communities in agricultural soils. New Phytologist 186:968-979.

Verbruggen E, van der Heijden MGA, Weedon JT, Kowalchuk GA, Roling WFM. 2012. Community assembly, species richness and nestedness of arbuscular mycorrhizal fungi in agricultural soils. Molecular Ecology 21:2341-2353.

Vermang J. 2012. Erosion processes and physical quality of loamy soils as affected by reduced tillage. PhD dissertation, Ghent University.

Vermoesen A, Van Cleemput O, Hofman G. 1996. Long-term measurements of N_2O emissions. Energy conversion and management 37:1279-1284.

Verstraeten G, Van Oost K, Van Rompaey A, Poesen J, Govers G. 2002. Evaluating an integrated approach to catchment management to reduce soil loss and sediment pollution through modelling. Soil Use and Management, 18, 386-394.

Viaene J, Van Lancker J, Vandecasteele B, Willekens K, Bijttebier J, Ruysschaert G, De Neve S, Reubens B. 2016. Opportunities and barriers to on-farm composting and compost application: A case study from northwestern Europe. Waste Management 48:181-192.

Viaene J, Reubens B, Willekens K, Van Waes C, De Neve S, Vandecasteele B. 2017. Potential of chopped heath biomass and spent growth media to replace wood chips as bulking agent for composting high N-containing residues. Journal of Environmental Management 197, 338-350.

VLACO. 2020. Steeds meer compost in de Vlaamse recyclageparken. VLACO-website, 3/5/2020. https://www.vlaco.be/nieuws/steed-meer-compost-in-de-vlaamse-recyclageparken

VMM. 2016. Bronnen van waterverontreiniging in 2016.

VMM, VITO, AWAC, IBGE-BIM, DG-Environment, IRCEL-CELINE, ECONOTEC. 2017. Belgium's greenhouse gas inventory (1990-2015). National Inventory Report submitted under the United Nations Framework Convention on Climate Change. p. 348.

Warrinnier R, Goossens T, Amery F, Vanden Nest T, Verbeeck M, Smolders E. 2019. Investigation on the control of phosphate leaching by sorption and colloidal transport: Column studies and multi-surface complexation modelling. Applied Geochemistry 100:371-379.

Willekens K. 2016. Nitrogen dynamics in relation to soil management and soil quality in field vegetable cropping systems. PhD dissertation, Ghent University.

Willekens K, Vandecasteele B, Buchan D, De Neve S. 2014a. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Applied Soil Ecology 82:61-71.

Willekens K, Vandecasteele B, De Neve S. 2014b. Hoofdstuk 2: Effecten van niet-kerende bodembewerking en composttoepassing op de bodemkwaliteit en de stikstofdynamiek in de intensieve groenteteelt - resultaten van de meerjarige Vegtilco-proef. In: Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw, ILVO Mededeling 171: 20-28.

Xu H, Vandecasteele B, Zavattaro L, Sacco D, Wendland M, Boeckx P, Haesaert G, Sleutel S. 2019. Maize root-derived C in soil and the role of physical protection on its relative stability over shoot-derived C. European Journal of Soil Science 70:935-946.

Annex I Questionnaire 2: “Beleid/praktijk”

Stakeholder questionnaire
EJP Soil Task 2.2.2 & 2.3

Sustainable soil management in Flanders: knowledge use, gaps and needs, barriers and opportunities

Questionnaire 2: “Beleid/praktijk”

EJP SOIL

*This questionnaire is part of the European Joint Programme Soil (**EJP SOIL)**. The overall objective of EJP SOIL is to provide solutions for sustainable soil management that contribute to addressing key societal challenges including climate change and future food supply. Please see www.ejpsoil.eu for further information.*

*EJP SOIL invites you to participate as a valuable **stakeholder** and to engage in the programme to represent the breadth of agricultural systems and soil management practices in Flanders. By contributing to this survey, you can grasp the opportunity to highlight the knowledge needs from Flanders*

*The information you provide will feed into an **EU roadmap** that will reflect the knowledge needs in each region in Europe and that will outline the key research and capacity building priorities, supporting soil data harmonisation, policy-making and knowledge implementation.*

Background information questionnaire

The specific aim of this questionnaire is (i) to **clarify the structure and functioning** of the agricultural knowledge system in relation to sustainable soil management in Flanders, (ii) to identify knowledge gaps and express **knowledge needs** and (iii) to **identify barriers and opportunities** for knowledge development, sharing, organizing and application within this agricultural knowledge system.

Step-by-step

The questionnaire template comprises **4 steps**: (1) Background information, (2) Soil challenges prioritization, (3) knowledge use, gaps and needs and (4) identification of barriers and opportunities for knowledge use.

IMPORTANT:

The answers you provide should be your own opinion based on your knowledge and expertise and do not have to be official statements of your organisation (if applicable). In the final report, results will be clustered by stakeholder group only, so it will not be possible to trace the answers back to your name, institute or organisation.

☐ I confirm that I have read and understood the objective of the questionnaire part of the EJP SOIL program, and agree that my answers will be processed anonymously.

Questions?

Should anything be unclear, please contact the coordinator for this task, being Miro Jacob, +32 (0)9 272 23 84.

Thank you for your valuable inputs!

Step 1: Background information

In this introductory step we ask you to provide some basic background information by answering the questions in Table 1. Names are for the track record of the coordinator of this task only, because there might be an interview afterwards for clarifications. In the final report, results will be clustered by stakeholder group only, so it will not be possible to trace the answers back to your name, institute or organisation.

Remark: This table is identical for all parallel questionnaires of the EJP Soil program. If you are participating in the different questionnaires the table should only be filled once, **except for your name and institute/organisation**.

STEP 1 – Table 1: Background information

Background information	
Can you provide your full name and job title?	*Name, Job title*
What stakeholder group do you identify yourself with most?	☐ *Research communities* ☐ *Research funders* ☐ *Middle & Higher educational institutions* ☐ *Farmer Schools* ☐ *Farmers and demonstration farms* ☐ *Advisors* ☐ *Farmers' organisations* ☐ *Agro-industry* ☐ *Laboratories, National science testing, Verification centers etc.* ☐ *Industry, Supply & Retail* ☐ *NGOs and community-based organizations*
If applicable, what institute or organisation do you work for?	*Institute/organisation*
What is the relevance of agricultural soils and soil management within your job?	*Relevance agricultural soils and soil management*
Have you completed the questionnaire on your own or have you consulted any colleagues? How many persons did you consult? And who are these persons? (*To be clear: it is not mandatory for this questionnaire that you have consulted your colleagues. This should not be an official answer of your organisation, rather your opinion based on your expertise*)	*[to be filled after finishing the questionnaire]*
Other (general remarks)	*[open question]*

Step 2: Prioritization soil challenges

Note: *this step can be skipped if you completed the stakeholder questionnaire of EJP Soil Task 2.1 on 'Validating current policy ambitions and defining aspirational goals on agricultural soils' and more specifically 'Step 4: Policy prioritization'.*

What: Prioritization of the soil challenges to identify the **key themes** in Flanders.

What do you expect that will be the main soil challenges that are most relevant for Flanders in the upcoming decades?

How: For this exercise, you should attribute a total of 100 points between the various soil challenges in Flanders.

STEP 2 - Table 2: Prioritization soil challenges

		Policy prioritization (a total of 100 points should be attributed between the various soil challenges)
	Example	***Flanders***
Maintain/increase SOC	*30*	
Avoiding N_2O, CH_4 emissiosn	*10*	
Avoid peat degradation		
Avoid soil erosion	*10*	
Avoid soil sealing		
Avoid salinisation		
Avoid acidification		
Avoid contamination		
Optimal soil structure		
Enhance soil biodiversity		
Enhance soil nutrient retention/use efficiency	*20*	
Enhance water storage capacity	*30*	
Total sum:	***100***	**100**

Step 3: Knowledge use, gaps and needs

<u>Important note</u>: In this step we ask you to clarify the functioning of the agricultural knowledge system and to express knowledge needs, as perceived from your perspective. We thus ask for **your stakeholder opinion** based on your expert knowledge.

<u>What</u>: disentangling the structure and functioning of the agricultural knowledge system and identifying knowledge gaps and needs in relation to sustainable soil management in three successive parts:

(1) ***Coordination*** *of the knowledge system*
Assessment of the nature of the formal links between stakeholders in the coordination and production of sustainable soil management knowledge.

(2) ***Strength*** *of the knowledge system*
Assessment of dissemination and availability of knowledge on sustainable soil management for stakeholders.

(3) ***Knowledge needs*** *of the knowledge system*
Assessment of sustainable soil management knowledge needs in Flanders.

<u>How</u>: For your response, we have provided three fill-in tables, one for each part. These tables include two types of questions:

- Closed questions in which you are asked to answer the question based on the Likert scale provided for each question. We recommend to provide a brief explanation of your answer. Although this is optional, it will strengthen the final recommendations that can be retrieved from your inputs.

- Open ended questions; these follow after the open questions and enable you to deepen your answer on the general topic.

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

STEP 2 – Table 1: Coordination of the knowledge system

Questions	**Likert scale**					**Remarks (advised, but optional)**
1.1 How well is **farmers access** to relevant knowledge about sustainable soil management?	Very good	Good	Neutral	Somewhat deficient	Very poor	
1.2 How well are **young farmers prepared** for sustainable soil management in farm schools?	Very well prepared	Well prepared	Neutral	Somewhat poorly prepared	Very poorly prepared	
1.3 How well is the **advisory service prepared** to promote knowledge on sustainable soil management to farmers?	Very well prepared	Well prepared	Neutral	Somewhat poorly prepared	Very poorly prepared	
1.4 How well is the **overall coordination** of knowledge transfer on sustainable soil management?	Very well coordinated	Coordinated	Neutral	Somewhat coordinated	Uncoordinated	
1.5 How well are **research activities** in relation to sustainable soil management **coordinated by policy-makers**?	Very well coordinated	Coordinated	Neutral	Somewhat coordinated	Uncoordinated	
1.6 Other reflections regarding the coordination of knowledge use and knowledge exchange between stakeholders?	*(open, max 500 words)*					
1.7 How can the coordination of knowledge production and use regarding sustainable soil management be improved?	*(open, max 500 words)*					

STEP 2 – Table 2: Strength of the knowledge system

Question	***Likert scale***					***Remarks (advised, but optional)***
2.1 To which extent is the current knowledge system effective in **communicating** knowledge on sustainable soil management to farmers?	Highly effective	Effective	Neutral	Somewhat effective	Ineffective	
2.2 To which extent are different **platforms** used to disseminate knowledge on sustainable soil management to farmers?	Highly used	Used	Neutral	Somewhat used	Not used	
Social media						
Printed media						
Electronic newsletters						
Peer-to-peer groups						
Farmer interest groups						
Advisory service						
Webpages and blogs						
Scientific literature						
Technical reports						
Other						
2.3 To which extent are **resources** available for the **dissemination** of knowledge on sustainable soil management?	To a very high extent	To some extent	Neutral	To a small extent	Not at all	
2.4 To which extent are financial **resources** available for the **production** of knowledge on sustainable soil management?	To a very high extent	To some extent	Neutral	To a small extent	Not at all	
2.5 Reflections regarding the dissemination of knowledge on sustainable soil management?	*(open, max 500 words)*					

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

2.6 How can knowledge availability and transfer for stakeholders be improved?	*(open, max 500 words)*

STEP 2 – Table 3: Knowledge gaps on sustainable soil management

Question	***Likert scale***					***Remarks (advised, but optional)***
3.1 How important are the **soil challenges** in Flanders?	Very important	Important	Neutral	Less important	Not important at all	
Maintain/increase SOC						
Avoiding N2O, CH4 emissions from soils						
Avoid peat degradation						
Avoid soil erosion						
Avoid soil sealing						
Avoid salinisation						
Avoid acidification						
Avoid contamination						
Optimal soil structure						
Enhance soil biodiversity						
Enhance soil nutrient retention/use efficiency						
Enhance water storage capacity						
3.2 How important are **research needs** for the following soil challenges in Flanders?	Very important	Important	Neutral	Less important	Not important at all	
Maintain/increase SOC						
Avoiding N2O, CH4 emissions from soils						
Avoid peat degradation						
Avoid soil erosion						
Avoid soil sealing						
Avoid salinisation						
Avoid acidification						

Avoid contamination						
Optimal soil structure						
Enhance soil biodiversity						
Enhance soil nutrient retention/use efficiency						
Enhance water storage capacity						
3.3 How important are the following **tasks** to improve soil knowledge in Flanders?	Very important	Important	Neutral	Less important	Not important at all	
New scientific knowledge on the prevalence of key soil challenges						*Key soil challenges as identified in 3.1. If multiple challenges, you can score them seperately (by adding a row for each).*
New management strategies for sustainable soil management						
Improve soil monitoring						
Increasing availability of existing research for practitioners						
Increase availability of existing research for policy makers						
Improving the coordination of knowledge exchange between actors						
Other (you can add rows to put in missing tasks)						
3.4 What are the most important scientific **research gaps** in Flanders?	*(Open, max 500 words)*					
3.5 What are the most important gaps in current **soil monitoring** in Flanders?	*(Open, max 500 words)*					
3.6 How can knowledge on sustainable soil management be made more relevant for policy-makers in Flanders? What are knowledge needs from the **policy perspective**?	*(Open, max 500 words)*					
3.7 What are the most important gaps in availability of knowledge on sustainable soil management in Flanders? What are knowledge needs from the **farmer perspective**?	*(Open, max 500 words)*					

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

3.8 How can the **use of knowledge** on sustainable soil management by farmers be promoted in Flanders?	*(Open, max 500 words)*
3.9 Other reflections regarding knowledge on and use of knowledge on sustainable soil management in Flanders?	*(Open, max 500 words)*

Step 4: Barriers and opportunities of knowledge development and use

Important note: In this step we ask you to identify barriers and opportunities of knowledge development and use. As perceived from your perspective, we thus ask for **your stakeholder opinion** based on your expert knowledge.

What: The evaluation of the knowledge system in step 2 forms a good initial source to identify potential barriers and opportunities of knowledge development and use in Flanders. Here we ask to further explore potential barriers and opportunities in a structured format. A joined identification of the key barriers and opportunities is important to enhance knowledge exchange in the future.

The questionnaire is subdivided in two parts:

(1) *Identification of general barriers and opportunities for soil knowledge development, sharing, organizing and application (to reach the EJP goals*).*
Here, the questions aim at disentangling knowledge development and use for all soil challenges in Flanders.

(2) *Identification of specific barriers and opportunities for soil knowledge development, sharing, organizing and application (to reach the EJP goals*).*
Here, the questions aim at disentangling knowledge development and use for specific soil challenges in Flanders. This allows to focus more in depth on barriers and opportunities of specific soil challenges that you tackle in your field.

* The overarching EJP SOIL goals are 'good agricultural soil management for: climate change mitigation and adaptation, sustainable production, ecosystem services and less soil degradation. The multiple links between the EJP SOIL goals with the different elements of climate smart sustainable soil management and the link between soil challenges and the elements of climate smart sustainable agriculture are illustrated in the soil concept framework (Fig. 1).

EJP SOIL
European Joint Programme
EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

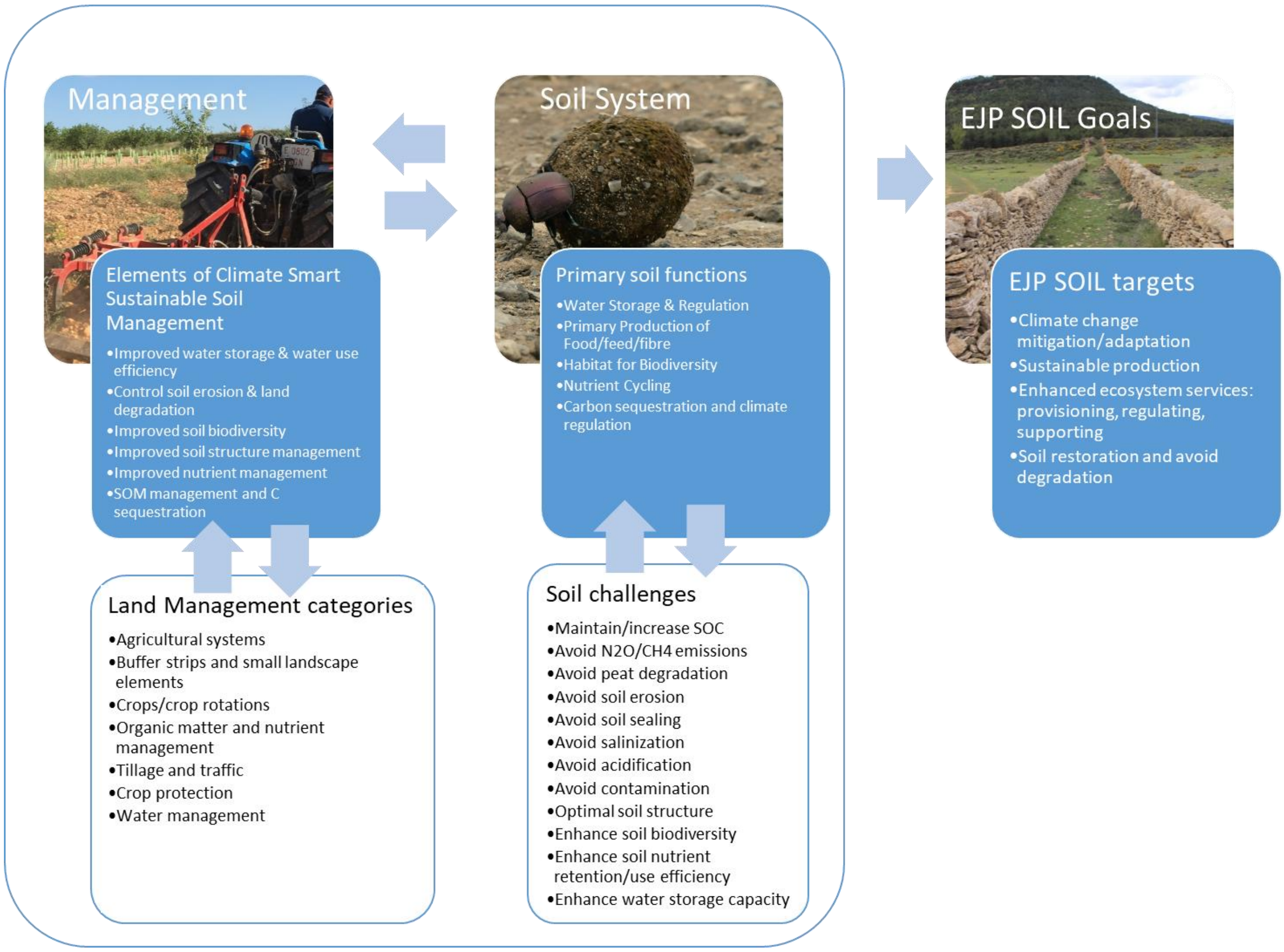


***Figure 1**: Soil Concept Framework: This linkages diagram illustrates how local land management choices can influence the elements defining climate smart sustainable soil management. Secondly, the diagram shows the interlinkage between the primary soil functions and soil challenges; and that the local soil conditions together impact and are impacted by the management choices made on a specific location.*

***How*:** We present a **four by two cross table** matching knowledge development, sharing, harmonization and application to barriers and opportunities.

When answering step 3, you might have listed already some existing barriers or opportunities of knowledge use. These can be integrated in the cross table, by referring to the question numbers.

Each question, contains a set of pre-listed barriers/opportunities (in grey). The pre-list is only to guide and facilitate your answer, if applicable you can refer to these when answering the question. When none of the pre-listed answers fits your statement, you are asked to include your specific answer.

When answering, you can clear the cell so only your answer remains visible in each cell. Your answer, for each cell, is **limited to 500 words**.

EJP SOIL European Joint Programme
EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695
ILVO Institute for Agricultural and Fisheries Research

STEP 3 – Table 1: General barriers and opportunities

	Barriers	**Opportunities** (*Please specify if these are existing opportunities that should be reinforced/developed further or opportunities that should be created newly*)
Knowledge development	*Which are the most important general barriers, at regional level (Flanders) or country level, to knowledge development, perceived as obstacles to reach the main EJP goals?* *Barriers might be:* □ *the identification of research needs is not effective, as a result research is not focusing on the most important topics;* □ *too large number of soil research institutions whose actions are fragmented and not coordinated;* □ *institutions working on soil science are not enough;* □ *scientific equipment in university/research organizations are obsolete;* □ *financial resources allocated to soil research are not sufficient;* □ *selection processes mechanisms for research project are not appropriate, bottlenecks and lack of coordination among national/regional institutions (ministries, regions and national agencies) within the research chain;* □ *lack of public-private partnership on soil research;* □ *lack of relations among research, advisory services and farmers (including their associations);* □ *lack of training for advisors and farmers on soil-related issues.* □ *Other drivers out of the knowledge compartment, such as economic constraints, institutional/regulatory political bottlenecks and limitations, social, cultural, gender and gaps?* □ *Other*	*Which opportunities are offered by soil knowledge development to reach the main EJP goals at regional level (Flanders) or country level?* *Opportunities can come from elements such as:* □ *promoting start-ups;* □ *increasing funding for soil related research;* □ *increasing the number and improving curricula of the soil science students;* □ *increasing training for farmers, advisors and other actors potentially involved in developing soil-related knowledge;* □ *promoting women participation to soil research;* □ *supporting multi- and trans-disciplinary research;* □ *supporting multi-actor projects (better involvement of farmers/advisors in the early stages of projects definition might boost more appropriate definition of research needs), activate/valorise/fund long term experiments;* □ *switch from top-down to bottom-up research, etc.* □ *Other*
Knowledge sharing and transfer	*Which are the general barriers/gaps to knowledge sharing and transfer perceived as obstacles to reach the main EJP goals?* *Barriers identified in this step could be:* □ *networks science-science, science-farmers, science-advisors, science-society, science-policy are not established;* □ *communication between researchers and farmers is not effective and this hampers the transfer of useful knowledge;* □ *lack of training for farmers and advisors;*	*Which opportunities at general level are offered by knowledge sharing and transfer?* *Opportunities might be:* □ *establishment of permanent national networks science-science, science-farmers, science advisors, science-society, sciencepolicy;* □ *improving training programmes for farmers and advisors;* □ *supporting peer-to-peer training between farmers/advisors;* □ *supporting the setting-up of demonstration activities (e.g. experimental and demonstration farms);*

	□ *lack of training for researchers on how better communicate with practitioners;* □ *difficult access to proper advice for farmers;* □ *dissemination is missing, dissemination content does not convey useful information, communication is not clear for all stakeholder categories, etc.* □ *Other*	□ *supporting multi-actor approach, particularly the exchange between researchers and farmers/advisors;* □ *improving dissemination activity;* □ *making dissemination mandatory in all funded projects;* □ *allowing for targeted and effective dissemination;* □ *using effective communication to increase awareness on the importance of soil in all of society, etc* □ *Other*
Harmonization, organization and storage of information	*Which are the most important general barriers to harmonization, organization and storage of information about soil-related knowledge, perceived as obstacles to reach the main EJP goals?* *Barriers on soil data might be:* □ *outdated information, different methodologies used for soil sampling, analysis and mapping, and/or storage data dispersed and often not available to the public;* □ *Barriers on data sharing might be lack of common data policy and data fragmentation;* □ *Technological barriers might be lack of internet access in rural areas, lacking common "decision support" ICT tools able to secure soil data storage facilities at EU level.* □ *Other*	*Which are the opportunities offered by harmonization, organization and storage of information about soil-related knowledge, to reach the main EJP goals?* *Opportunities to overcome soil data fragmentation might be:* □ *promotion of harmonization and standardization methodologies;* □ *creation of national infrastructures and interactive web-based communication of soil data;* □ *data storage with international standards, etc.* □ *Another opportunity can be the validation and integration of large data sets by using new developments in information technology (such as geographic information systems, statistics and modelling, contributing to reporting on the international commitments (Kyoto protocol, UNFCCC, CAP)).* □ *Other*
Knowledge application	*Which are the most important general barriers to knowledge application perceived as obstacles to reach the main EJP goals?* *Barriers might be:* □ *Economic barriers can be costs and lags in return from changing land management practices, yields and profits may not respond as farmer/land managers expect; lack of appropriate incentives.* □ *Social barriers can be lack of communication structure in which dissemination, communication and knowledge exchange activities are facilitated (i.e. lack of soil specific website, popular articles, soil guidelines...) or/and communities pressure/traditional practices and gender norms that can hinder change of soil management practices.* □ *Institutional and legal barriers can affect implementation of sustainable soil management practices as well as land tenure and access; lack of good*	*According to stakeholders, which are the opportunities offered by soil knowledge application to reach the main EJP goals?* *Opportunities might be:* □ *soils are better integrated in the circular economy and bio-economy with a good consequence in farms profits;* □ *good policies and incentives with effective policy measures;* □ *development of region-specific soil management strategies;* □ *farmers have adequate ICT tools and use them;* □ *the existence of specific mechanisms to support farmers in applying this knowledge (access to training and advice, demonstration activities, field visits, etc.).* □ *Other*

EJP SOIL European Joint Programme
EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

	policies and incentives; lack of scientific support to policy makers and/or vice versa. □ *Technological barriers can be lack of internet access in rural areas, lacking "decision support" ICT tools, lack of applied agricultural technology.* □ *In addition to these four main categories of barriers, it should also be considered the lack of exchange, often reported, between researchers and farmers/advisors. Correct application of knowledge and research results require specific capacities that often farmers or advisors do not possess or the reverse, researchers might lack feeling with farmer activities. The lack of tools that facilitate positive exchanges among farmers and researchers, or among farmers (peer-to peer) might represent an important barrier to applying knowledge already developed and tested.* □ *Other*	

STEP 3 – Table 2: Specific barriers and opportunities

	Barriers	**Opportunities** *Please specify if these are existing opportunities that should be reinforced/developed further or opportunities that should be created newly:*
Knowledge development	*Which are the most important specific barriers and gaps, at national level, in the actual knowledge development, which are perceived as obstacles to overcome the challenge [name of the challenge]?* *Elements of knowledge gaps specific for soil and the soil challenge are of the type:* □ *lack of understanding of basic processes of water, nutrients and organic matter in soils in this pedoclimatic area;* □ *new research topics;* □ *missing a national database on soils;* □ *lack of spatially explicit soil data;* □ *gaps in local specific knowledge (effect of soil, crop, residues management on the soil challenge);* □ *scaling issues for the soil challenge;* □ *links between soil management;* □ *farming systems and soil quality;* □ *training for young researchers; etc.* □ *Other*	*Which are the opportunities offered by soil knowledge development for the challenge [name of the challenge]?* *Opportunities focusing on soil science development could be:* □ *evaluation of the connection between the land use and the [name of the challenge];* □ *development and application of soil sustainable management indicators;* □ *development and validation of relevant bio-physical models for predicting the long term dynamics of soil phenomena;* □ *measuring at local level, could fit more detailed for local knowledge needs.* □ *Other opportunities can descend from specific regulations, agro-environmental measures at national and regional level, country or regional incentives.* □ *Other*

Knowledge sharing and transfer	*Which are the most important barriers/gaps to sharing and transfer knowledge perceived as obstacles to overcome [name of the challenge] in this country?* *Possible issues in knowledge sharing and transfer specific to the soil can be of the type:* □ *there is knowledge on the issue, but it is not disseminated, the knowledge is not available for all actors involved in soil;* □ *there is no communication among all stakeholders;* □ *there are not appropriate methods to support an effective sharing among researchers and farmers; etc.* □ *Other*	*Which are the opportunities offered by knowledge sharing and transfer for the soil challenge [name of the challenge]?* *Opportunities to overcome the soil challenge might be:* □ *availability of knowledge for stakeholders;* □ *capacity building from universities and schools;* □ *technical networks science-farmers;* □ *establishing soil networks for scientists, science-policy and science-society;* □ *improving dissemination; continuous knowledge synthesis and feedback loop;* □ *stakeholder participation; setting-up operational groups and taking stock from those already working on soil-related themes;* □ *strengthening scientific capacities and cooperation;* □ *setting-up capacity building programmes for young soil scientists and societal stakeholders i.e. farmers and advisors, policy makers, landowners and managers, civil society and industry.* □ *Other*
Harmonization, organization and storage of information	*Which are the most important barriers/gaps to knowledge harmonization, organization and storage (i.e. soil data acquisition, organization in open soil data base, georeferencing of soil properties, standard protocols for soil analyses, sharing long term experiment data) perceived as obstacles to overcome the challenge [name of the challenge]?* *Possible issues specific to the soil are:* □ *lack of harmonization and standardization in data collected over time;* □ *common methodologies used for soil sampling;* □ *analysis and mapping;* □ *data fragmentation;* □ *integrated framework and ICT tools to secure soil data storage facilities at different levels.* □ *Application of specific knowledge management, common tools, organizational learning can overcome the current fragmentation.* □ *Other*	*Which are the opportunities offered by knowledge harmonization, organization and storage for soil challenge [name of the challenge]?* *Opportunities focusing on data harmonization, organization and data storage can be related to:* □ *the standardization of methodologies with international standards and accepted procedures,* □ *the interactive web-based communication of soil data.* □ *Other opportunities can descend from specific regulations, agro-environmental measures at national and regional level, country or regional incentives.* □ *Other*

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Knowledge application	Which are the most important barriers/gaps, at national level, to knowledge application perceived as obstacles to overcome the challenge [name of the challenge]? Possible issues in knowledge application specific for the soil are: □ lack of technologies, ICT tools and DSS (Decision Support Systems); □ willingness of farmer to apply new soil management practices; □ farmer loss yield and profit; □ lack of specific regulations and EU Policies; □ barriers to adoption and enabling conditions to implement soil challenge; etc. □ Other	*Which are the opportunities offered by knowledge application for soil challenge [name of the challenge]?* *Opportunities of the application of knowledge can be:* □ *improving thematic guidelines (water, nutrient and fertilizer…);* □ *certification principles for tools and advisory services; ready-to-use technologies, openness and contact between the soil science community and society;* □ *good interfacing between science and policy;* □ *improving access to long-term field sites and development of specific advice;* □ *ICT decision support system; good specific policies and incentives, address future policy needs for new knowledge;* □ *facilitate knowledge sharing and mutual learning science-society-policy.* □ *Other*

EJP SOIL
European Joint Programme
EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695
ILVO
Institute for Agricultural and Fisheries Research

Thank you for your valuable inputs!

Please return this completed questionnaire to the coordinator for this task, being Miro Jacob, +32 (0)9 272 23 84.

EJP SOIL
European Joint Programme

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Annex II Questionnaire 3: "Onderzoek"

Stakeholder questionnaire
EJP Soil Task 2.2.1 & 2.4

Knowledge availability and needs on agricultural soils and soil management in Flanders

Questionnaire 3: "Onderzoek"

EJP SOIL

*This questionnaire is part of the European Joint Programme Soil (**EJP SOIL)**. The overall objective of EJP SOIL is to provide solutions for sustainable soil management that contribute to addressing key societal challenges including climate change and future food supply. Please see www.ejpsoil.eu for further information.*

*EJP SOIL invites you to participate as a valuable **stakeholder** and to engage in the programme to represent the breadth of agricultural systems and soil management practices in Flanders.*

Background information questionnaire

The specific aim of this questionnaire is to **identify** the state of knowledge availability and needs on agricultural soils and soil management **in Flanders**, to **prioritize** the main soil challenges for the upcoming decades and to **pinpoint** the strategies for improved soil management.

Specifically, focus is put on two topics: (a) **Carbon stock** and (b) **Soil quality, degradation and fertility**. Carbon stock relates to state-of-the-art knowledge on soil organic carbon (SOC) monitoring and modelling, i.e. soil carbon seen from a carbon sequestration and climate regulation point of view. Soil quality, degradation and fertility relates to state-of-the-art knowledge on soil functions such as water storage & regulation, primary production of food/feed/fibre, habitat for biodiversity and nutrient cycling and on related soil threats (here called soil challenges). For each of the topics we also ask about investigated and potential management practices.

Step-by-step

The questionnaire template comprises **3 steps**: (0) Background information, (1) Main soil challenges prioritization, (2a) Soil carbon research and/or (2b) Soil quality, degradation and fertility research.

IMPORTANT:

- For step 2 you can choose for only one topic (Carbon stock or Soil quality, degradation and fertility) but (if applicable) you also can give input on both topics.
- The answers you provide should be your own opinion based on your knowledge and expertise and do not have to be official statements of your organisation (if applicable). In the final report it will not be possible to trace the answers back to your name, institute or organisation.

☐ I confirm that I have read and understood the objective of the questionnaire part of the EJP SOIL program, and I agree that my answers will be processed anonymously.

Questions?

Should anything be unclear, please contact the coordinator for this task, being Maarten De Boever, +32 (0)9 272 26 80.

Thank you for your valuable inputs!

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Step 0: Background information

In this introductory step we ask you to provide some basic background information by answering the questions in Table 1. Names are for the track record of the coordinator of this task only, because there might be an interview afterwards for clarifications. In the final and public report, results will be clustered.

Important note: this table is identical for all parallel questionnaires of the EJP Soil program. If you are participating in the different questionnaires the table should only be filled once, except for your name, contact details and institute/organisation. In case you completed the questionnaire with colleagues, also specify the contact details of the person to be contacted.

STEP 0 – Table 1: Background information

Background information	
Can you provide your full name, job title and contact details?	*Name, Job title, Email, Telephone*
What stakeholder group do you identify yourself with most?	☐ *Research communities* ☐ *Research funders* ☐ *Middle & Higher educational institutions* ☐ *Farmer Schools* ☐ *Farmers and demonstration farms* ☐ *Advisors* ☐ *Farmers' organisations* ☐ *Agro-industry* ☐ *Laboratories, National science testing, Verification centres etc.* ☐ *Industry, Supply & Retail* ☐ *NGOs and community-based organizations*
If applicable, what institute or organisation do you work for?	*Institute/organisation*
What is the relevance of agricultural soils and soil management within your job?	*Relevance agricultural soils and soil management*
Have you completed the questionnaire on your own or have you consulted any	*[to be filled after finishing the questionnaire]*

Background information	
colleagues? How many persons did you consult? And who are these persons? (*To be clear: it is not mandatory for this questionnaire that you have consulted your colleagues. This should not be an official answer of your organisation, rather your opinion based on your expertise*)	
In case you completed the questionnaire with colleagues, who can be contacted for further questions?	*Name, Email, Telephone*
Other (general remarks)	*[open question]*

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Step 1: Prioritization soil challenges

<u>Important note</u>: this step can be skipped if you completed the stakeholder questionnaire of EJP Soil Task 2.1 on 'Validating current policy ambitions and defining aspirational goals on agricultural soils' and more specifically 'Step 4: Policy prioritization'.

<u>What</u>: Prioritization of the soil challenges to identify the **key themes** in Flanders.

(Q1) *What do you expect that will be the main soil challenges that are most relevant for **Flanders** <u>in the upcoming decades</u>?*

<u>How</u>: For this exercise, you should attribute a total of 100 points between the various soil challenges in Table 2. In case you fill in this questionnaire with colleagues, each person can do this exercise and if needed you can add an extra column '*Input stakeholder*' in Table 2.

STEP 1 – Table 2: Prioritization soil challenges

	Prioritization soil challenges (A total of 100 points should be attributed between the various soil challenges)		
	Example	Input stakeholder 1	Input stakeholder 2
Maintain/increase SOC	*30*		
Avoiding N2O, CH4 emissions	*10*		
Avoid peat degradation			
Avoid soil erosion	*10*		
Avoid soil sealing			
Avoid salinisation			
Avoid acidification			
Avoid contamination			
Optimal soil structure			
Enhance soil biodiversity			
Enhance soil nutrient retention/use efficiency	*20*		
Enhance water storage capacity	*30*		
Other			
Total sum:	***100***	**100**	**100**

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Step 2a: Research on soil carbon.

Important note: In this step we ask the stakeholder to identify the state of knowledge availability and knowledge needs on soil carbon. This is an **objective assessment** of your current and past research and other related relevant research. For future research we ask for **your stakeholder opinion** based on your expert knowledge.

What: Identification of the state-of-the-art **knowledge (Q2) and knowledge needs (Q3 and Q4) on soil carbon research and management strategies in Flanders** targeting the soil challenge maintaining and/or increasing soil organic carbon stocks in agricultural soils. This also includes the soil challenge 'peat degradation'.

(Q2) *What is your current and past research and other related research on soil carbon?*

- *What type of research is performed and on which scale (laboratory, field parcel, farm level, regional scale,…)? Was this based on measurements or modelling?*
- *Which management strategies/practices were investigated in your research?*
- *Which carbon related indicator(s) did you investigate in your research? Which other indicator(s) not related to soil carbon did you investigate in your research?*
- *Which model(s) did you apply in your research?*
- *Which impacts (biophysical, chemical and socio-economical) does your research evidence?*
- *Does your research include estimations of achievable carbon sequestration or sequestration rates given a certain management strategy (carbon sequestration potential)?*
- *In case of targeting the soil challenge 'peat degradation', does your research include estimations of reduction in greenhouse gas (GHG) emissions or GHG mitigation potentials?*
- *How was your research used for policy support or implemented in a decision support tool (for farmers, extension services,…)?*
- *How feasible are the investigated management strategies/practices to be implemented in practice (practical, socio-economic, legislation,…)?*

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

***How*:** For this exercise, you should describe briefly your research on soil carbon in the text box below referring to own (personal or your institute) projects and publications (reports and journal papers) or other key publications using the questions in the blue box above as a guideline. Details can be specified in Table 3.

[Describe briefly your research on soil carbon; max 500 words]

STEP 2a – Table 3: Mapping research on soil carbon

Type of study(*)	***Management strategy investigated***	***Soil quality indicators included***	***Soil modelling applied***	***Used for policy support or as decision support tool?***	***Related projects/publications (reports and journal papers) of past 10 years***
[laboratory study, pot trial, field experiment, regional study,…]	*[name of management strategy]*	*[name indicator]*	*[name model + on which international model based]*	*[yes/no; if yes please specify]*	*[full reference]*

(*)Please specify what kind of research you have applied an on which scale: laboratory studies (e.g. incubation trials), pot trials, (long-term) field experiments (which one?), on-farm monitoring plots, regional study,…

(Q3) *What are <u>your reflections</u> on the state-of-the-art knowledge and which are for you the most important/relevant <u>knowledge needs</u> to be covered in future soil carbon research?*

- *Is this seen from a farmer or a policy point of view?*

How: For this exercise, you should describe briefly your reflections on soil carbon research and knowledge needs in the text box below.

[Describe briefly your reflections and knowledge needs; max 300 words]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

(Q4) *Which management strategies to maintain and/or increase soil carbon stocks seem promising for you and need to be <u>further investigated</u>? What about the <u>feasibility to implement</u> those management strategies (practical, socio-economic, legislation…)?*

- *Is this seen from a farmer or a policy point of view?*

***How*:** For this exercise, you should describe briefly your reflections and knowledge needs on management practices in the text box below.

[Describe briefly your reflections and knowledge needs on management strategies; max 300 words]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

Step 2b: Research on soil quality, degradation and fertility.

__Important note__: In this step we ask the stakeholder to identify the state of knowledge availability and knowledge needs on soil quality, degradation and fertility. This is an **objective assessment** of your current and past research and other related relevant research. For future research we ask for **your stakeholder opinion** based on your expert knowledge.

__What:__ Identification of the state-of-the-art **knowledge (Q5) and knowledge needs (Q6 and Q7) on soil quality, degradation and fertility research and management strategies** in Flanders targeting soil challenges such as avoid N_2O/CH_4 emissions, soil erosion, soil sealing, soil compaction, salinization, acidification or contamination, optimal soil structure, enhance soil biodiversity, soil nutrient retention/use efficiency or water storage capacity.

(Q5) *What is __your current and past research and other related research__ on soil quality, degradation and fertility?*

- *Which soil challenges were targeted in your research?*
- *What type of research is performed and on which scale (laboratory, field parcel, farm level, regional scale,…)? Was this based on measurements or modelling?*
- *Which management strategies/practices were investigated in your research?*
- *Which indicator(s) did you investigate in your research?*
- *Which model(s) did you apply in your research?*
- *Which impacts (biophysical, chemical and socio-economical) does your research evidence?*
- *In case of targeting the soil challenge 'avoid N_2O/CH_4 emissions', does your research include estimations of reduction in greenhouse gas (GHG) emissions or GHG mitigation potentials?*
- *How was your research used for policy support or implemented in a decision support tool (for farmers, extension services,…)?*
- *How feasible are the investigated management strategies/practices to be implemented in practice (practical, socio-economic, legislation,…)?*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

<u>How</u>**:** For this exercise, you should describe briefly your research on soil quality, degradation and fertility in the text box below referring to own projects and publications (reports and journal papers) or other key publications using the questions in the blue box above as a guideline. Details can be specified in Table 4.

[Describe briefly your research on soil quality, degradation and fertility; max 500 words]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

STEP 2b – Table 4: Mapping research on soil quality, degradation and fertility

Type of study(*)	***Soil challenge(s) targeted(**)***	***Management strategy investigated***	***Soil quality indicators included***	***Soil modelling applied***	***Used for policy support or as decision support tool?***	***Related projects/publications (reports and journal papers) of past 10 years***
[laboratory study, pot trial, field experiment, regional study,…]	*[name challenge(s) targeted]*	*[name of management strategy]*	*[name indicator]*	*[name model + on which international model based]*	*[yes/no; if yes please specify]*	*[full reference]*

(*)Please specify what kind of research you have applied and on which scale: laboratory studies (e.g. incubation trials), pot trials, (long-term) field experiments (which one?), on-farm monitoring plots, regional study,…

(**)Categories of soil challenges (non-limitative): avoid N_2O/CH_4 emissions, avoid soil erosion, avoid soil sealing, avoid soil compaction, avoid salinization, avoid acidification, avoid contamination, optimal soil structure, enhance soil biodiversity, enhance soil nutrient retention/use efficiency, enhance water storage capacity,…

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

(Q6) *What are your reflections on the state-of-the-art knowledge on soil quality, degradation and fertility and which are for you the most important/relevant knowledge needs to be covered in future research?*

- *Is this seen from a farmer or a policy point of view?*

***How*:** For this exercise, you should describe briefly your reflections on soil quality, degradation and fertility research and knowledge needs in the text box below.

[Describe briefly your reflections and knowledge needs; max 300 words]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652615.

(Q7) *Which management strategies on soil quality, degradation and fertility seem promising for you and need to be further investigated? What about the feasibility to implement those management strategies (practical, socio-economic,…)?*

- *Is this seen from a farmer or a policy point of view?*

***How*:** For this exercise, you should describe briefly your reflections and knowledge needs on management practices in the text box below.

[Describe briefly your reflections and knowledge needs on management strategies; max 300 words]

Thank you for your valuable inputs!

Please return this completed questionnaire to the coordinator for this task, being Maarten De Boever, +32 (0)9 272 26 80.

Contact

Greet Ruysschaert
Instituut voor Landbouw-, Visserij- en Voedingsonderzoek
Plant
Burg. Van Gansberghelaan 109
9820 Merelbeke
T +32 9 272 26 98
greet.ruysschaert@ilvo.vlaanderen.be

Deze publicatie kan ook geraadpleegd worden op:
https://ilvo.vlaanderen.be/nl/nieuws

ILVO

Instituut voor Landbouw-, Visserij- en Voedingsonderzoek
Burg. Van Gansberghelaan 92
9820 Merelbeke - België

T +32 9 272 25 00
ilvo@ilvo.vlaanderen.be
www.ilvo.vlaanderen.be