SoilCare

SOILCARE FOR PROFITABLE AND SUSTAINABLE CROP PRODUCTION IN EUROPE

A review of soil- improving cropping systems

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Deliverable 2.1
Review of soil-improving cropping systems (SICS)

Work Package 2 of the EU-project SOILCARE

Oene Oenema, Marius Heinen, Yang Peipei, Rene Rietra, Rudi Hessel (Eds.)

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Foreword

Soils are the basis for food production and essential ecosystem services. However, soils become overexploited due to the need to increase food production in an increasingly globalizing market. A total of 11 different soil threats have been defined, which indirectly also threat global food production and essential soil ecosystem services. Though global in nature, the occurrence of soil threats appear spatially diverse, and their alleviation and prevention require site-specific measures and guidelines.

The overall aim of the EU-funded project SOILCARE is "*to assess the potential of soil-improving cropping systems and to identify and test site-specific soil-improving cropping systems that have positive impacts on profitability and sustainability in Europe*". The term 'soil improving cropping systems' (SICS) is relatively new, and a hypothesis. Intuitively, the term SICS is well-understood and perceived, but the scientific underpinning as such is still lacking.

Here, we summarize the results of a 'review and selection of soil-improving cropping systems' based on extensive literature study and meta-analyses, to provide underpinning of the concept and to make it operational. Some 30 scientists from SoilCare institutions throughout Europe have contributed to the main review and analyses. This deliverable is the executive summary of that work. The underlying full report is published separately as SoilCare report 7.

We gratefully acknowledge the 16 contributions of the lead authors and more than 20 contributing authors of the main report. This Executive Summary could not have been written without their contributions.

Oene Oenema, Marius Heinen, Yang Peipei, Rene Rietra, Rudi Hessel (Eds.)
Wageningen, 28 August 2017

Contents

1 Introduction

Soils are vital to life on earth. Soils perform many critical functions within ecosystems and societies. Soils serve as media for growth of plants, provide habitat for animals and organisms that live in the soil, modify the atmosphere by emitting and absorbing gases and dust, absorb and purify water, process recycled nutrients, including carbon, so that plants can use them again, and serve as engineering media for construction of foundations, roadbeds, dams and buildings (FAO and ITPS, 2015).

Generally, crop farmers consider soil as their main capital good that needs to be managed well (e.g. Cassman, 1999). Farmers know that there are differences in productivity between soil types and between farms, which are in part related to differences in soil management[1] and soil quality. However, soil management is complex, knowledge and labour demanding and may be costly, while effects on soil quality are often not directly visible, and mismanagement may show up only after several years. Investments in soil quality are therefore often neglected, also because the increased globalization and competition force farmers to lower costs and increase land and labour productivity.

Soil quality is defined briefly as '*the capacity of the soil to function'* (Karlen et al., 1997; FAO and ITPS, 2015). Soil quality depends on a combination of soil physical, chemical and biological characteristics. In crop production, soil quality is often defined as '*the capacity of the soil to sustain high crop yields with a minimum of external inputs and with minimal environmental impacts*'. Differences in crop yields within regions may in part be related to differences in soil quality, although differences in management and micro-climate may also contribute to spatial differences in crop yields. Various indicators are being used for the quantification and assessment of soil quality, in part because soil has various functions. There is as yet no common, universal and approved set of indicators.

Soils are under threat of physical, chemical and/or biological degradation due to the intensification, specialization and up-scaling of agricultural production. A total of 11 threats have been defined in Europe: soil acidification, salinization, erosion, compaction, contamination, desertification, flooding & water logging, landslides, loss of organic matter, loss of biodiversity and soil sealing (Toth et al, 2008; Jones et al., 2012; Stolte et al., 2016). These threats are caused in part by agricultural activities, but in part also (enforced) by natural processes and/or by industry and citizens. Fortunately, there is also a range of activities that may contribute to the mitigation of soil threats and to an improvement of soil quality and hence to an improvement of soil functioning.

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[1] Crop yield is a function of G_{enes} x $E_{nvironment}$ x $M_{anagement}$, i.e., crop yield is a function of (i) crop type and variety, (ii) climate, landscape, soils, and hydrology, and (iii) the management of planting, harvesting, water, nutrients, pests, diseases, weeds, etc (Van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999; Hatfield and Walthall, 2015).

Cropping systems can be considered soil-improving if they result in an improved soil quality, i.e., in a durable increased ability of the soil to fulfil its functions, including food and biomass production, buffering and filtering capacity, and provision of other ecosystem services. Soil improving cropping systems prevent and/or mitigate soil degradation, and contribute to restoring and improving degraded soils. The term 'cropping system' refers to crop type, crop rotation, and the agronomic management techniques used on a particular field over a period of years (Nafziger, 2012); Annex 1 provides an overview of spatial and temporal dimensions in cropping systems. The term '***s****oil* ***i****mproving* ***c****ropping* ***s****ystems*' (SICS) is relatively new. Intuitively, the term SICS is well-understood and perceived, but the scientific underpinning as such is still lacking. Yet, there are many examples across the world showing that soils have been improved through 'cropping systems', including so-called man-made soils (e.g., plaggen soils, terra preta soils), fertilized soils, drained soils). Also, conservation agriculture, soil conservation, soil amelioration, and soil improvement are also well-established concepts (Blanco and Lal, 2008; Pittelkow et al. 2015; WOCAT, 2017).

The overall aim of the EU-funded project SoilCare is "*to assess the potential of soil-improving cropping systems and to identify and test site-specific soil-improving cropping systems that have positive impacts on profitability and sustainability in Europe*". SoilCare deals with arable land, with cropping systems that improve soil quality. This summary report of work package 2 lists 'promising cropping systems that may improve soil quality'; it is based on literature review and assessments of 'cropping systems that influence soil quality. Two approaches have been applied in the review: (i) SICS for preventing and remediating specific soil threats, and (ii) SICS that improve soil quality in general. These two approaches are explained further below. Chapter 2 provides a more in-depth description of the concept of SICS. In Chapter 3 the soil threat-specific SICS are described, and Chapter 4 deals with SICS that improve soil quality in general. Finally, Chapter 5 is a general discussion and suggest a selection of most promising SICS.

This executive summary is based on the full report 'Review of soil-improving cropping systems' (Oenema et al. 2017). The report can be accessed at the website of SoilCare (http://www.soilcare-project.eu/) as SoilCare report 7.

2 Concept of soil improving cropping systems (SICS)

The term SICS is new, and a search for the term SICS in literature gives no 'hits', apart from the publications of He et al (2012) and Reckling et al (2016), which mentioned the terms for specific potato and rice systems, respectively. A review and assessment of literature on SICS is, therefore, indirect. It involves examination of cropping systems that change soil threats, properties, functions in a positive manner. Cropping systems refer to both crop type, crop rotation, and associated agronomic management techniques. Soil improving cropping systems are "*cropping systems that improve soil quality (and hence its functions), prevent and/or minimize soil threats, and have positive impacts on the profitability and sustainability of cropping systems*".

Soil improving cropping system encompass soils/land, crops, inputs, and management (Table 2.1). Inputs refer to labour, machines, irrigation, pesticides, fertilizers, manures. Management is often called the 'fourth production factor' next to the traditional production factors land, labour and capital. Management encompasses a coherent set of activities related to the cultivation of crops and land, and the handling and allocation of inputs, to achieve objectives (including agronomic, economic, environmental, social objectives). Hence, management is target oriented; in the case of SICS, management activities are also targeted at improving soil quality and preventing/minimizing soil threats. The concept of SICS appears at first sight broader than the concept of soil conservation, which strongly focusses on preventing erosion and conserving soil and water (Blanco and Lal, 2008), but seems rather similar to the concept of sustainable soil management recently promoted by FAO (FAO, 2017).

Table 2.1. Components of cropping systems that can be adjusted so as to create soil improving cropping systems (SICS).

Nr	Components of cropping systems
A	Crop rotations, including cover crops, etc.
B	• Nutrient management, techniques and inputs
C	• Irrigation management, techniques and inputs
D	• Drainage management and techniques
E	• Tillage management, techniques and inputs
F	• Pest management, techniques and inputs
G	• Weed management, techniques and inputs
H	• Residue management, techniques and inputs
J	• Mechanization management, including planting and harvesting machines
K	• Landscape management techniques and inputs

Following the law of the optimum, which was formulated more than one hundred years ago (Liebscher 1895; De Wit, 1992), all crop yield influencing factors and soil quality improving factors need to be 'optimal' to make soil improving cropping systems effective, efficient and thereby attractive. Hence the ideal SICS consist of a particular crop rotation and an optimal combination of inputs, techniques and management (Table 2.1), as function of soil type (soil threat), climate, and socio-economic conditions. If there is no optimal combination of crop rotation and inputs, techniques and management, soil quality will be under threat and crop yields suboptimal.

A few examples are given now to illustrate the case. If crop rotations are too narrow or if a crop is grown continuously, the incidence of soil borne diseases will increase, and the efficiency of inputs, labour and capital (in terms of yield per euro) will decrease. In case of soil nutrient mining, the soil will be impoverished, and the efficiency of all other inputs, labour and capital (in terms of yield per euro) will decrease. In case of excessive fertilization, the soil and surrounding environment may become polluted, and thereby impeding soil, plant, animal and human health. Soil drought may be alleviated through irrigation, which also greatly increases the efficiency of other inputs, labour and capital (in terms of yield per euro). Hence, all activities have to be in balance, and the balance depends on the current status of soil quality, the soil threat and the environmental and socio-economic conditions.

The action of soil improving cropping systems may be basically brought about through three principles or mechanisms (Wezel et al., 2014), i.e.,

i) changes in input-output ratio's,
ii) substitution, and
iii) redesign.

The first mechanism relates to inputs (in relation to outputs), including water (irrigation, drainage), nutrients, pesticides, energy, etc. Substitution practices refer to the substitution of an input or practice by another input or practice (e.g., labour vs machines vs pesticides). Redesign refers to changes in crop types, crop rotations, farming systems, and/or market orientation (e.g., specialization vs diversification, commodities vs special niche products, conventional vs organic). Here our focus is on mechanisms that can be handled at the farm level.

Cropping systems and soil types greatly vary across Europe due to different environmental and socio-economic conditions. Also soil threats are often site- and region-specific due the differences in environmental and socio-economic conditions and the differences in the vulnerability of soil types. For example, salinization and desertification are greater risks in the Mediterranean than in northern Europe, while human-induced soil compaction is a greater risk in the intensive, mechanized and large-scale cropping systems in western Europe and some part of central Europe than in the small-scale and less intensive cropping systems in, for example Romania, eastern part of Poland and southern part of Italy. These spatial variations suggest a highly differentiated spectrum of SICS; soil management is indeed highly site and cropping system specific. However, some generalizations can be made across the large spatial variations in practice, to derive general principles, mechanisms, guidelines and recommendations. This will result in a tool box from which farmers and advisors can choose an appropriate combination of measures that can be applied site-specific.

Farmers' incentives for implementing SICS will depend on landownership, the degree of 'soil improvement', economic costs and benefits, and crop yield enhancing potentials of the SICS. For assessing the overall impacts of SICS, i.e., the profitability and sustainability of the cropping systems, five general indicators have been suggested in the SoilCare proposal:

1) crop yield and crop quality,
2) farm profitability, i.e., the net balance between yield and production costs,
3) soil quality,
4) resource use and resource use efficiency, a measure for the ratio of output over inputs, and
5) environmental effects (losses of nutrients and pollutants, emissions of greenhouse gases) and effects on human health.

The emphasis here is on farm profitability and soil quality.

As indicated in the Introduction, SICS can be soil threat-specific, i.e., specific in prevented or overcoming a certain soil threat, as well as have a more general soil quality improving mode of action. Chapter 3 below discusses soil threat-specific SICS. Chapter 4 discusses SICS aimed at improving soil quality in general. Soil threat-specific SICS have the advantage of being specific, but may thereby neglect other aspects of soil physical, chemical and/or biological degradation than that of the soil threats, and/or make integration of various soil-threat-specific SICS more complicated. SICS with a more general mode of action may have the potential advantage of greater applicability, but run the risk that specific soil threats are not addressed effectively and efficiently.

The results discussed in the next chapters are based on literature review, meta-analyses and expert judgement, and have been described in detail in the main report (Oenema et al., 2017). Results of specific components of SICS have been summarized here as relative effects, i.e., the ratio of the specific treatment and the reference (control treatment) in percent. The method is summarized in Annex 2; a few examples of quantitative results are provided in Annex 3. For reasons of readability, and to cope with the fact that control treatments, reviews and meta-analyses may differ between studies, we use here semi-qualitative scores. The reference (control) has been given a score of 0 (zero), a positive effect of the specific treatment in terms of productivity and sustainability has been given the score + or ++, while a negative score has been given the score – or --, using the following key:

0	reference
+	positive effect of 5 to 10% relative to the reference
++	strong positive effect of significantly more than 10% of the reference
-	negative effect of 5 to 10% relative to the reference
- -	strong negative effect of significantly more than 10% of the reference
-/+	unclear effect, but tendency towards a negative effect (up to 5%)
+/-	unclear effect, but tendency towards a positive effect (up to 5%)

The term 'optimal' has been used in case agro-management techniques do not have specific soil threat-specific impacts; optimal refers here to the need to optimize agro-management techniques in general so as to improve soil quality and functioning (including crop yields).

3 Soil threat-specific Soil Improving Cropping Systems

This chapter provides brief descriptions of soil threat-specific SICS, each ending with a table providing semi-qualitative scores (as explained at the end of Chapter 2) for changes in farm profitability and changes in soil quality (soil properties; physical, chemical and biological) for the 10 (A-K) components of cropping systems as listed in Table 2.1. The change in profitability relates to the cost-benefit ratio associated with the implementation of a component (change in crop type or rotation and changes in agro-management techniques) of the SICS. Estimation of farm profitability is based on the balance of changes in crop yield and additional costs of implementing the SICS. The amount of quantitative data and information found in literature on farm profitability is however very limited and most scores are based therefore on expert judgement by the reviewers involved.

Soil threat-specific SICS may have also other, additional environmental effects, including on resource use efficiency at farm level. Where relevant and significant, this has been mentioned in the subsequent sections.

The soil threat-specific SICS considered are:

- 3.1 Acidification-specific SICS
- 3.2 Erosion-specific SICS
- 3.3 Compaction-specific SICS
- 3.4 Pollution-specific SICS
- 3.5 Organic matter-specific SICS
- 3.6 Biodiversity-specific SICS
- 3.7 Salinization-specific SICS
- 3.8 Flooding-specific SICS
- 3.9 Landslides-specific SICS
- 3.10 Desertification-specific SICS
- 3.11 Sealing-specific SICS

Section 3.12 provides a general discussion of all soil threat-specific SICS.

3.1 Acidification-specific SICS

Acidification refers to a decrease of the acid neutralizing capacity of the soil, followed by a drop in pH. Soil acidification is a natural process but accelerated by atmospheric deposition of acidifying elements (mainly nitrogen and sulphur oxides and ammonia in dry and wet deposition), withdrawal of harvest crop, urine droppings by grazing animals, and acidifying (ammonium-based) fertilisers. Soil acidification may lead to distorted root growth, nutrient imbalances, low crop yield and quality, and low biological activity. It increases the risk of uptake of toxic elements in plants. The risk of soil acidification is largest in soils with low acid neutralizing capacity, i.e., sandy soils with low content of base-cations, and in a climate where precipitation exceeds evapotranspiration, i.e. with a rainfall surplus.

Acidification-specific SICS prevent and nullify/remediate the effects of acidification; they involve substitution and redesign mechanisms. Acidifying nitrogen fertilizers should be replaced by nitrate-based fertilizers. Applications of manures, composts, crop residues also enhance the acid-neutralizing capacity of the soil. Applying acid-neutralizing substances (lime, primary soil minerals) has been practiced successfully already since Roman times, to raise soil pH values to agronomic recommended levels. Redesign mechanisms may involve the growth of crops that tolerate relatively high soil acidity; this may be needed in local areas for example near coal mines where coal wastes have been dumped, and in areas with naturally occurring acid-sulphate (sub)soils.

Most promising acidification-specific SICS include regular monitoring of soil pH, application of acid-neutralizing substances. In specific cases, replacement of nitrogen fertilizer types and crop types may be needed. These SICS increase resource use efficiency

Table 3.1. Qualitative assessment of acidification-specific SICS.

	Components of cropping systems	Components of Acidification-specific SICS[1]	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	• Crop rotations	When possible/needed: +acid-tolerant crops	+/-	+/-	+/-	+/-
B	• Nutrient management	Liming, manuring; no acidifying N fertilizers	++	+	++	+
C	• Irrigation management	No excess irrigation/leaching	+/-	+/-	+/-	+/-
D	• Drainage management	optimal				
E	• Tillage management	optimal				
F	• Pest management	optimal				
G	• Weed management	optimal				
H	• Residue management	No removal of crop residues	+/-	+	+	+
J	• Mechanization management	optimal				
K	• Landscape management	optimal				

[1]: The term 'optimal' for specific agro-management techniques refers to the need to optimize agro-management techniques in general so as to improve soil quality and functioning (including crop yields); these management techniques do not have soil threat-specific impacts.

3.2 Erosion-specific SICS

Erosion refers to the transport of soil particles by water and wind, and the subsequent deposition of the soil particles elsewhere. Erosion may affect food and biomass production directly through removal of seeds and damage to plants, and indirectly through the loss of fertile topsoil. Erosion negatively affects the storage, filtering, buffering and transformation capacity of the soil, and the habitat function. The risk of erosion is high on sloping land, with erodible soil and low soil cover, during heavy rains or strong winds.

Erosion-specific SICS prevent erosion or lower erosion rates. Erosion-specific SICS are water erosion and wind erosion specific, and involve mainly substitution and redesign mechanisms. The substitution mechanisms relate to minimum or zero tillage instead of conventional tillage, and mulching. Using organic manures and green manures improves soil aggregate stability and water holding capacity and thereby lowers soil erodability. The redesign mechanism relates to the replacement of annual short cycle crops by perennial crops, relay cropping, strip cropping, cover crops, agroforestry, as well as to the management of landscape elements (terracing, contour planting and ridging, planting hedges, permanent cropping strips, field borders, etc.).

Most promising erosion-specific SICS are highly site (morphology), climate (high rainfall areas) and soil specific. Erosion-specific SICS involve a whole range of actions, including a permanent groundcover (crops, mulches), reduced tillage, contour ridging, terracing, drainage, agroforestry (Table 3.2), which in general also have a positive impact on soil carbon sequestration, landscape appearance and resource use efficiency.

Table 3.2. Qualitative assessment of erosion-specific SICS.

	Components of cropping systems	Components of Erosion-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	Permanent cropping or +inter/relay/cover cropping +strip cropping, agroforestry	-/+[2]	+	+/-	+
B	• Nutrient management	Optimal				
C	• Irrigation management	optimal				
D	• Drainage management	optimal				
E	• Tillage management	Reduced & contour tillage	+	+	+/-	+
F	• Pest management	Optimal				
G	• Weed management	Optimal				
H	• Residue management	Mulching	+/-	+	+/-	+
J	• Mechanization management	Contour traffic	-/+	+	+/-	+
K	• Landscape management	Agroforestry, terracing, contour treelines	+	+	+/-	+

[2] Change in profitability strongly depends on the accounting period; in the short term costs may exceed benefits, due to the costs involved, change in crop types, and smaller cropping area; on the longer term benefits may exceed costs.

3.3 Compaction-specific SICS

Compaction refers to the densification of soil and the distortion of soil pores. Soil compaction leads to lower water and air infiltration rates, water logging, risks of anaerobicity, a lower root penetration ability, lower crop yields, poor soil structure, lower biodiversity and biological activity, increased greenhouse gas emissions and erosion and runoff. Compaction of the subsoil is especially a concern because subsoil compaction is difficult to remediate (through natural processes and/or deep ploughing/soil lifting).

Compaction-specific SICS prevent compaction and/or lower the density of the soil, increase the water infiltration rate, lower the penetration resistance, and improve soil structure. Compaction-specific SICS address the cause of compaction as well as compaction itself and its effects. Compaction-specific SICS mainly involve substitution and redesign mechanisms. The substitution mechanisms relate to lowering wheel loads and tyre pressures, and to reduced tillage, avoiding driving in the open furrow during ploughing, and working in the field under proper soil and weather conditions. The redesign mechanism relates to controlled trafficking, the growth of deep rooting crops like cereals, alfalfa, some cabbages and trees. Deep soil cultivation and stimulating biological activity through manuring may alleviate the effects of soil compaction.

Most promising compaction-specific SICS (i) prevent further densification of the (sub)soil, and (ii) remediate compacted soils and/or alleviate their effects. They may involve controlled trafficking, adjusting mechanization and the planning of activities, growing deep rooting crops, and stimulating biological activity through addition of organic matter (Table 3.3). It will decrease flooding, overland flow and resource use efficiency.

Table 3.3. Qualitative assessment of compaction-specific SICS.

	Components of cropping systems	Components of compaction-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible: +deep-rooting crops	-/+	+	+/-	+
B	• Nutrient management	Manuring	+/-	+	+/-	+
C	• Irrigation management	optimal				
D	• Drainage management	optimal				
E	• Tillage management	Reduced tillage	+	+	+/-	+
F	• Pest management	Optimal				
G	• Weed management	Optimal				
H	• Residue management	Optimal				
J	• Mechanization management	Controlled traffic; low-wheel loads, low-inflation tyres	+[3]	++	+/-	+
K	• Landscape management	optimal				

[3] Controlled traffic has been shown to increase yields significantly, while soil physical properties are improved. However, it requires investments in equipment and machines. On the longer term, benefits seem to outweigh the costs.

3.4 Pollution-specific SICS

Pollution (or contamination) is the accumulation and occurrence of contaminants in soil, including heavy metals, pharmaceuticals, pesticides, disinfection by-products, and wood preservation and industrial chemicals. The origin of pollutants may be natural (genetic), industrial (deposition via air or dumping wastes) and/or agricultural (through contaminated inputs, including those by reusing waste-water). Soil contamination affects crop yield and quality, human health, biodiversity and biological activity, and may cause malnutrition and nutrient imbalances.

Pollution-specific SICS are directed towards (i) preventing pollution, (ii) minimizing the mobility and toxicity and/or stimulating the breakdown of pollutants, and (iii) lowering pollutant concentrations in soil through phytoremediation. In serious cases, contaminated soils may have to be treated chemically or physically (through heating). Pollution-specific SICS may involve the following three mechanisms, i.e., (i) changes in inputs, (ii) substitution, and (iii) redesign. The first mechanism relates to a drastic lowering of pollutant inputs (and to withdrawal of pollutants with harvested crops through phytoremediation, where possible). The second mechanism involves soil amendments which stimulate the biological breakdown of organic pollutants, and/or the lock-up of pollutants in soil in a less mobile and less toxic form. The third mechanism involves the growth of crops that are less sensitive to pollutants and/or the change of food and feed crops to bio-energy crops and set-aside land. Certain crops are called hyperaccumulators, i.e. these crops accumulate pollutants in the plant tissue, or degrade or render pollutants in less harmful contaminants.

Most promising pollution-specific SICS (i) prevent further pollution, and (ii) remediate polluted soils through phytoremediation (Table 3.4). They will improve resource use efficiency and the quality and safety of the crop products.

Table 3.4. Qualitative assessment of pollution-specific SICS.

	Components of cropping systems	Components of pollution-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible: +hyper-accumulating crops	-	+/-	+	+/-
B	• Nutrient management	Manuring, low in pollutants, Soil pH adjustment	+/-	+/-	++	+
C	• Irrigation management	optimal				
D	• Drainage management	optimal				
E	• Tillage management	optimal				
F	• Pest management	Low pesticide use	-/+	+/-	+/-	+/-
G	• Weed management	Optimal				
H	• Residue management	Optimal				
J	• Mechanization management	optimal				
K	• Landscape management	optimal				

3.5 Organic matter-specific SICS

Decline of soil organic matter (SOM) refers to a loss of organic matter mass (and quality) in soils over time, which may lead to a deterioration of soil structure, a loss of water and nutrient retention and biological activity, and in the end to a reduction in crop productivity and water and nutrient use efficiency. Land use change (from forest and pastures to arable land) and intensive soil cultivation are major causes of a loss of soil organic matter. There is some evidence that climate change also contributes to a decline in SOM.

Organic matter-specific SICS relate to measures that decrease mineralization of soil organic matter and/or increase inputs of organic matter. Organic matter-specific SICS may involve all three mechanisms, i.e., (i) changes in inputs, (ii) substitution, and (iii) redesign. The first mechanism relates to (increased) inputs of compost, crop residues, and animal manures. The second mechanism involves reduced soil tillage, direct seeding in untilled soil instead of intensive soil cultivation, and controlled drainage[4]. The third mechanism involves the growth of crops with large biomass production and a relatively low harvest index, straw and crop residues return to soil, and the growth of perennial crops, cover crops, leys and green manures.

Most promising organic matter-specific SICS (i) reduce net soil organic matter mineralization (minimal tillage, drainage), and (ii) enhance the organic matter input into the soil (through crop residues, manures, composts) (Table 3.5).

Table 3.5. Qualitative assessment of organic matter-specific SICS.

	Components of cropping systems	Components of organic matter-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	Deep-rooting crops and/or +large % cereals in rotation +cover crops, green manures	-/+	+	+/-	+
B	• Nutrient management	Application of manure and compost	+/-	+	+/-	+
C	• Irrigation management	Optimal				
D	• Drainage management	Reduced drainage of organic-rich soils and peat soils	-	-/+	-/+	-/+
E	• Tillage management	Reduced tillage	+/-	+	+/-	+
F	• Pest management	Optimal				
G	• Weed management	Optimal				
H	• Residue management	Residue return	-/+	+	+/-	+
J	• Mechanization management	optimal				
K	• Landscape management	optimal				

3.6 Biodiversity-specific SICS

Soil biodiversity, abundance and function are important aspects of soil quality, and acknowledge that soil is a living ecosystem. Decline of soil biodiversity relates to a loss of

[4] Controlled drainage may be needed in drained organic soils (peat soils) to slow down the mineralization of soil organic matter (and the subsidence of the soil surface)

diversity of living organisms in soil and their inter-relationships; it may occur as a result of poor soil management. The decline may relate to i) species diversity, ii) genetic diversity, and/or iii) functional diversity.

Biodiversity-specific SICS may involve all three mechanisms, i.e., (i) changes in inputs, (ii) substitution, and (iii) redesign. The first mechanism relates to inputs of energy – increasing organic matter as substrate, changing the available nitrogen source used. The second mechanism relates to possible substitution of chemical (pesticides), physical (tillage) and/or biological measures (mycorrhizal amendments). The redesign mechanism relates to the diversification of crop rotations, i.e., various crop types in sequence and/or in mixtures (intercropping), cover crops, fallow crops, set-aside, and the inclusion of hedges and other landscape elements (Table 3.6).

Numerous studies have shown that agricultural intensification decreases the abundance and biodiversity of soil biota. However, there are examples of measures and practices that combine high crop yields with promoting soil biodiversity.

Most promising biodiversity-specific SICS relate to the diversification of crop rotation by providing a greater range of food sources, increasing soil organic matter, and reducing the build-up of soil-borne pathogens. Reducing the intensity of tillage will also reduce soil biodiversity loss (conventional tillage is known to have a detrimental effect on many groups of organisms from arbuscular mycorrhizal fungi (AMF) to earthworms). Reducing pesticide use also helps, as well as controlled traffic (less compaction).

Table 3.6. Qualitative assessment of biodiversity-specific SICS.

	Components of cropping systems	Components of biodiversity-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	Wide (1:6) crop rotations +intercropping +cover crops, green manures	-	+	+/-	+
B	• Nutrient management	Manuring	+/-	+	+/-	+
C	• Irrigation management	Optimal				
D	• Drainage management	optimal				
E	• Tillage management	Reduced tillage	+/-	+	+/-	+
F	• Pest management	Integrated pest management	+/-	+/-	+/-	+
G	• Weed management	Mechanical weeding	-	-/+	+/-	+/-
H	• Residue management	Residue return	-/+	+	+/-	+
J	• Mechanization management	Controlled trafficking	-/+	+	+/-	+
K	• Landscape management	Treelines, hedges, fringes	+/-	+/-	+/-	+

3.7 Salinization-specific SICS

Salinization refers to the accumulation of water soluble salts in soil. It leads to a lower soil fertility, poor soil structure, decreased infiltration, lower crop yields, lower biodiversity and biological activity. It may occur in areas where evapotranspiration is larger than precipitation, in deltas, plains and valleys with salty groundwater intrusion, and/or through the addition of fertilizers and salty irrigation water. The impact of salinization depends on the type and concentration of the salt and soil pH.

Salinization-specific SICS prevent salinization and/or lower the accumulation of unwanted salts and contribute to improving soil structure. Salinization-specific SICS are highly site-specific, and may involve all three mechanisms, i.e., (i) changes in input-output ratio's, (ii) substitution, and (iii) redesign. The first mechanism involves improved drainage through groundwater level control and channelling, reduced evaporation (through mulching), less input of soluble fertilisers, and targeted irrigation with low EC water. The second mechanism involves drip irrigation instead of surface irrigation. The third mechanism includes ridging, (plastic) mulching, growing tolerant crops.

Most promising salinization-specific SICS (i) reduce the input of unwanted salts into the soil, (ii) decrease the content of unwanted salts in soil, and (iii) minimize the impact of unwanted salts in soil on soil functioning (Table 3.7). Greatest effects can be expected from irrigation and drainage management.

Table 3.7. Qualitative assessment of salinization-specific SICS.

	Components of cropping systems	Components of salinization-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible/needed: +salt tolerant crops/varieties	+	+	+	+
B	• Nutrient management	Minimize salt input	+	+	+	+
C	• Irrigation management	Excess/drip irrigation (leaching fraction), using low-salt irrigation water	++	+	+	+
D	• Drainage management	Lower groundwater level	++	+	+	+
E	• Tillage management	Ridging	+	+/-	+/-	+/-
F	• Pest management	Optimal				
G	• Weed management	optimal				
H	• Residue management	Surface mulching, to lower evaporation	+	+	+/-	+/-
J	• Mechanization management	Optimal				
K	• Landscape management	optimal				

3.8 Flooding-specific SICS

Flooding is defined as the inundation of land. Water logging is where the soil becomes water-saturated, often due to flooding. Flooding may occur in delta's, plains, and valleys. It may affect humans, flora and fauna, crop yield and quality, infrastructure, cultural heritage, and a range of soil functions.

Flooding-specific SICS aim at (i) preventing flooding and water logging, and (ii) coping with flooded conditions and water logging. Flooding-specific SICS mainly involve changes in input-output ratios and redesign mechanisms. The first relate to flood prevention and increased discharge/drainage at regional scale. This is the most important measure. Redesign involves growing crops on ridges and growing crops that are less sensitive to temporary flooding. At the landscape scale water storage buffer zones may be created, and/or excess water may be redirected. Evidently, the latter is beyond the scope of an individual farm, and also not a SICS in sensu stricto.

On the other hand, some water logging may be needed in delta's to lower the risk of soil subsidence. This is particular the case in organic soils and in recently reclaimed clay soils in polders.

Most promising flooding-specific SICS (i) reduce the risk of flooding, and (ii) reduce the impacts of flooding (Table 3.8). Greatest effects can be expected from drainage management. However, lowering ground water level and creating water buffering basins may not be possible at farm level; it may have to be done at regional level. When flooding can be prevented, the benefits on crop yield will be large. Flooding will also reduce nutrient losses.

Table 3.8. Qualitative assessment of flooding-specific SICS.

	Components of cropping systems	Components of flooding-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible/needed: +flood-tolerant crops	-/+	+/-	+/-	+/-
B	• Nutrient management	optimal				
C	• Irrigation management	optimal				
D	• Drainage management	Lower groundwater level; create buffer capacity	++	+	+/-	+/-
E	• Tillage management	Ridging, to enhance aerobicity	+/-	+/-	+/-	+/-
F	• Pest management	Optimal				
G	• Weed management	optimal				
H	• Residue management	optimal				
J	• Mechanization management	Optimal				
K	• Landscape management	Creation of water buffer zones	-/+	+/-	+/-	+/-

3.9 Landslides-specific SICS

Landslides refer to the movement of a mass of earth down a slope, under the force of gravity. Landslides occur in mountainous regions and on slopes, following heavy rains, snow melt, deforestation, undermining slope stability, road construction, and/or earth quakes. The actual movement of soil mass often has dramatic effects on food production, human and biological habitats, and cultural heritages.

Landslides-specific SICS relate to measures that enhance the stability of the soil and prevent landslides. Landslide-specific SICS basically involve one mechanism, i.e., redesign. Landslide-prone land should not be used for arable land, but planted with deep-rooted perennial crops, including trees (forest) and left for nature conservation. Terracing and drainage may also help in specific cases. Forest harvesting and site regeneration also need special management attention in landslide-prone sites.

Most promising landslides-specific SICS aim at reducing the risk of landslides (Table 3.9). Changes in profitability are difficult to assess, as these SICS require investments and/or changes in farming practices, which are most likely associated with a drop in income (high-value crops may have to be replaced by low-value crops, including trees).

Table 3.9. Qualitative assessment of landslides-specific SICS.

	Components of cropping systems	Components of landslides-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible/needed: +permanent, deep-rooting crops	-	+/-	+/-	+/-
B	• Nutrient management	optimal				
C	• Irrigation management	optimal				
D	• Drainage management	Controlled drainage, to increase stability of the soil	-/+	+	+/-	+/-
E	• Tillage management	optimal				
F	• Pest management	Optimal				
G	• Weed management	optimal				
H	• Residue management	optimal				
J	• Mechanization management	Minimal traffic	-	+/-	+/-	+/-
K	• Landscape management	Afforestation, give area back to nature	--	+/-	+/-	+/-

3.10 Desertification-specific SICS

Desertification is the degradation of land in arid and semi-arid areas, as a result of loss of vegetation due to climatic fluctuations and human activities, including over-grazing, fires, soil erosion, and/or nutrient depletion through withdrawal of harvested crop without return of nutrients. Degraded soils lose their capacity to capture and store water, nutrients and carbon, and to support biological processes. Desertification negatively affects food and other biomass production potential, the storage, filtering, buffering and transformation of carbon and nutrients, and the biological habitat and gene pool.

Desertification-specific SICS prevent desertification and/or lower desertification rates. Desertification-specific SICS mainly involve mechanisms that change input-output ratios and may involve redesign mechanisms. External inputs of water and nutrients may be needed to enhance the soil fertility and productivity of the soil and thereby to prevent degradation. However, the main mechanism is redesign of the land-use and incorporating suitable landscape elements. Whenever possible C-4 grasses and crops with high water use efficiency (WUE) should be grown. Overgrazing must be prevented, as well as long-term animal camping sites (to improve nutrient recycling). Measures to minimize or control water flow are needed to minimize erosion risk and downstream flooding during incidental rains. Landscape elements such as tree lines and hedges may also contribute to minimizing erosion and land degradation, and to water harvesting.

Most promising desertification-specific SICS aim at reducing (i) the risk of desertification and (ii) the impacts of desertification (Table 3.10). They may have a significant impact on landscape and resource use efficiency.

Table 3.10. Qualitative assessment of desertification-specific SICS.

	Components of cropping systems	Components of desertification-specific SICS	Change in profitability	Changes in soil properties		
				Physical	Chemical	Biological
A	**Crop rotations**	When possible/needed: +permanent vegetation & crops with high WUE	+	+	+/-	+/-
B	• Nutrient management	optimal				
C	• Irrigation management	Targeted (drip) irrigation	+	+/-	+/-	+/-
D	• Drainage management	optimal				
E	• Tillage management	Reduced tillage	+	+/-	+/-	+/-
F	• Pest management	Optimal				
G	• Weed management	optimal				
H	• Residue management	Surface mulching, to reduce evaporation	+/-	+	+/-	+
J	• Mechanization management	Optimal				
K	• Landscape management	Treelines, hedges, agroforestry	+	+/-	+/-	+/-

3.11 Sealing-specific SICS

Sealing is the covering of the soil surface with materials like concrete, stone and buildings, which physically block the soil from the atmosphere as well as the links between belowground and aboveground biotic communities. Roads, stores, buildings, glasshouses all contribute to soil sealing in agriculture.

Sealing-specific SICS aim at preventing further soil sealing. One may argue that there is no sealing-specific SICS, as there are no cropping systems and agro techniques involved in preventing further soil sealing. On the other hand, substrate cultivation of specific vegetables, herbs, fruits and flowers in greenhouses is increasing in densely populated areas, especially near urban areas. This is a special case of soil sealing, as the function of the soil is in part replaced by artificial material, while the growth of the crops is controlled to a high-degree.

Sealing-specific SICS are not further discussed further here, as they are not directly related to agriculture. None of the components of cropping systems are related to soil sealing. The only effective measure is preventing further soil sealing.

3.12 Discussion of soil threat-specific SICS

Soil threat-specific SICS are cropping systems that prevent and/or mitigate soil threats, and/or improve the quality of the soil that was degraded under influence of the specific soil threat. Which cropping systems are soil threat-specific SICS?

The soil threat-specific SICS summarized in Sections 3.1-3.11 have in common that the choice of crop type and crop rotation scheme are relevant, although different criteria may have to be used for the selection of proper crop types and rotations as function of soil threat. Relevant means here that the choice of crop type and crop rotation has to be targeted (prioritized) to the prevention/mitigation of soil threats. The summary overviews in Sections 3.1-3.11 also indicate that the agro-management techniques, which are an integral part of a cropping systems, are often as important as crop type and crop rotation. Tillage management was identified to be relevant to 7 soil threats, and nutrient management and residue management to 6 soil threats. Pest management was found to be relevant to 2, and weed management to 1 soil threat (Table 3.11). Reducing biodiversity loss may involve adjustments to 8 components of crop systems. In contrast, remediation of soil acidification involves adjustment of 3 components of cropping systems (Table 3.11). Clearly, a soil threat-specific SICS is a combination of specific crop types and rotations and specific agro-management techniques.

Table 3.11. Summary overview; components of cropping systems that are relevant and need to be prioritized to the prevention and/or remediation of soil threats.

	Components of cropping systems	**Soil threats[5]**									
		1. Acidification	2. Erosion	3. Compaction	4.Pollution	5. SOM decline	6.Biodiversity decline	7.Salinization	8.Flooding	9.Landslides	10. Desertification
A	**Crop rotations**	X	X	X	X	X	X	X	X	X	X
B	• Nutrient management	X		X	X	X	X	X			
C	• Irrigation management	X			X			X			X
D	• Drainage management					X		X	X	X	
E	• Tillage management		X	X		X	X	X	X		X
F	• Pest management				X		X				
G	• Weed management						X				
H	• Residue management		X	X		X	X	X			X
J	• Mechanization management		X	X			X				
K	• Landscape management		X				X		X	X	X

The requirements to crop type and crop rotation differ for different soil threats (Table 3.12). Soil threat-specific SICS clearly have highly specific crop types and crop rotations, when the objective is to maximally prevent and/or remediate the specific soil threat. This does not

[5] Empty cells indicate that optimal conditions are required; see further the explanation of footnote under Table 3.1.

automatically mean a high profitability (Table 3.12); often there is a trade-off between improving soil quality and profitability in the short term. Farm income from cropping tends to decrease during the first year(s) due to the investments needed in the growth of specific crops, and due to constraints on the growth of crops with high profitability. In the longer term, effects on profitability appear to be positive, because the devastating effects of the soil treats on farming are minimized.

Table 3.12. Requirements set to crop type and rotation for soil threat-specific SICS.

	Soil threat	Requirements set to crop type and rotation for soil threat-specific SICS	Effect on profitability	
			Short-term	Long-term
1	Acidification	Acid-tolerant crops; crops with low base cation content	-/+	+/-
2	Erosion	Groundcover all year round, strip, alley, inter cropping, agroforestry	-	++
3	Compaction	Deep-rooting crops	-	++
4	Pollution	Pollutant tolerant crops / hyper accumulators	-	+/-
5	Organic matter decline	High-yielding crops, low harvest index, deep rooting crops, green manures, cover crops	-	+
6	Biodiversity decline	Wide (1:6) crop rotations, multi-species crops, green manures, cover crops	-	++
7	Salinization	Salt-tolerant crops, high pH tolerant crops	+/-	+
8	Flooding	Flooding tolerant crops	-/+	+/-
9	Landslides	Permanent cropping systems, deep rooting crops	-/+	++
10	Desertification	Crops with high water use efficiency, drought resistant crops, agroforestry	+/-	++

Some soil threat-specific SICS have synergistic effects. Soil carbon sequestration will increase, and nutrient losses through leaching and overland flow will decrease, when SICS include crops with a long growing season, deep rooting crops, cover crops, green manures, year-round green cover, and permanent cropping systems, and tillage is minimized. However, the denitrification potential of the soils and nitrous oxide (N_2O) emissions to air may increase when soil carbon increases, and the soil remains more moist through mulching. Further, resource use efficiency (land, water, nutrients, energy) will increase when inputs of resources are optimized towards increasing yields and minimizing and preventing soil threats. Many of soil threat-specific SICS may have a positive effect on the characteristics of the landscape through diversification of cropping systems, more groundcover, tree lines, etc., and thereby may indirectly enhance its attractiveness for tourism as well as improve human health. These possible indirect effects are mainly based on expert judgement, as there has been little or no empirical research.

Soil threats are dependent on soil types (e.g. soil texture, mineralogy, and depth), geomorphology (e.g. slope, hydrology), climate (e.g. rainfall distribution, evapotranspiration, wind), and management (e.g. components of cropping systems). Conversely, effects of soil threat-specific soil improving cropping systems (SICS) are also dependent on soil type, geomorphology, climate and management. This reiterates the fact that soil threat-specific SICS are also soil and site specific. In the farm system optimization process, farm income is commonly maximized (cost are minimized and/or yield maximized) within a number of socio-economic and environmental constraints. In the optimization process of soil threat-specific SICS, farm income will be maximized within soil threat-specific constraints. The soil threat-specific constraints require high priority.

Bai et al (2015) present a qualitative overview of measures for preventing, mitigating and remediating soil threats in Europe as function of climate and geomorphology (but not of soil type). For each soil threat, a range of specific measures have been given. FAO (2017) provide guidelines to policy and farmers to prevent and minimize soil threats. The measures identified by Bai et al (2015) and FAO (2017) are rather similar to the measures summarized in Tables 3.1 to 3.12. The review of Bai et al (2015) did not include soil acidification and desertification.

The sustainable soil management guidelines of FAO (2017) address:

1. Minimal rates of soil erosion by water and wind;
2. The soil structure is not degraded;
3. Sufficient surface cover is present to protect the soil;
4. The store of soil organic matter is stable or increasing;
5. Availability and flows of nutrients are appropriate to maintain or improve soil fertility;
6. Soil salinization, sodification and alkalinization are minimal;
7. Water is efficiently infiltrated and stored, drainage of any excess is ensured;
8. Contaminants are below toxic levels;
9. Soil biodiversity provides a full range of biological functions;
10. Optimized and safe use of inputs for producing food, feed, fuel, timber, and fibre; and
11. Soil sealing is minimized through responsible land use planning.

Hence, the soil threat-specific SICS discussed in Sections 3.1-3.11 cover most aspects of the FAO guidelines for sustainable soil management, apart from soil structure and availability of nutrients (See also Chapter 4), while optimized and safe use of inputs is addressed through the agro-management techniques.

In conclusion, soil treat-specific SICS prioritize specific crop types, crop rotations and agro-management techniques above other crop types, crop rotations and agro-management techniques, so as to minimize and prevent particular soil threats. There are no SICS that are universally applicable; soil treat-specific SICS are soil treat-, soil type-, and environmental/social-economic conditions- specific.

4 General Soil Improving Cropping Systems

4.1 Further elaboration of the concept of SICS

This chapter discusses SICS that have not been designed specifically for a soil threat but have a general mode of soil quality improvement, and thereby contribute to a general improvement of soil functioning. These general SICS are based on the notion that all soils in agriculture need good management, so as to improve soil quality (irrespective of the aforementioned 11 soil threats). The concept of 'soil threat' is not well-perceived and/or accepted in agricultural practice, in part because of the negative connotation, and this may hinder implementation of soil threat specific SICS. Stakeholders may perceive the concept of 'soil threats' as a policy construct, meant to implement restrictive regulations (which farmers often do not like). Though soil threats may occur throughout Europe and other parts of the world, not all soils are prone to one of the 11 soil threats. Also, soil threats are not always recognized and understood, and hence, soil threat specific SICS may not be taken up easily.

Yet, many farmers are concerned about soil quality. Some of the concerns of farmers that are not (sufficiently) addressed by the concept of 'soil threats' include for example

a) improving soil structure, so as to ease seedbed preparation and the workability and earliness of the soil in spring, as well as the harvest ability of the soil in autumn,
b) enhancing yield potential, closing yield gaps and improving gross margin,
c) enhancing soil nutrients and balanced nutrition (addressing all 14 essential nutrient elements[6]), while reducing nutrient losses through GHG emissions, leaching and denitrification, and
d) spatial variations in soil quality and soil functioning, which may cause a yield penalty (lower yield due to insufficient input optimization) or a cost penalty (due to high inputs in the wrong places).

Hence, there is also a need for 'general SICS', which include also the 10 components (A-K) identified in Table 2.1.

Agronomists commonly define the crop yield potential of a site (land/field) by three main 'yield factors' (Van Ittersum and Rabbinge, 1997; Evans and Fisher, 1999), i.e.

i) yield <u>defining</u> factors: climate, carbon dioxide concentration, and genetic potential of the crop,
ii) yield <u>limiting</u> factors: water and nutrient availability, and
iii) yield <u>reducing</u> factors: pests, diseases, weeds and pollutants (including high concentrations of salts) and excess water (causing oxygen stress). Soil threats have not been mentioned explicitly, but these may also reduce crop yield.

In this concept, soil quality boils down to its roles in crop yield limiting and reducing factors.

[6] N, P, K, Mg, Ca, S, Fe, Mn, Zn, Cu, B, Mo, Cl, Ni

Based on this concept, a total of six indicators may be used to assess the capacity of the soil to produce biomass (crop yield):

1) Water retention and delivery to crops, i.e. soil depth and water holding capacity.
2) Nutrient retention and delivery to crops, fertility indices.
3) Control of pathogens and weeds, and improve soil biodiversity.
4) Soil structure and tilth.
5) Control of pollutants.
6) Control of organic matter content and quality.

The first five indicators directly follow from the yield limiting and reducing factors. The sixth indicator (soil organic matter content) has been added because of its overarching role in the five main crop yield limiting and reducing factors, including erosion, but also because soil organic matter content can be managed. Quantifying the first five indicators requires the measurement of a range of soil characteristics. Note that these indicators provide indirectly also information about other soil functions than crop productivity (e.g. regulation, biodiversity).

The results discussed in this chapter are based on literature study, meta-analyses and in part also expert judgements. Results of specific components of SICS have been quantified as relative effects, i.e., the ratio of the specific treatment and the reference (control treatment) (see Chapter 2 and Annexes 2 and 3).

4.2 An assessment of the effects of components of SICS on soil quality

A semi-qualitative assessment of the effects of components of SICS on soil characteristics that influence crop yield limiting and reducing factors is presented in Table 4.1, using the 6 main indicators (1) soil water delivery, (2) soil nutrient delivery, (3) control of soil-borne pathogens and weeds, (4) soil structure and tilth, (5) control of pollutants, and (6) control of soil organic matter content and quality. The greatest number of subcomponents is shown in Table 4.1 for crop types and crop rotations, and yet this list is just a very short summary of all possible crop types and crop rotations. For example, the crop statistics of Eurostat distinguishes 17 categories for cereals and 29 for other main crops, 40 categories for vegetables, 41 for permanent crops. Within a crop type, large differences in varieties can exist, which can have a profound effect on crop productivity, farm income, resource use and environmental impacts.

Crop rotations do have a positive effect on soil functioning, compared to monocultures, which is mainly related to suppressing soil-borne diseases and weed infestations (Table 4.1). Crop rotations have a positive effect on soil biodiversity. They may have a positive effect on soil water and nutrient delivery, because healthy crop rotations often explore a greater volume of soil. Crop rotations also tend to have a positive effect on soil structure and soil tilth, because of the diversity of rooting patterns and soil organic matter sources. Root crops in crop rotations often have a negative effect on soil structure due to the disturbance of soil structure during harvesting and the low amounts of residual biomass left in the soil . This effect may be mitigated/restored again by a subsequent cereal crop or oilseed crops.

Table 4.1. Semi-qualitative assessment of components of SICS: crop yield limiting and reducing factors.

Components of SICS	Water delivery	Nutrient delivery	Control of Pathogens	Improving Structure	Control of Pollutants	Improving SOM
Monocultures (reference)						
wide rotations (1:6)	+	+/-	++	+	+/-	+
narrow rotations (1:3)	+	-/+	+	+/-	-/+	+
+ root crops (1:2)	+	-/+	+/-	-	-/+	-
+ legumes(1:3)	+	+	+	+	-/+	+
+ allelopathic plants (1:4)	-/+	-/+	+	-/+	+/-	-/+
+ cover crops(1:1)	-/+	+/-	+/-	+	-/+	-/+
+ intercropping	+	+/-	+	+/-	+/-	+/-
+ green manures (1:1)	-/+	+/-	+/-	+	+/-	+
+ phytoremediation	+	-/+	+/-	+/-	+	+/-
Fallow/set-aside (1:6)	++	+	+	+	+/-	-/+
No fertilization (reference)						
organic fertilization	+	++	-/+	+	-	++
mineral fertilization	+	++	-/+	+/-	-	+/-
No irrigation (reference)						
irrigation	++	+/-	-/+	-/+	+/-	-/+
fertigation	++	++	-/+	+/-	-/+	-/+
No drainage (reference)						
drainage	+/-	+/-	-/+	+	+	-
No tillage						
conventional tillage	-/+	+/-	+	+/-	+/-	-
minimum tillage	-/+	+/-	+/-	+/-	+/-	-/+
No pest management (reference)						
chemical control	+	+	++	-/+	--	+/-
biological control	+	+	++	+/-	+/-	+/-
No weed control (reference)						
chemical weed control	+	+	+	-/+	--	+/-
biological/mechanical control	+	+	+	+/-	-/+	+/-
No mulching						
organic mulching	+	+/-	-	+	+/-	+
plastic mulching	++	+/-	-/+	-	-	+/-
No controlled trafficking						
controlled trafficking	+/-	+/-	+/-	+	+/-	+/-
No landscape management (ref)						
landscape management	+	+/-	+	+/-	+/-	+/-

Fertilization enhances the capacity of the soil to deliver nutrients, and thereby increases crop production and residual crop biomass returned to the soil (Table 4.1). However, fertilization commonly increases the environmental impacts through leaching and the emission of nitrous oxide (N_2O). The fertilization source (inorganic vs organic) has a large effect on the nutrient delivering capacity, soil carbon sequestration and emissions. Fertilization indirectly enhances also the water delivery capacity of the soil, because a more vigorous crop explores a larger volume of soil. The production of synthetic fertilizers is energy intensive and is associated with CO_2 emissions.

Drainage is extremely important in the case of temporary water logging and high groundwater levels. Drainage will increase the rooting depth, decrease the heat capacity of the soil and thereby accelerate the warming up of the soil in early spring. Drainage may also increase the mineralization of soil organic matter and thereby lower the soil organic matter content and increase the release of carbon oxide (CO_2) to the air. Drainage may decrease nutrient losses via denitrification (Table 4.1).

Irrigation enhances the water delivering capacity of the soil, and indirectly the nutrient delivery (because of the increased volume of roots and the increased solubility and accessibility of soil nutrients). However, irrigation may increase the risk of leaching and denitrification, and of salinization (in arid and semi-arid regions) (Table 4.1).

Tillage is important for weed control and seedbed preparation. Interestingly, the invention and improvements of the plough have greatly contributed to soil productivity in history (Mazoyer and Roudart, 2006), but tillage is currently associated with organic matter decline, high energy use, erosion and loss of biodiversity. As a result, reduced tillage (minimum and zero tillage) is promoted. However, reduced tillage often leaves crop residues on the soil surface, which has been associated with increased infestations of crop diseases, which then may require additional inputs of chemicals. Deep ploughing is locally practiced to bring 'virgin' and high quality subsoil to the top and at the same time bury the less desirable top soils. Results of deep ploughing are variable and often questioned, because of the high energy use. Subsoil lifting is done to alleviate subsoil compaction; again results are often variable, but with the development of new cultivation machinery e.g. low disturbance subsoiler, there is the potential to obtain some of the no-till benefits without all the negatives (Table 4.1).

Pest management has greatly contributed to the increased crop yields obtained during the last century. Two variants are often distinguished, i.e. chemical pest control and biological pest control. The first allows somewhat more narrow rotations at the expense of pesticides. Biological control is based on wide rotations, multispecies crops, buffer strips and landscape management. The best option is often a combination of the two: integrated pest management (Table 4.1).

Weed management is also extremely important in agriculture, as weed infestations can ruin the target crop. Again, two variants are often distinguished, i.e. chemical weed control and mechanical/biological weed control. The first variant makes use of herbicides, while the second variant makes use of mechanical weeding, ploughing and target crop rotations. The best option is often a combination of the two: integrated weed management. Proper selection of crops in rotation may greatly contribute to weed suppression (Table 4.1).

Mulching is often practiced in combination with zero tillage, also to reduce evaporation and water erosion, and thus to enhance crop yield and water productivity. Plastic mulching is extensively practiced in semi-arid regions of for example China and India and in intensively managed horticulture cropping systems in Europe, as a method to increase water productivity and the temperature of the soil in early spring (Table 4.1). However, plastic mulching often leaves large amounts of plastic fragments in soil and the wider environment.

Traffic management is important in mechanized agriculture where wheel loads are often too high to prevent subsoil compaction. Controlled trafficking is a way to minimize traffic on land, in combination with using the same wheel tracks more often (to spare the remainder of the land). It has often a positive effect on crop yield, soil quality and energy use (Table 4.1).

Landscape management goes beyond the farm scale and is not yet much considered in cropping system management. It often involves more stakeholders than just farmers. In the UK, there have been initiatives to set up "farm clusters" and "river catchment clusters", to get all the stakeholders working together towards a common goal. There is increasing evidence that landscape management may contribute to soil quality, crop productivity and sustainability, as it may contribute to the control of various threats (e.g., erosion, desertification, acidification, pollution, loss of biodiversity and flooding) and may affect the micro-climate and the control of pests. Landscape management allows to broaden the sources of income and market orientation. A special aspect is the integration of crop-livestock production systems, which has advantages also for the environmental sustainability of livestock production (Table 4.1).

4.3 An assessment of possible climate, soil and socio-economic constraints for SICS

The feasibility/suitability of (components of) SICS depend in part also on climatic conditions, land and soil conditions, and socio-economic conditions. Conversely, the combination of the these conditions also determine the risk of soil threats.

Governing climate factors are photosynthetic active radiation, rainfall, and temperature during the growing season, which together determine the length of the growing season. These factors influence the choice of crop type and crop rotation, as well as the agro-management techniques. The factors vary from north to south and from west to central Europe, and show up in the map of environmental zones. Europe is divided in 12 main environmental zones, with clear differences in climatic conditions (Metzger et al., 2005). Main climate constraints for crop production are a short growing season for northern Europe, and low rainfall during the main growing season in the Mediterranean and central Europe. Photosynthetic active radiation (PAR, in Wm^{-2}) is mainly determined by latitude and the inclination of the slope, and increase from north to south Europe. Rainfall during the growing season (Rain, total and distribution) is determined by a number of meteorological factors, including oceanity, latitude, altitude, and geomorphology. Rainfall distribution is as important as total rainfall, as dry spells during critical crop growth stages, or heavy rains can be damaging to crop yield and contribute to soil treats. Mean temperature during the growing season (Temp, °C) is also determined by meteorological factors, including oceanity, latitude, altitude, and geomorphology.

Main governing land and soil conditions are slope and relief, soil depth, stoniness, soil texture, soil structure, and soil organic matter content. These factors also influence the choice of crop type and crop rotation, as well as the agro-management techniques. Slope and aspect (SA) influence the micro-climate and hence yield potential, mechanization options and labour demands. Slope and aspect also determine the risk of nutrient losses via overland flow and erosion. Soil depth (SD) determines the soil volume that can be explored by roots, as well as the soil water and nutrient storage and delivering capacity. Stoniness (St) also influences the soil volume that can be explored by roots, as well as the soil water and nutrient storage and delivering capacity. Stoniness will also influence crop choice and mechanization. Soil texture (ST) determines the soil water and nutrient storage delivering capacity, soil fertility, workability and hence may influence crop choice and mechanization. Soil organic matter (SOM) content influences the soil water and nutrient storage and delivering capacity, biodiversity, workability and hence may influence crop choice and mechanization; both a low and high SOM content is suboptimal. Soil structure (SS) influences the workability and hence crop choice and mechanization. Soil structure also influences the germination of plant seeds, as well as the soil water storage and delivering capacity of the soil.

Main socio-economic factors relate to access to markets, technology, labour, advice and financial capital. These factors also influence the choice of crop type and crop rotation, as well as the agro-management techniques. Access to markets (AM) is of key importance, as it affects the ability to market products and thereby the price of the produce and hence farm income. Access to markets also be important for obtaining farm inputs. Access to (new) farm technology (AT) determines the modernization potential of the farm; this may both reduce the risk of some soil threats as well as form a barrier for the implementation of components of SICS (e.g., machines and equipment for controlled traffic). Access to labour (AL) is important for crops with high labour demand during the planting and harvest seasons; some crops may not be grown without sufficient qualified labour. Access to advice (AT; agronomic and economic) from specialists may hinder the modernization of the farm (cropping systems) and the improvement of farm performance (allocation of production factors may be suboptimal). Access to capital (AC) is important for investments and hence farm modernization and size. All these socio-economic factors are influenced by infrastructure and the distance to markets, cities and R&D centres. In addition to these external socio-economic factors, there are personal factors and preferences that influence farmers' behaviour and choices. These personal factors and preferences may have a background in culture and education, and may be influenced also by the local society.

Evidently, the various components of SICS have to be adjusted / depend on the aforementioned conditions set by the site-specific climate, land and soil, and market and society. Not all crops can be grown under all environmental conditions. The growth and success of a cover crop depends on the harvest of the main crop and the length of the remaining growing season. Similarly, not all fertilization practices can be applied al environmental conditions; fertilizers and manures have to be incorporated into the soil on sloping land to prevent the loss of the nutrients. However, main barriers for the implementation of SICS seem farm profitability (on the short-term) and lack of knowledge and awareness among farmers and land managers about soil threats and SICS. Benefits of SICS often emanate on the longer term, while farmers and land managers have to bear the cost upon implementation of the components of SICS.

Summarizing, climatic conditions, land and soil conditions, and socio-economic conditions determine the risk of soil threats as well as the feasibility/suitability of implementing (components of) SICS. The implementation of components of SICS depend on their flexibility to become adjusted to the site-specific conditions set by climate, land and soil, and market and society. In practice, main barriers for the implementation of SICS seem farm profitability (on the short-term) and lack of knowledge and awareness among farmers and land managers about soil threats and SICS.

4.4 Assessment of the effects of SICS on cropping system sustainability

An assessment of components of SICS in terms of cropping system sustainability is presented in Table 4.2. The impacts of components of SICS are assessed in terms of five indicators for cropping system sustainability:

(i) soil quality (see above; composite of the six crop yield limiting/reducing factors),
(ii) crop yield and crop quality,
(iii) farm income, i.e., the net balance between sales and production costs,
(iv) resource use efficiency, a measure for the ratio of output over inputs of resources, and
(v) environmental effects (emissions of nutrients, pollutants and greenhouse gases).

Table 4.2 distinguishes the same components of SICS as in Table 4.1. The reference (control) has been given a score of 0 (zero), a positive effect of the specific treatment on cropping system sustainability has been given the score + or ++, while a negative score has been given the score – or --.[7]

Crop rotations, fertilization, irrigation, drainage, and pest and weed control all have a large effect on farm income. Tillage, mulching, traffic management and landscape management have in general a modest effect on farm income. Fertilization, irrigation, drainage, and pest and weed control often have a negative effect on the environment, but the assessment differs when the effects are based on a product or area basis. The environmental effects often have a minimum at optimal inputs of fertilizers, irrigation, drainage, and pest and weed control when the environmental effects are expressed on a product basis (De Wit, 1992; Van Groenigen et al., 2010). The same holds for resource use efficiency. High (excessive) inputs generally have negative environmental effects, both expressed on a product and area basis. Hence, the assessment of the effects of inputs depend on (i) the level (rate) of input, and (ii) the units chosen, i.e. area or product basis.

[7] The scores highly depend on the reference situation, i.e., positive effects will be obtained only if the reference situation does not have an optimal soil quality and/or result in optimal crop production, and vice versa (see also chapter 2).

The assessments in Table 4.2 do not consider possible interactions between components, which can be positive (synergistic) and negative (antagonistic). For example, fertilization is most attractive when there are no other growth constraints than nutrient elements. The same applies to irrigation; it is economically most profitable when no other growth limiting and reducing factors occur.

Table 4.2. Assessment of components of SICS: aspects of cropping system sustainability.

Components of SICS	Crop yield & quality	Soil quality	Farm income	Resource use efficiency	Environmental impacts
Monocultures (reference)					
Wide rotations (1:6)	+	+	+	++	++
Narrow rotations (1:3)	+/-	+/-	++	+/-	+/-
+ root crops (1:2)	++	-	++	+/-	-
+ legumes(1:3)	+	+	+	++	+
+ allelopathic plants (1:4)	-/+	+	-/+	+/-	0
+ cover crops(1:1)	+	+	-/+	+	+
+ intercropping	++	+	+/-	++	+
+ green manures (1:1)	++	++	+/-	+	+
+ phytoremediation	+/-	+	+/-	+/-	+
Fallow/set-aside (1:6)	--	+	--	--	-
No fertilization (reference)					
organic fertilization	++	+	++	+	-
mineral fertilization	++	+	++	+	-
No irrigation (reference)					
irrigation	+	+/-	+	+/-	+/-
fertigation	++	+	++	++	+/-
No drainage (reference)					
drainage	+	+	+	+	+/-
No tillage (reference)					
conventional tillage	+	-/+	-/+	-/+	-/+
minimum tillage	+	+/-	+/-	+/-	+/-
No pest management (reference)					
chemical control	++	-	++	++	-
biological control	++	+/-	++	++	+/-
No weed control (reference)					
chemical weed control	++	-/+	++	++	-
biological/mechanical control	++	-/+	++	++	+/-
No mulching					
organic mulching	+/-	+/-	+	+	+
plastic mulching	+	-/+	+	+	-/+
No controlled trafficking (reference)					
controlled trafficking	+	+	+/-	+	+
No landscape management (reference)					
landscape management	+/-	+/-	+/-	+/-	+/-

5 General Discussion

5.1 The concept of SICS

The aim of work package 2 of SOILCARE is to review and assess literature so as to identify and assess SICS (soil improving cropping systems), and to come up with a selection of promising SICS, to be discussed and tested further in the other work packages of SOILCARE. Promising SICS reduce or alleviate soil threats and improve soil quality and the sustainability of cropping systems (Chapters 3 and 4).

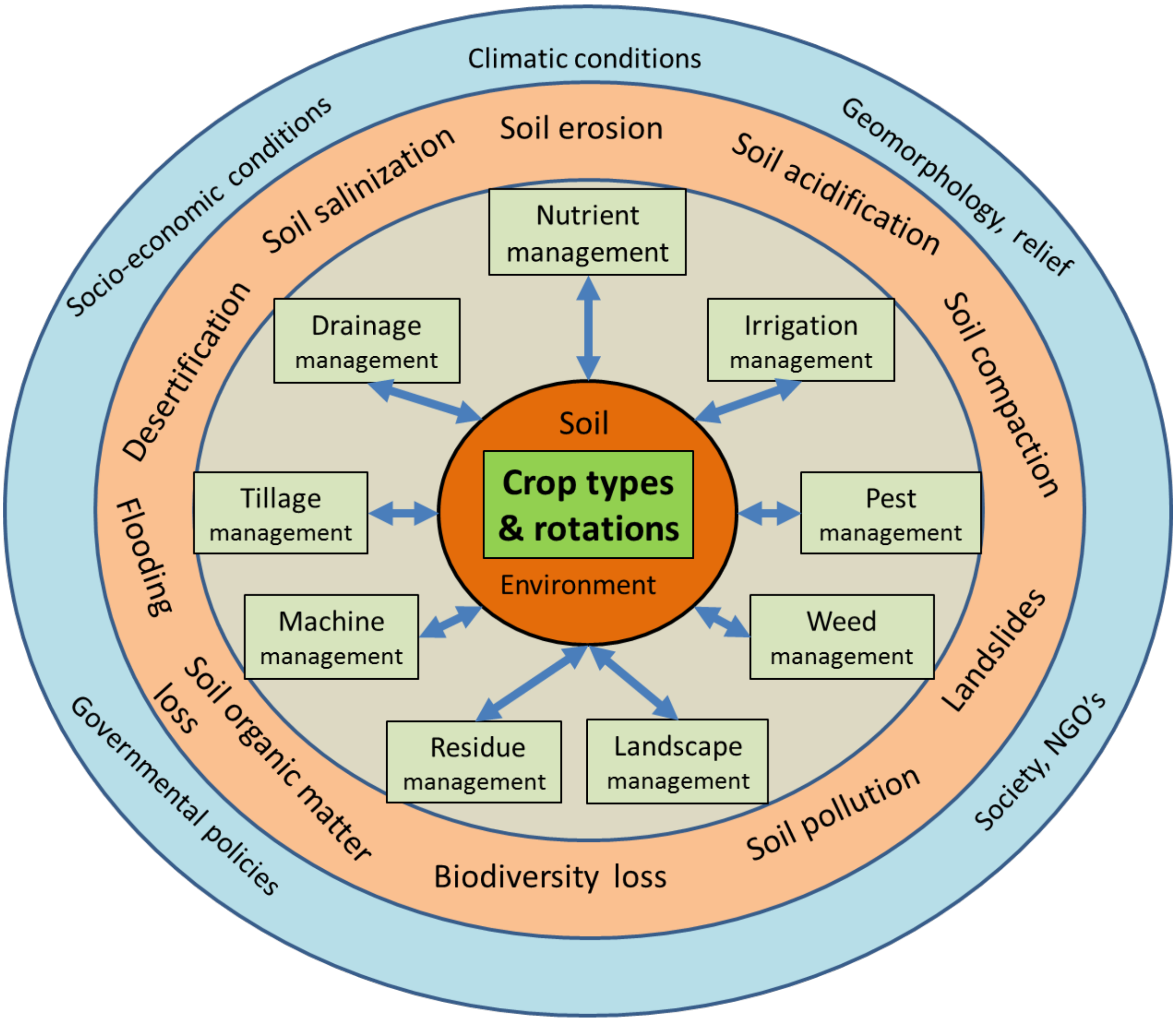

Figure 5.1. Concept of Soil Improving Cropping Systems (SICS), with crop rotations and the soil environment in the centre and the nine key agro-management techniques (light-green boxes) surrounding and directly affecting soil quality and the sustainability of cropping systems. Soil threats (light-brown circle) are surrounding the SICS, while the external driving forces for the soil threats and SICS are in the outer (light-blue) circle.

The concept of SICS is as yet rather new and theoretical, i.e., there are ideas and partial proofs of its applicability, effectiveness and efficiency, but there are no comprehensive descriptions of a framework, handbook, guidance document, and/or results of the concept in practice. These need to be developed further, for which use can be made of the recently published FAO

Guidelines for Sustainable Soil Management (FAO, 2017). Given its broad aims (reduce soil threats and improve soil quality and the profitability and sustainability of cropping systems), SICS encompasses cropping systems and its agro-management techniques, soils and the natural environment, and the socio-economic environment (Figure 5.1). By nature, SICS are highly site-specific.

The wider circle of the SICS concept presented in Figure 5.1 encompasses the external driving forces of both soil threats and SICS. Five main drivers have been distinguished, i.e., (i) geomorphology, soils and hydrology, (ii) climate, (iii) socio-economic conditions (development in markets, including developments in science and technology), (iv) societal opinions and NGO's, and (v) governmental policies. The Common Agricultural Policy (CAP) of the European Union provides several incentives to stimulate the adoption of components of SICS, including crop rotation, permanent cropping systems, biodiverse strips, soil organic matter maintenance, and erosion control. Further, there are various voluntary measures with compensation for cost incurred and/or income forgone in the Rural Development Program. These EU-governmental policy measures address some main soil threats, including soil organic matter decline, soil biodiversity decline and erosion. The EU fertilizer, pesticide and animal feed Regulations (and many national policies) provide incentives to minimize the inputs of possible contaminant materials into agriculture and thereby safeguard food quality and prevent/minimize soil pollution. There are also strict regional/national regulations in landslide-prone areas aimed at minimizing the risk of landslides. Further, countries with desertification-prone areas and soil degradation problems are under the regime of the United Nations Convention to Combat Desertification (UNCCD) with a legally binding international agreement. However, other soil threats like acidification, compaction, salinization, soil structure deterioration, and soil nutrient imbalances are not addressed specifically, and there are no clear incentives to address/maintain and improve soil quality in general.

Figure 5.2 briefly explains the decision environment of the farmer. Crop rotations and agro-management techniques are selected while considering socio-economic conditions (markets, policy, technology incentives), environmental conditions (soils, climate), and own preferences. In SICS, the decisions about crop rotations and agro-management techniques are also based on (i) preventing soil threats, (ii) alleviating the effects of soil threats, and (iii) enhancing soil quality and functions in general. This requires that the farmer is (a) convinced about the need to do so, (b) is able to do so, and (c) has the information and tools to do so. Hence, the crop rotations and agro-management techniques are also based on the occurrence of soil threats and the need to enhance soil quality and functions.

Crop rotations and the 9 agro-management techniques are the tools for deriving optimal SICS. Following the law of the optimum, all growth limiting and reducing factors have to be considered (removed/minimized) for establishing profitable and sustainable cropping systems. The law of the optimum is often implicitly expressed by the term 'integrated' in for example integrated pest management and integrated nutrient management. It is also expressed by the terms 'controlled', 'enhanced' and 'smart'. These terms emphasize that all factors for enhancing soil quality and the profitability and sustainability of cropping systems have to be considered in an harmonious, integrated manner.

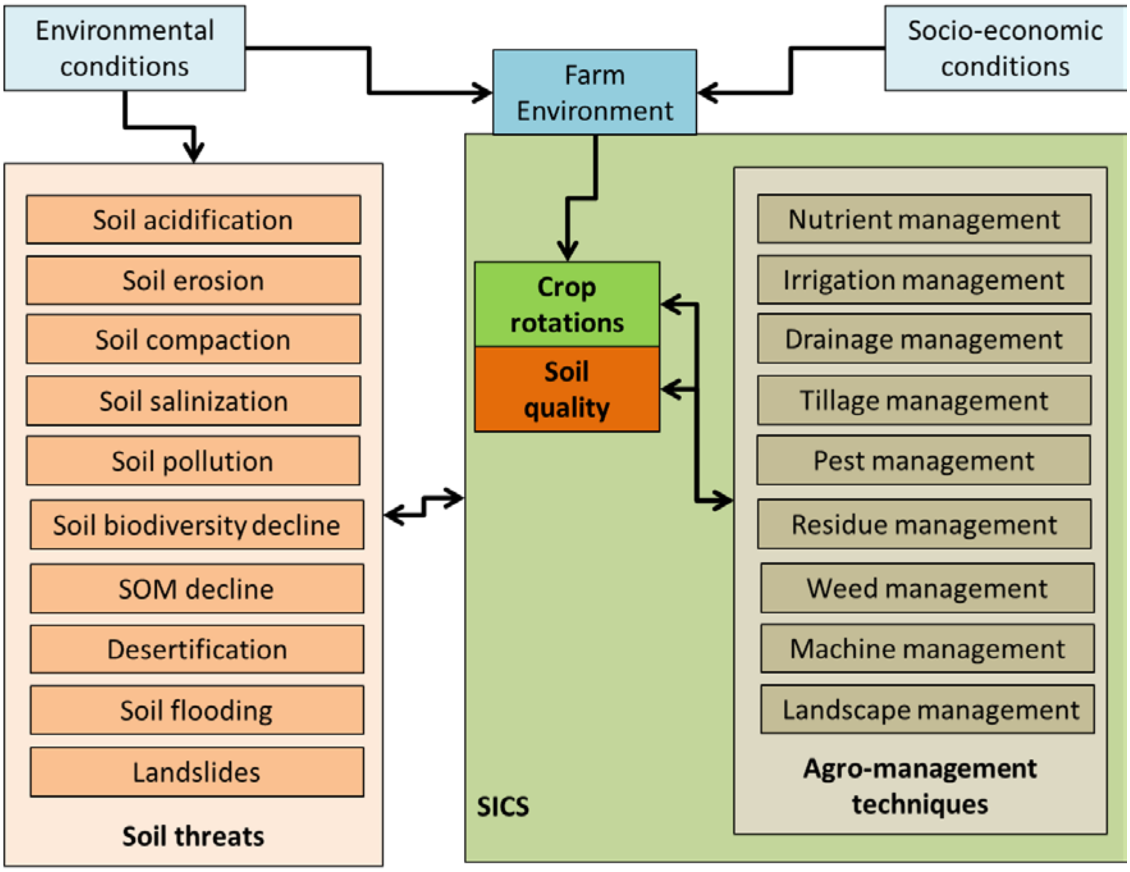

Figure 5.2. Main driving forces and components of cropping Systems. The farmer selects the crop rotation and then the agro-management techniques while considering socio-economic conditions (markets, policy technology), environmental conditions (soils, climate and emanating soil threats), and own preferences.

In practice, farm income is commonly maximized (through lowering cost and increasing yield/sales) in the optimization of cropping systems, so as to provide sufficient income to farmers, who increasingly have to compete in a globalized market, on the basis of the cost of production (e.g., Mazoyer and Roudart, 2006). This competition and intensification of cropping systems is one of the causes of soil threats, and at the same time a barrier for implementing SICS, because farmers give priority to farm income to be able to survive in what Mazoyer and Roudart (2006) the 'global rat race'.

This indicates that greater priority has to be given to SICS; the need for specific crop rotations and specific agro-management techniques must receive greater priority (setting more serious constraints) in the cropping system optimization. The prioritized crop rotations and prioritized agro-management techniques depend on the site-specific conditions. Most promising SICSs consist therefore of particular crop rotations and an 'integrated' combination of inputs and management techniques, which reflect a site-specific prioritization and subsequent optimization process. The prioritization has to precede the optimization process. Hence, the priority crop types, crop rotations and agro-management techniques are the constraints in the optimization process. Alternatively, equal weight is given to farm profitability and soil quality (and/or the priority crop types, crop rotations and agro-management techniques of SICS).

Prioritization and optimization of crop types, crop rotations and agro-management techniques, as function of site-specific socio-economic and environmental conditions is the key to successful SICS. The proof of the SICS concept is in the prioritization of specific crop rotations and specific agro-management techniques, and the subsequent optimization (and ultimately in the testing. This is further conceptualized in Figure 5.3, where a total of 9 common crop rotations have been distinguished (and the aforementioned 9 agro-management techniques). Six crop rotations have cereals, which is a dominant crop type in EU-28. Most cereals are also an important crop in SICS (perhaps with the exception of maize), because of their relatively long-growing season and full soil cover, deep and extensive root system, and the large crop residues. However, cereals do in general not provide much farm income, and that is the reason why especially small farms prefer to growth crops that provide higher revenues per ha (e.g., vegetables, fruits, potatoes, flowers).

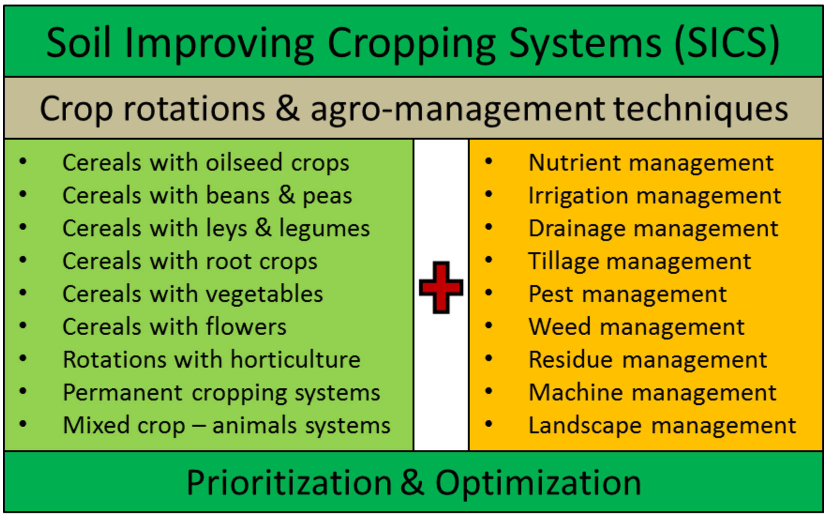

Figure 5.3. Soil Improving Cropping Systems (SICS) consists of optimal combinations of crop rotations and key agro-management techniques. The prioritization and optimization depends on the environmental and socio-economic conditions.

Mixed crop – animal production systems were common in the past, but they have largely disappeared in modern agriculture. Specialization is a main driving economic factor, with specialized crop production and specialized animal production systems and increased productivity as results. The disappearance of mixed crop – animal systems in many countries is largely a result of economic out-competition by specialized systems. Mixed crop-livestock production systems are however attractive from the perspectives of soil quality, resource use efficiency and nutrient recycling, landscape diversity, human health, and minimizing environment impacts. The integration of crop-livestock production systems may take place also at regional or landscape level. There is, as yet, limited quantitative information on the effect of mixed crop – livestock production on soil quality effectives.

5.2 A preselection of soil-improving cropping systems

A proposed delivery (Milestone 2) of work package 2 of SOILCARE is a 'pre-selection of soil improving cropping systems'. This pre-selection falls apart in two, i.e., soil-threat specific SICS and general SICS. Soil-threat specific SICS have been summarized in Chapter 3, general SICS in chapter 4.

Soil-threat specific SICS target a specific soil threat through specific crop rotations and agro-management techniques. Soil-threat specific SICS require specific adjustments of crop rotations and agro-management techniques, to reduce the threat and alleviate the effects of the threats, as a function of the environmental and socio-economic conditions. A summary overview of promising soil-threat specific SICS is presented in Table 3.11 (Chapter 3).

General SICS improve soil quality and soil functions generally. The main soil function in cropping systems is crop production, which is mainly determined by the 6 crop yield limiting and reducing factors indicated in section 4.1 and also below:

1) Water retention and delivery to crops, i.e. soil depth and water holding capacity
2) Nutrient retention and delivery to crops, fertility indices,
3) Control of pathogens and weeds, and improve soil biodiversity,
4) Soil structure and tilth,
5) Control of pollutants, and
6) Control of organic matter content and quality

General SICS are also composed of crop rotations and specific agro-management techniques, which have to be prioritized in the optimization process (Figure 5.3).

Table 5.1 presents combinations of priority crop types and priority agro-management techniques of soil threat-specific SICS, which serve as a pre-selection of soil threat-specific SICS. Table 5.2 lists those for SICS with a general/additional mode of action, and are a pre-selection of general SICS.

Table 5.1. Prioritization of crop types and agro-management technique in soil threat-specific SICS.

Nr	Soil threat-specific SICS	Priority crop types	Priority agro-management techniques
1	Acidification	No specific crop type	Liming, manuring
2	Erosion	Permanent groundcover, Deep-rooting crops Cereals with cover crops Alfalfa, Agroforestry	Zero-tillage, landscape management, contour traffic Proper timing of activities
3	Compaction	Deep-rooting crops, Cereals, perennial rye, alfalfa	Controlled traffic Low wheel load, low tyre pressures Proper timing of activities
4	Pollution	Biofuel crops Some fodder crops No leafy vegetables	No use of polluted inputs Tree lines to scavenge air-born pollution
5	Organic matter decline	Permanent groundcover, deep-rooting crops Cereals with cover crops, alfalfa	Minimum tillage, Residue return, Mulching Manuring
6	Biodiversity loss	Crop diversification	Manuring, minimum tillage, residue return, No pesticides, Minimal fertilization
7	Salinization	Salt-tolerant crops	Drainage Targeted irrigation Ridging
8	Flooding	Flooding-tolerant crops	Drainage Landscape management
9	Landslides	Deep-rooting crops, trees	Landscape management, No arable cropping
10	Desertification	Deep-rooting C4 crops	Landscape management

Table 5.2. Prioritization of crop types and agro-management technique in general SICS.

Nr	Targets of general SICS	Priority crop types	Priority agro-management techniques
a	Soil structure improvement	Permanent groundcover, Deep-rooting crops Cereals with cover crops Alfalfa, clovers	Minimum tillage, Proper timing of activities Manuring Liming
b	Balanced nutrition	No specific crops	Fertilization based on soil fertility and plant leaf analyses, targeted manuring
c	Increasing crop yield	High-yielding crop varieties	Proper timing of activities, in-depth soil analyses, frequent field observation, targeted irrigation, fertilization, pest management and weed control
d	Coping with and benefiting from spatial variations in soil quality	No specific crops	Establishing relationships between spatial variations in soil quality and spatial variations in crop yield, Variable rate tillage, liming, manuring, irrigation seeding, fertilization, and crop management.
	Improving soil quality, farm profitability and cropping system sustainability	Wide crop rotations with high values crops, leguminous crops, cover crops	Site-specific optimization of the agro-management techniques

Tables 5.1. and 5.2 list only the priority crop types and agro-management techniques, because these have been shown in the literature studies and meta-analyses to prevent and/or alleviate soil threats, and improve soil quality. The listed crop types and agro-management techniques have to be combined / optimized with other crop types and agro-management techniques, so as to further increase farm income and the sustainability of the cropping system. Common to most soil threat-specific SICS are crop rotations with cereals, green manures, cover crops and

catch crops so as to have groundcover, deep-rooting crops and crops with relatively large amounts of crop residues. Such crops may increase soil organic matter content, increase biodiversity, suppress soil-borne pathogens (depending on crop species), improve soil structure, and decrease nutrient leaching, run-off and erosion. The feasibility of green manures, cover crops and catch crops depends on the date of harvest of the main crop, the planting date of the next crop, climatic conditions during autumn and winter seasons, and the characteristic of the green manures, cover crops and catch crops (susceptibility for soil borne diseases, winter hardness, etc.).

Agroforestry systems are useful in sloping areas to prevent/minimize soil erosion. They may be considered a subsystem of permanent cropping systems or of landscape management elements (tree lines, hedges, riparian zones). Agroforestry may contribute to biodiversity and landscape diversity; it modifies the micro-climate and reduces erosion.

Intercropping, mixed cropping, alley cropping, strip cropping, double cropping all may have specific benefits for enhancing total crop yield, soil organic matter input, increasing biodiversity, and improving soil structure under certain conditions, but often have disadvantages in terms of mechanization and labour efficiency. They have not been considered here.

5.3 Monitoring of SICS

Indicators as used in this review report are defined as measurable phenomena with a specific function. The six indicators identified for assessing the capacity of the soil to deliver high crop yields are so-called combined or integrated indicators, i.e. they are based on a number of different measurements. This paragraph provides lists of

1. Indicators for the profitability and sustainability of SICS (in Table 5.3),
2. Soil quality indicators and properties that have to be measured for a proper monitoring of changes in soil quality (in Table 5.4), and
3. Soil properties that have to be measured for a proper monitoring of the effectiveness of soil threat-specific SICS (in Table 5.5).

Table 5. 3. General indicators for the profitability and sustainability of SICS. Last column indicates the frequency of the measurements/observations

Indicators	Unit	Frequency, yr^{-1}
Crop yield	kg ha^{-1} yr^{-1}	1
Crop quality	Contents of starch, protein, fatty acids, oils, minerals, vitamins, form, shape, colour, etc.	1
Marketable yield (gross)	Euro ha^{-1} yr^{-1}	1
Land cost	Euro ha^{-1} yr^{-1}	1
Labour costs	Hours ha^{-1} yr^{-1} and Euro ha^{-1} yr^{-1}	1
Building and infrastructural costs	Euro ha^{-1} yr^{-1}	1
Nutrient management costs	Euro ha^{-1} yr^{-1}	1
Irrigation costs	Euro ha^{-1} yr^{-1}	1
Drainage costs	Euro ha^{-1} yr^{-1}	1
Soil cultivation costs	Euro ha^{-1} yr^{-1}	1
Pest management costs	Euro ha^{-1} yr^{-1}	1
Weed control costs	Euro ha^{-1} yr^{-1}	1
Crop residue /mulching costs	Euro ha^{-1} yr^{-1}	1
Machine costs	Euro ha^{-1} yr^{-1}	1
Landscape management costs	Euro ha^{-1} yr^{-1}	1
		1
Carbon sequestration	kg CO_2-eq ha^{-1} yr^{-1}	1
Methane emissions	kg CO_2-eq ha^{-1} yr^{-1}	1
Nitrous oxide emissions	kg CO_2-eq ha^{-1} yr^{-1}	1
Fuel use	kg CO_2-eq ha^{-1} yr^{-1}	1
Electricity use	kg CO_2-eq ha^{-1} yr^{-1}	1
	-	
Nitrogen balance	kg N ha^{-1} yr^{-1}	1
Phosphorus balance	kg P ha^{-1} yr^{-1}	1
Potassium balance	kg K ha^{-1} yr^{-1}	1
Nitrate concentration in waters	mg NO_3-N L^{-1}	1
Phosphate concentration in waters	mg P L^{-1}	1
Total nitrogen in waters	mg N L^{-1}	1
Ammonia emissions to air	kg NH_3-N ha^{-1} yr^{-1}	1

Table 5. 4. Possible soil quality indicators and related soil properties for assessing the quality of the soil for crop production. The last column indicates the frequency of the measurements.

nr	Indicator of soil quality	Measurable soil properties	Frequency, yr^{-1}
1	Soil water retention and delivery	Soil depth (m)	0.1
		Mean groundwater level (m)	2-12
		Soil moisture retention curve	0.1
		Bulk density (g cm^{-3})	0.2
2	Soil nutrient retention and delivery (rating; low-high)	pH	0.2
		Bulk density (g cm^{-3})	0.2
		SOM (%)	0.2
		Extractable N, P, K, Ca, Mg, Na, S, Cl, Cu, Zn, Co, Mn, Fe, Mo (mg kg^{-1})	0.2
		Texture: clay, silt, sand (%)	0.1
3	Soil-borne pathogens & soil biodiversity	Earthworms diversity (number per species)	1
		Collembola (springtails) diversity (number per species)	1
		Microbial respiration (mg CO_2-C m^{-2} day^{-1})	1
		Parasitic fungi,	1
		Parasitic nematodes	1
		DNA sequencing	0.1
4	Soil-borne weeds	Germination of weeds (number m^{-2})	1
		Stubborn weeds	1
5.	Soil structure and tilth	Size of soil aggregates (mm)	
		Shape and stability of aggregates	
		Water infiltration rate (cm hr^{-1})	
6.	Soil pollutants	Extractable (in µg kg^{-1}) - Heavy metals - Organic micro pollutants - Oil residues - Metals from actinide series	0.2
		Plastics	0.1
		Antibiotics	0.2
7	SOM content and quality	Total C (%)	0.2
		Mineralizable C (g kg^{-1} yr^{-1})	0.2
		Extractable C & N (DOC, DON) (mg L^{-1})	0.2
		C/N ratio	0.2

Table 5. 5. Main soil quality indicators and related soil properties for assessing the effectiveness of soil threat specific SICS.

	Soil threat specific SICS	Soil Quality indicator	Measurable soil properties
1	Acidification	Change of acid neutralizing capacity (mol_c ha^{-1} yr^{-1})	Sum of basic cation minus sum of anions
		Change of soil pH	pH (H_2O), pH (KCl), pH ($CaCl_2$)
2	Erosion	Loss of soil (ton ha^{-1} yr^{-1})	Mass of soil (via wind / water)
		Soil surface phenomena	Visual observation
		Aggregate stability of surface soil (%)	Aggregate stability
		Soil cohesion	Shear strength
3	Compaction	Bulk density (g cm^{-3})	Bulk density
		Water infiltration rate (mm day^{-1})	Water infiltration rate
		Penetration resistance (MPa cm^{-2})	Penetration resistance
4	Pollution	Metal content (mg kg^{-1})	Cd, Pb, Cr, Zn, Cu, As contents
		Organic pollutants (µg kg^{-1})	PACs, PCBs
		Radiation pollution (beq kg^{-1})	Actinides
		Oil (mg kg^{-1})	Oil
		Plastics (mg kg^{-1})	plastic
		Antibiotics (µg kg^{-1})	Antibiotics
5	Organic matter decline	Total organic C (g kg^{-1})	Organic C
		Mineralizable C (g kg^{-1} yr^{-1})	Mineralizable organic C
		C/N ratio	C/N ratio
6	Biodiversity decline	Earthworms diversity (number per species)	Number per species
		Collembola (springtails) diversity (number per species)	Number per species
		Microbial respiration (mg CO_2-C m^{-2} day^{-1}	Respiration
		Parasitic fungi (m)	
		Parasitic nematodes (number per species)	Number per species
7	Salinization	Extractable salt contents (mg kg^{-1})	Na, K, Cl, SO_4^{2-}, HCO_3^-
		EC (mS)	Electric conductivity
		pH	pH (H2O), pH (KCl), pH (CaCl2)
		Soil structure (descriptive)	Soil structure
8	Flooding	Period and number of days $year^{-1}$	Flooding
		Regional drainage (canals, dams, pumping stations)	Descriptive
9	Landslides	Tree density (number m^{-2})	Number of trees
		Drainage (canals, rivers)	Descriptive
10	Desertification	Change in green cover (ha yr^{-1})	Surface mapping
		Water infiltration rate (mm day^{-1})	Infiltration rate

5.4 Conclusions

Soil improving cropping systems (SICS) are "*cropping systems that improve soil quality (and hence its functions), prevent and/or minimize soil threats, and have positive impacts on the profitability and sustainability of cropping systems*". The SICS concept is rather new; possible measures/components have been reviewed, the concept has been further elaborated and a preselection of SICS has been made. Indicators needed for its monitoring have been defined.

Soil improving cropping systems (SICS) are a combination of crop rotations and 9 agro-management techniques. Specific components of the SICS have to be prioritized to address soil quality concerns, which likely depend on site-specific conditions and socio-economic drivers. Next, crop rotations and the 9 agro-management techniques have to be integrated and optimized for site-specific environmental and socio-economic conditions, so as to both address soil quality, farm profitability and the sustainability of the cropping system.

Two categories of SICS have been distinguished, (i) soil threat specific SICS, which mitigate the threat and alleviate its effects, and (ii) general SICS, which enhance soil quality and soil functions in general.

The concept of SICS is still somewhat theoretical, i.e., there are ideas and partial proofs of its applicability, effectiveness and efficiency, but there are no comprehensive descriptions of a framework, handbook, guidance document, and/or results of the concept in practice yet. These have to be developed, tested and refined further in SOILCARE. The current report forms the start for defining the concept and setting up such a framework.

The list of promising SICS are formulated in a rather general manner, mainly because SICS are site-specific and the crop rotations and agro-management techniques have to optimized and integrated for site and farm specific conditions. The SICS concept presented here basically is a tool box of crop types, crop rotations and agro-management techniques. Depending on the local/regional environmental and socio-economic conditions, the farmer (with or without advisors) will select the appropriate combinations of crop types, crop rotations and agro-management techniques. The effectiveness of the selected combinations has to be assessed on the basis of monitoring programs of profitability, sustainability and soil quality indicators. This summary document provide tables with selected indicators.

Recommendations	For whom
• Define hypotheses and treatments to test soil-improving cropping systems • Test the concept and usefulness of general SICS and soil threat-specific SICS	Science
• Test the SICS concept in practice, and consider the options and possible barriers for its implementation. • Make use of demonstration fields to show the importance of SICS	Practice
• Raise awareness on the importance of soil quality in society and practice	Policy

• Consider to include priority crop types and agro-management techniques (section 5.2) in the CAP and/or Rural Development Regulation.	

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7 Annexes

7.1 Annex 1. Spatial and temporal dimensions in Cropping Systems

Mono-cropping or Single Cropping: growing only one crop on a particular land year after year.

Multiple Cropping: growing two or more crops consecutively on the same field in the same year.

Mixed Cropping: growing two or more crops simultaneously on the same piece of land, without any definite row arrangement.

Intercropping: growing of two or more generally dissimilar crops simultaneously on the same piece of land. Usually the base crop is grown in a distinct row arrangement. The recommended optimum plant population of the base crop is suitably combined with appropriate additional plant density of the associated crop, and there is crop intensification in both time and space dimensions.

Strip Cropping: growing soil conserving and soil degrading crops in alternate strips running perpendicular to the slope of the land or to the direction of prevailing winds for the purpose of reducing erosion.

Alley Cropping: growing arable crops in between alleys formed by trees or shrubs, established mainly to hasten soil fertility restoration and for shelter.

Agro-forestry: growing crops in combination with trees, and often also with livestock simultaneously on the same unit of land.

7.2 Annex 2. Definition of effect size in the analyses of SICS

The results discussed in this report are based on literature study and meta-analyses. Results of specific components of SICS have been quantified as relative effects, i.e., the ratio of the specific treatment and the reference (control treatment) according to

$$ES = \frac{Y_T - Y_C}{Y_C} = \frac{Y_T}{Y_C} - 1 \tag{1}$$

where *ES* is the effect size (dimensionless; or percentage), Y_T is the component observed (e.g. yield), and Y_C is the component of a reference or control treatment. In case a treatment does not result in a (significant) different outcome than the control treatment, then $ES = 0$. For $Y_T > Y_C$ this results in $ES > 0$, and vice-versa.

In meta-analyses studies the means and standard deviations of the effects are often determined based on ln-transformed ratio's (following the protocol of Hedges et al (1999) as given by

$$L = \ln\left[\frac{Y_T}{Y_C}\right] \tag{2}$$

Once the ln-transformed average ratio (and standard deviation) are known, it can be back-transformed to obtain the average effect size according to

$$ES_{avg} = \exp\left[L_{avg}\right] - 1 \tag{3}$$

Similarly the confidence interval for *ES* can be determined by back-transforming the confidence interval limits for *L*. In what follows we assume that the reported average *ES* is significant when the available confidence interval (based on standard deviation) does not include the value zero.

Formal meta-analysis studies often are based on the ln-transformed approach, whereas single studies and some reviews mostly consider the effect size or the ratio Y_T/Y_C.

One cannot generalize the interpretation of *ES* that positive values for *ES* are always the best. Sometimes $ES > 0$ indicates an improvement, e.g., an increase in yield due to the implementation of a certain SICS. In other cases $ES < 0$ indicates an improvement, e.g., a decrease in leaching due to the implementation of a certain SICS.

A common way to present the outcome of meta-analyses for ES (or L) is by presenting this in so-called forest plots (see examples in Annex 3).

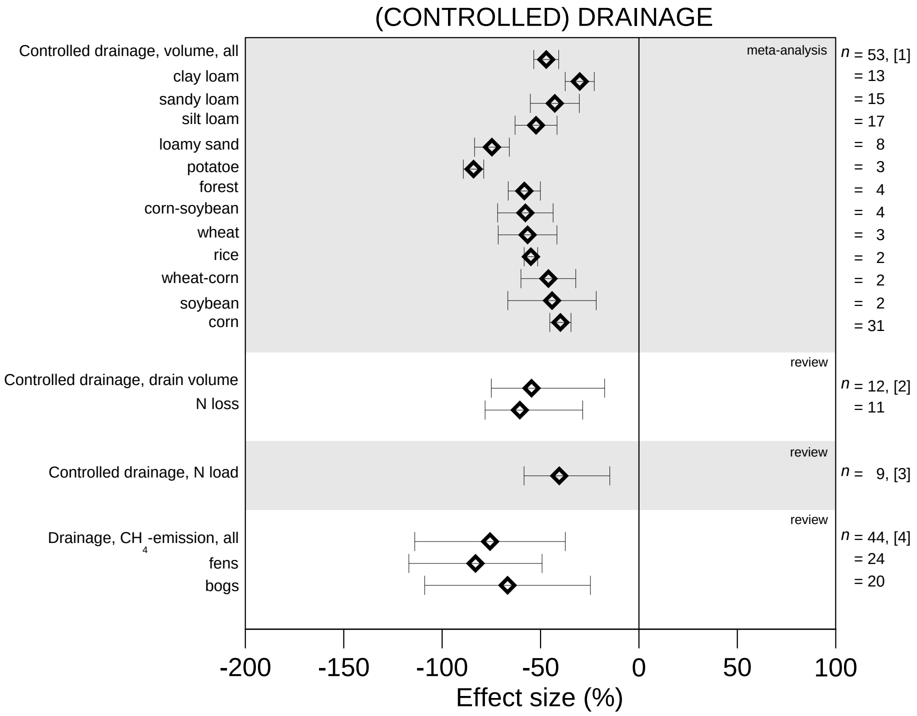
7.3 Annex 3. Forest plots

In a forest plot the effect size *ES* (or *L*; see Annex 2) is plotted on the horizontal axis for different studies (or studied quantities) as listed along the vertical axis. At the left side of the forest plots studies or quantities are listed, in the middle part the average *ES* is plotted as a symbol together with a confidence interval (e.g. ± standard deviation; or, 95% confidence interval). At the right side sometimes additional information is provided regarding the number of underlying studies. In the middle part a vertical line is drawn that indicates the reference situation, i.e. at *ES* = 0 (or *L* = 1). A certain effect is significant when the available confidence interval (based on standard deviation) does not include the reference value, i.e. does not intersect the vertical line.

Below, a few forest plots are presented which have been compiled within the SoilCare project.

Controlled drainage

Compared to conventional drainage, controlled drainage resulted in significant lower drainage volumes, irrespective of soil type or crops grown ([1]: Amenumey et al., 2009). This, together with lower N-loads, was also reported by [2]: Skaggs et al. (2010) and [3]: Christianson et al. (2013). Abdalla et al. (2016; [4]) reported lower drainage and lower CH_4 emision in drained fens or bogs compared to the natural, undrained situation.



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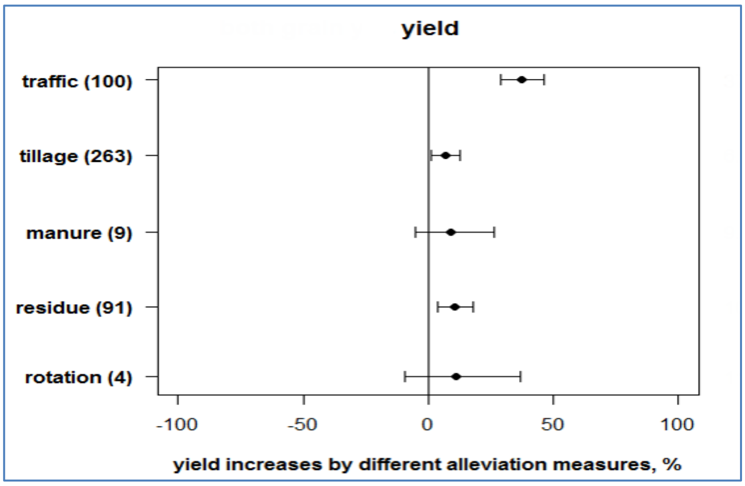
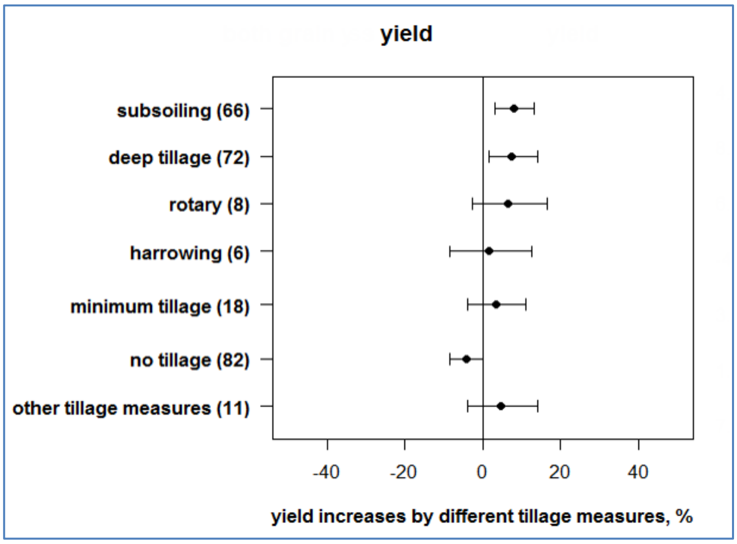
Soil compaction alleviation measures

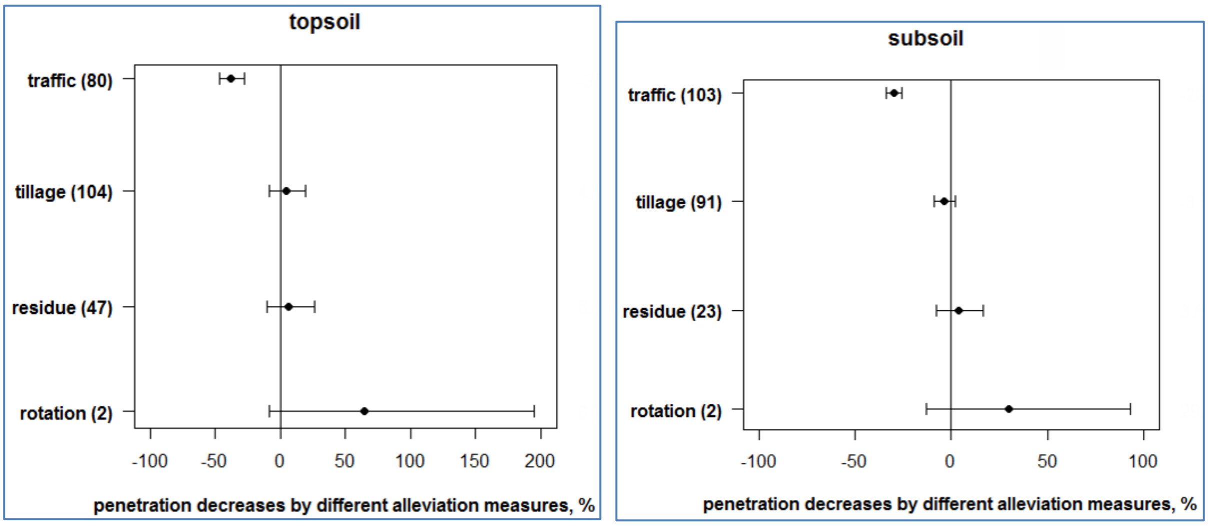
A meta-analysis study on the effects of soil compaction alleviation measures on crop yield and soil physical propertiess have been summarized in the next figures (source: Wang et al., 2017; in preparation). Dots show means, error bars represent 95% confidence intervals. The numbers of observations are displayed in parentheses. The measures considered were: controlled traffic, overall tillage measures, crop rotation, residue cover, and manure application. Except for crop rotation and manure application, all measures resulted in a significant increase in yield (and biomass). Crop rotation and manure application, however, show a tendency of increased yield.



Effects of soil compaction alleviation measures on crop yield. Dots show means, error bars represent 95% confidence intervals. The numbers of observations are displayed in parentheses. Traffic means control traffic, tillage means effects of overall tillage measures, rotation means crop rotation, residue means residue cover, manure means manure application.



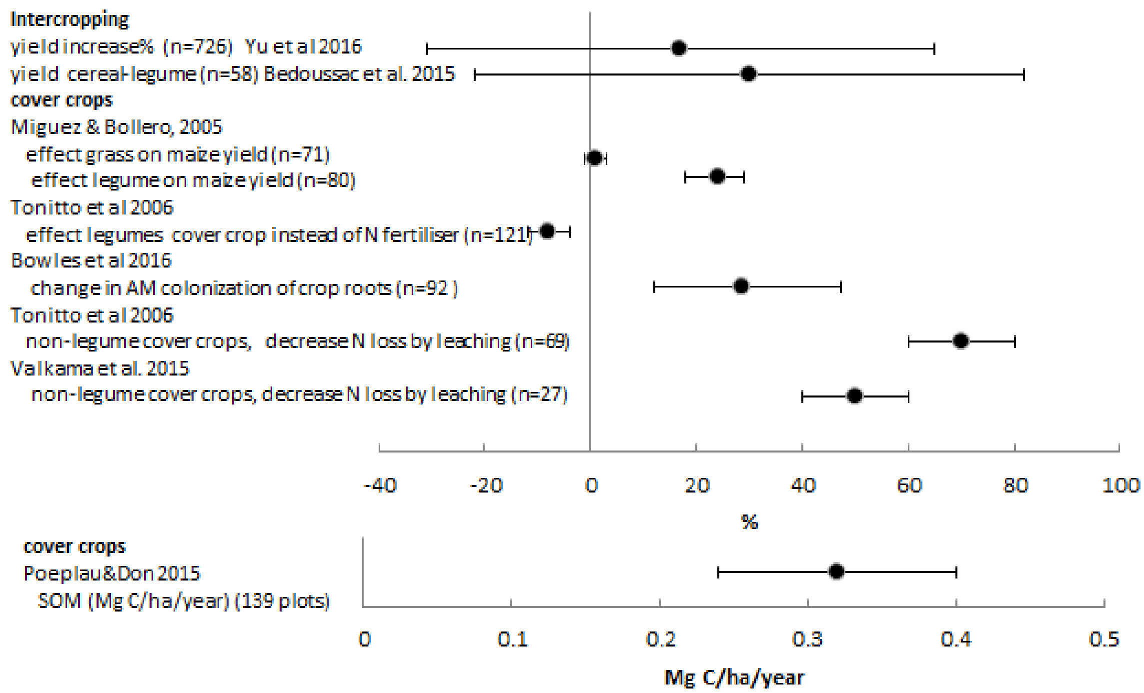
Effects of various tillage measures on crop yield. Dots show means, error bars represent 95% confidence intervals. The numbers of observations are displayed in parentheses.



Effects of different alleviation measures on soil penetration in the topsoil (left panel) and subsoil (right panel). Dots show means, error bars represent 95% confidence intervals. The numbers of observations are displayed in parentheses.

Intercropping and cover crops

The effect of intercropping on crop yield was positive, but not significant, except for the effect of legumes on maize yield (see figure below). Other effects of intercropping or cover crops as shown in the figure below are all significant, such as decrease in N loss via leaching, nicrease in SOM, or the change in AM coloninzation of crop roots.



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