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Soil-Improving Cropping Systems for Sustainable and Profitable Farming in Europe

Rudi Hessel [1,*], Guido Wyseure [2], Ioanna S. Panagea [2], Abdallah Alaoui [3], Mark S. Reed [4,5], Hedwig van Delden [6], Melanie Muro [7], Jane Mills [8], Oene Oenema [1], Francisco Areal [4], Erik van den Elsen [1], Simone Verzandvoort [1], Falentijn Assinck [1], Annemie Elsen [9], Jerzy Lipiec [10], Aristeidis Koutroulis [11], Lilian O'Sullivan [12], Martin A. Bolinder [13], Luuk Fleskens [14], Ellen Kandeler [15], Luca Montanarella [16], Marius Heinen [1], Zoltan Toth [17], Moritz Hallama [15], Julián Cuevas [18], Jantiene E. M. Baartman [14], Ilaria Piccoli [19], Tommy Dalgaard [20], Jannes Stolte [21], Jasmine E. Black [8] and Charlotte-Anne Chivers [8]

1 Wageningen Environmental Research, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands; oene.oenema@wur.nl (O.O.); erik.vandenelsen@wur.nl (E.v.d.E.); simone.verzandvoort@wur.nl (S.V.); falentijn.assinck@wur.nl (F.A.); marius.heinen@wur.nl (M.H.)
2 Department of Earth and Environmental Sciences, KU Leuven, 3001 Leuven, Belgium; guido.wyseure@kuleuven.be (G.W.); ioanna.panagea@kuleuven.be (I.S.P.)
3 Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland; abdallah.alaoui@giub.unibe.ch
4 Centre for Rural Economy, School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK; mark.reed@sruc.ac.uk (M.S.R.); francisco.areal-borrego@newcastle.ac.uk (F.A.)
5 Thriving Natural Capital Challenge Centre, Scotland's Rural College (SRUC), King's Buildings, W Mains Rd, Edinburgh EH9 3JG, UK
6 Research Institute for Knowledge Systems (RIKS), Hertogsingel 11A, 6211 NC Maastricht, The Netherlands; hvdelden@riks.nl
7 Milieu Consulting SRL, Chau. de Charleroi 112, 1060 Brussels, Belgium; melanie.muro@web.de
8 Countryside and Community Research Institute, University of Gloucestershire, Cheltenham GL50 4AZ, UK; jmills@glos.ac.uk (J.M.); jblack2@glos.ac.uk (J.E.B.); cchivers@glos.ac.uk (C.-A.C.)
9 Bodemkundige Dienst van België, Willem de Croylaan 48, 3001 Heverlee, Belgium; aelsen@bdb.be
10 Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland; j.lipiec@ipan.lublin.pl
11 School of Chemical and Environmental Engineering, Technical University of Crete, Akrotiri Campus, Chania 731 00, Crete, Greece; akoutroulis@isc.tuc.gr
12 Teagasc, Environment, Crops, Environment & Land Use Programme, Johnstown Castle, Co., Y35 TC97 Wexford, Ireland; lilian.osullivan@teagasc.ie
13 Department of Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7044, 75007 Uppsala, Sweden; martin.bolinder@slu.se
14 Soil Physics and Land Management Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands; luuk.fleskens@wur.nl (L.F.); jantiene.baartman@wur.nl (J.E.M.B.)
15 Institute of Soil Science and Land Evaluation, Soil Biology Department, University of Hohenheim, Emil Wolff Str. 27, 70599 Stuttgart, Germany; ellen.kandeler@uni-hohenheim.de (E.K.); hallama@uni-hohenheim.de (M.H.)
16 Joint Research Centre, European Commission, Via E. Fermi, 2749, 21027 Ispra, Italy; luca.montanarella@ec.europa.eu
17 Georgikon Campus Keszthely, Institute of Agronomy, Hungarian University of Agriculture and Life Sciences, 2100 Gödöllő, Hungary; toth.zoltan@uni-mate.hu
18 Agronomy Department, CeiA3, University of Almería, 04120 Almería, Spain; jcuevas@ual.es
19 Department of Agronomy, Food, Natural Resources, Animals and Environment, University of Padova, Viale dell'Università 16, 35020 Legnaro, Italy; ilaria.piccoli@unipd.it
20 Department of Agroecology, Aarhus University, Blichers Alle 20, 8830 Tjele, Denmark; tommy.dalgaard@agro.au.dk
21 Norwegian Institute of Bioeconomy Research (NIBIO), Oluf Thesens vei 43, 1433 Ås, Norway; jannes.stolte@nibio.no
* Correspondence: rudi.hessel@wur.nl; Tel.: +31-3174-86-530

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Abstract: Soils form the basis for agricultural production and other ecosystem services, and soil management should aim at improving their quality and resilience. Within the SoilCare project, the concept of soil-improving cropping systems (SICS) was developed as a holistic approach to facilitate the adoption of soil management that is sustainable and profitable. SICS selected with stakeholders were monitored and evaluated for environmental, sociocultural, and economic effects to determine profitability and sustainability. Monitoring results were upscaled to European level using modelling and Europe-wide data, and a mapping tool was developed to assist in selection of appropriate SICS across Europe. Furthermore, biophysical, sociocultural, economic, and policy reasons for (non)adoption were studied. Results at the plot/farm scale showed a small positive impact of SICS on environment and soil, no effect on sustainability, and small negative impacts on economic and sociocultural dimensions. Modelling showed that different SICS had different impacts across Europe—indicating the importance of understanding local dynamics in Europe-wide assessments. Work on adoption of SICS confirmed the role economic considerations play in the uptake of SICS, but also highlighted social factors such as trust. The project's results underlined the need for policies that support and enable a transition to more sustainable agricultural practices in a coherent way.

Keywords: soil quality; sustainable soil management; adoption; crop management; environmental dimension; sociocultural dimension; economic dimension

1. Introduction

Crop production in Europe faces the challenge to remain profitable while at the same time achieving environmental sustainability. Average wheat yields in several European. countries are less than what is locally attainable [1–4], possibly because of suboptimal management and/or impairment caused by poor soil quality (defined as 'the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health', following [5]). In addition, agricultural land faces a number of other threats that may lead to physical, chemical, and biological degradation of the soil [6–9]. These include erosion, compaction, salinization [10], soil pollution, loss of organic matter [11], and loss of soil biodiversity [12]. For example, the use of heavy machinery can lead to soil compaction and impaired root growth [13]; increased soil cultivation and climate change can lead to soil organic matter decline [14]; and narrow rotations may cause biodiversity decline and increased incidence of soil-borne diseases [15]. These forms of soil degradation are often neglected by land managers because of low awareness, low visibility during initial stages of degradation, and a lack of appropriate tools, benchmark values, and policies. As a result, production levels in some cropping systems are maintained by high input (e.g., nutrients and pesticides) and technology (e.g., machinery and breeding), which may mask losses in long-term productivity due to reduced soil quality [16,17]. Such increased use of agricultural inputs may reduce long-term farm profitability because of their costs while also negatively affecting the environment because of unsustainable use of energy and resources in producing inputs [18] and as a consequence of their application (e.g., [19–21]). Soil improvement is necessary to break the negative spiral of degradation, increased inputs, increased costs, and damage to soil and the environment [22]. Maintaining or improving soil quality is crucial for crop production [23] and can especially contribute to remediating forms of soil degradation that are initially hardly visible, such as gradual loss of soil biodiversity and soil organic matter.

Soils are at the intersection of a broad range of land use and environmental challenges. They are critical for economic and environmental well-being, because they form the basis for agricultural production, support high-quality food output [24], and provide a range of other ecosystem services. For example, good-quality soils are more resilient to weather extremes [25] and provide better buffering and cycling of nutrients [26], water

purification and regulation, and resilience to pests [27] and climate variability/change [28]. Other ecosystem services provided by soils [29] include provision of biodiversity [30,31] and carbon sequestration, cycling, and regulation [32,33]. Thus, to ensure that sufficient healthy food for expanding human populations can be grown within planetary boundaries [34], soil management should aim at improving the quality and resilience of land and soil [35].

Attention on soil quality is increasing (e.g., [5,7,36–43]). In Europe, various projects (see, e.g., CORDIS|European Commission (europa.eu), domain 'Food and Natural Resources') have worked on soil threats, prevention of soil degradation, sustainable land management, agricultural management practices, soil functions, and soil quality. There is also increasing recognition of the fact that crop production should be enhanced without compromising the environment [44,45]. More than ever, the important role that soil plays in sustaining life on the planet is being recognized, with high-level objectives at the E.U. scale (e.g., [46]) and the UN Sustainable Development Goals (SDGs) being reliant in large part on sustainable land and soil management [47].

More sustainable farming systems (defined as 'Farming systems that use land resources, including soils, water, and plants, for the production of crops, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions', following the definition of sustainable land management given by WOCAT (www.wocat.net/en/slm (accessed on 13 April 2022)) ' and practices, such as organic farming, conservation agriculture, and precision farming have taken a foothold in Europe [48,49]. For example, Bioland, an association for organic farmers in Germany and Austria, already had more than 5800 members in 2014 [50] and 8500 in 2021 (see https://www.bioland.de/fileadmin/user_upload/Verband/Entwicklung_Betriebe_und_Flaeche_01.svg (accessed on 13 April 2022)). However, these farming systems were not adopted to their full potential and were in some cases even abandoned [51]. Reasons behind this may be the possible negative effect of conservation agriculture on crop yield [39]; the complexity of conservation agriculture, which is management and knowledge intensive [52]; problems with weed and residue management [51]; or the increased occurrence of pests and diseases. There are also cultural and political barriers to the adoption of more sustainable agricultural practices [53]. Barriers to adoption often involve issues around land tenure, access to credit and inputs [7], and other socioeconomic factors, and the lack of knowledge, credible scientific evidence, and good-quality technical advice has also been highlighted [54].

This paper proposed and operationalized a multidisciplinary, multi-actor approach to identifying soil-improving cropping systems (SICS) that are both sustainable and profitable, and hence are more likely to achieve mainstream adoption in agriculture. The focus is on two main aspects, namely evaluation of SICS based on field experiments and modelling and adoption of SICS. To do this, we:

- Present the concept of SICS, as developed in the H2020 SoilCare project (2016–2021) https://www.soilcare-project.eu/ (accessed on 13 April 2022);
- Review literature on factors influencing farmer adoption of SICS;
- Propose a methodological framework for identifying and evaluating SICS that have a high likelihood of adoption;
- Present findings from the application of this framework in 16 study sites across Europe and from its upscaling to E.U. scale.

The paper starts by describing the concepts and methodology used for evaluating SICS and studying their adoption (Section 2) and then proceeds by presenting and discussing key findings from SoilCare (Sections 3 and 4). For a literature review that summarizes the main findings of published meta-analyses on SICS, the reader is referred to [55].

2. Concepts and Methodology

2.1. Conceptualization of SICS

The term 'cropping system' refers to the crop type, crop rotation, and agronomic management techniques used on a particular field over a period of years [56]. Choices made for these factors can influence the profitability and sustainability of crop production [57–59]. We considered these systems soil-improving if they resulted in a durable increased ability of the soil to maintain its functions, including food and biomass production, buffering and filtering capacity, and provision of other ecosystem services.

The basic concept adopted in the SoilCare project was that profitability and sustainability of crop production in Europe should be integrated and enhanced. Both are influenced by choices made in farm management, which are in turn influenced by external drivers and factors (Figure 1). External drivers and factors include E.U. policies and international agreements, supply chain and market effects (suppliers, industry, processing, retail, and consumers), macroeconomic conditions, society (public opinion), and pedoclimatic conditions. These external drivers and factors are dynamic and change because of socioeconomic developments, geopolitics, and climate change. As the focus of SoilCare was on arable cropping systems, grazing systems, multisystem farms, and other on-farm activities were not considered.

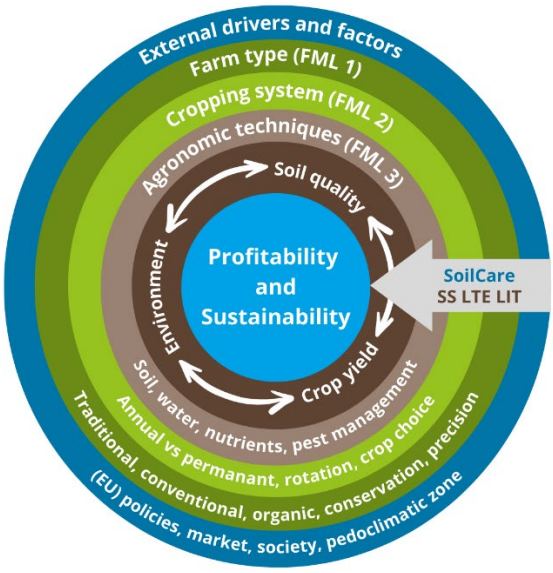

Figure 1. Methodological framework for assessing sustainability and adoptability of soil-improving cropping systems, showing the influence of farm management levels (FML 1–3) on soil quality, environment, crop yield, profitability, and sustainability. LIT refers to literature and other published data, LTE to long-term experiments, and SS to work in the study sites.

At the highest farm management level (FML1, see Figure 1) a choice is made among different types of farming; cropping systems are decided on at FML2, while choices regarding agronomic techniques that are used for management of soil, water, nutrients, and pests are made at FML3. Which farm type is chosen depends on external factors but also on the farm's ownership, resources and social context, such as the education, age, and preferences of the farmer (e.g., [60]). Choices made at this level also influence FML2 and FML3. For example, a choice for organic farming made at FML1 implies crop rotation at FML2 and biological pest management at FML3.

Choices made at all three FMLs have impacts on soil quality, on the environment, and on yield (thus farm economy) (Figure 1). These also influence each other. For example, the occurrence of a soil threat such as erosion influences soil quality as well as crop yield [61]. Crop yield can also influence soil quality, for example, through nutrient mining, rooting effects, and below-ground biomass. When impacts on soil quality and environment

are positive, and the balance between production costs and revenues is also positive, the dual targets of farm profitability and environmental sustainability are reached.

The use of SICS improves soil quality and environmental benefits and has positive impacts on the farm economy (Figure 2). Some benefits result directly from the application of proper agronomic techniques; for example, avoiding overapplication of nutrients reduces greenhouse gasses (GHGs) and pollution (soil degradation). Other benefits of SICS are indirect, as they result from improved soil quality brought about by application of the SICS. For example, improved soil quality improves infiltration and hydrological properties, increases rooting depths and resilience to climate change impacts, and stimulates soil biodiversity [11]. Finally, SICS also have above-ground impacts on vegetation and landscape (e.g., through the use of hedges, buffer strips, trees, terraces, ditches). Such impacts may also contribute to the conservation of biodiversity and wildlife, which may in turn positively influence soil quality.

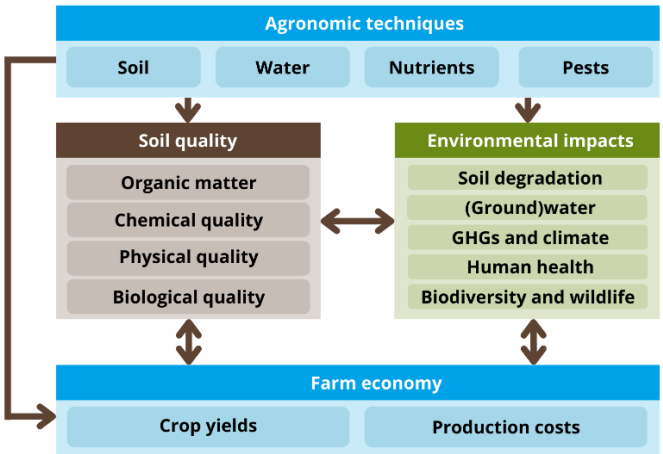

Figure 2. Impacts of agronomic techniques for managing soil, water, nutrients, and pests. One-sided arrows indicate impact, while two-sided arrows indicate that factors influence each other. Note that agronomic techniques are part of cropping systems and correspond to FML3 in Figure 1.

Profitability is a key factor influencing the adoption of SICS [62–66] that is partly influenced by the choice of cropping system and its management and partly by factors that farmers (in Europe) cannot typically control, such as global markets and policies [53]. A key aspect of profitability is production costs, as farmers have more control over this aspect than over the prices they get for their products. Different cropping systems require different types and levels of inputs (e.g., [67]) with different costs. In addition, the choice of cropping system influences the price of the product, which is often higher for organic than for conventional farming.

Conventional farming may become increasingly costly because of rising costs for external inputs and/or for mitigation/restoration measures against soil degradation. In addition, prices of external inputs fluctuate. For example, refinery curtailments due to the COVID-19 pandemic have limited supplies of raw materials, raising input costs by increasing the price of fertilizers for farmers [68]. Price fluctuations of agricultural products are expected to persist and continue to challenge the ability of consumers, producers and authorities to cope with the consequences [69]. In this context of rapid change and long-term challenges, farm profitability is at risk. In line with the Europe 2020 Strategy [70] on achieving smart, sustainable, and inclusive growth, boosting profitability is not only about reducing production costs, or increasing productivity, but also about more sustainable agriculture and the transformation of the food market to green, high-quality products. Smarter and greener agriculture also has the potential to contribute to a more circular bioeconomy and increase the value of agricultural products and the willingness of

consumers to buy European agricultural products both inside and outside of the European Union [71,72].

SICS have the potential to reduce costs in the long run by reducing the need for external, costly inputs such as fertilizers and pesticides, reducing energy use for operating machinery, and/or reducing labour input [73–75]. While some SICS may lead to reduced productivity, they may make more efficient used of inputs and thus be more profitable. Costs associated with current unsustainable land use and management are estimated to be in excess of EUR 50 billion per year in the European Union [46]. In the long term, adoption of SICS should help reverse the current trajectory, and when soil quality has improved, efficiency is expected to increase further as a consequence of the reduced need for external inputs and possibly higher production. Additional long-term benefits lie in the reduction of expenditures due to reduced land degradation, GHG emissions, and risk to damages from natural disasters such as storms, droughts, or floods [25].

Various factors influence where SICS are most needed and best suitable and thereby determine the balance between the benefits and drawbacks of SICS and the ways in which these drawbacks can be minimized. These factors include the pedoclimatic zone (zones that are relatively homogeneous concerning climate and soil; see, e.g., [76]), the type of problem that constrains soil quality and crop production, biophysical conditions, and socioeconomic and political conditions. These different conditions require the use of different SICS and determine the applicability, profitability, and environmental impacts of the SICS across Europe. Hence, an assessment of SICS should incorporate environmental, economic, social, and policy aspects while also taking into account future trends in land use and climate change.

2.2. Methods Used for Evaluation of SICS

The first step in evaluating selected SICS was an in-depth analysis of the benefits and drawbacks of SICS as reported in literature and other published sources [55,77]. This was followed by investigating data from existing long-term experiments (LTEs). Next, we conducted field experiments and stakeholder research in 16 study sites located in different parts of Europe (Table 1, Figure 3), covering different pedoclimatic, socioeconomic, and policy conditions. Literature and other published data were mainly used to assess external drivers and factors (Figure 1). This was supplemented by stakeholder consultation at the E.U. level and modelling. Data from LTEs were mainly used to investigate SICS that show effects only in the long term. The focus of field experiments and stakeholder research in the study sites was primarily on FML3, since soil, water, nutrient and pest management can be adapted in the course of the year and these choices generally have more immediate effects than choices made at FML1 and FML2.

Table 1. Overview of SoilCare study sites. Types of crops listed here represent the study site region, not the sites where monitoring was conducted.

Study Site	Types of Crop	Pedoclimatic Zone [1]	Problems That Caused Reduced Soil Quality or Crop Yield or Increased Cost
1. Flanders, Belgium	Winter wheat, sugar beet, potato, vegetables, forage crops, orchards	Atlantic Central, soil depends on site	N and P leaching, erosion, compaction, SOC [2]
2. Viken, Norway	Cereals	Nemoral/Boreal, marine clay soils	Erosion, nutrient loss, pests, disease, SOC, compaction
3. Keszthely, Hungary	Cereals, maize	Pannonian, sandy loam, Eutric Cambisol	Soil compaction, humus degradation, nitrate leaching, acidity, weeds
4. Frauenfeld, Switzerland	Grass, cereals, maize, rape, potato, sugar beet, vegetables	Continental/Alpine South, Fluvisol	Soil structure, subsoil compaction, pounding risk
5. Viborg, Denmark	Winter cereals (wheat, 25%), forage crops	Atlantic North, sandy–loamy soils	SOC, compaction, erosion, nutrient losses (N and P)
6. Loddington, United Kingdom	Cereals, oilseeds, pulses, grass/clover leys	Atlantic Central/North, clay soils	Compaction, SOC
7. Tachenhausen, Germany	Maize, wheat, barley, oilseed rape, soya	Atlantic Central, karst, silty loam	Soil structure, compaction, reduced infiltration
8. Draganesti Vlasca, Romania	Cereals, sunflower	Panonnian, Phaeozem	Soil compaction
9. Legnaro, Italy	Maize, wheat, sugar beet, soybean, alfalfa	Mediterranean North, Cambisol	SOC, compaction, climate variations
10. Szaniawy, Poland	Barley, rye, wheat, oats, potatoes, maize, grassland.	Continental, Sandy, loamy soils	Water deficit, SOC, acidity, compaction, weeds.
11. Caldeirão, Portugal	Cereals (maize and rice), vineyards	Lusitanean, silty–clayey soils	Water availability
12. Chania, Crete, Greece	Olive, citrus vineyards	Mediterranean South, Calcisol	Erosion, compaction, water availability
13. Orup, Sweden	Winter wheat, spring barley, spring oilseed rape, peas	Nemoral, sandy loams	Compaction
14. Prague-Ruzyně, Czech Republic	Barley, rye, wheat, oats, potatoes, maize, grassland	Continental, Luvisol	Erosion, compaction, SOC, acidification, reduced water retention
15. Almeria, Spain	Olive, stone fruit crops	Mediterranean South, Regosol, Leptosol	Erosion, salinization, water shortage
16. Brittany, France	Wheat, maize, grassland	Lusitanian/Atlantic Central, Cambisol	Compaction, weeds

[1] climatic zones based on the Environmental Stratification of Europe (version 8) [76]; [2] SOC = soil organic carbon decline.

Figure 3. The 16 SoilCare study sites. Details on each study site can be found in Table 1.

Within the study sites, different SICS were selected, tested in field, and evaluated in collaboration with stakeholders. Evaluation of SICS was conducted by applying the same assessment methodology at each study site. This general methodology was based on a shared database [78], a common monitoring plan, a unified statistical analysis (according to the experimental design of each experiment) and sustainability assessment. In the field experiments, SICS were compared with a control (usually a standard conventional practice) [79], and SICS were monitored for 2–4 years. Data from the field trials were assessed using a decision tree in terms of soil quality (physical, biological, and chemical); environmental, economic, and sociocultural dimensions; and sustainability, resulting in a score between −1 and 1 for each dimension [80]. For the three dimensions, the following methods were used for scoring:

- Environmental (including soil quality): Monitoring results compared SICS and control for several chemical, physical, and biological soil properties such as infiltration, aggregate stability, bulk density, mineral nitrogen, soil organic carbon (SOC), pH, earthworm density, crop yield, yield quality, crop cover, pests, root diseases, and weed diseases (see [79,80]). For each parameter, it was determined whether there was a statistically significant difference between SICS and control using mixed-effects models adjusted to the different experimental designs. For each experiment, the status of the soil was also evaluated as 'good' or 'bad' using threshold values based on expert opinion. A score of 1 was assigned if the SICS resulted in improvement, 0 if there was no change, and −1 if there was a deterioration. The overall environmental score (Table 2) was then obtained by averaging the scores for the individual parameters.
- Economic: The impact score compared costs and benefits for SICS and control (see [80]), where costs were calculated as the sum of investment costs, maintenance costs, and production costs. Equipment costs were not included. The analysis was conducted at the field/farm level and did not consider (monetization of) off-site effects of SICS.
- Sociocultural: Sociocultural impact was based on workload, perceived risk, and farmer reputation. Workload and farmer reputation were scored between −1 and 1,

where negative values indicated a deterioration for the SICS compared with the control or usual practice. Perceived risk was scored between −1 and 0, where 0 meant no risks were perceived to be associated with the SICS. However, we did not assess whether a SICS reduced risks compared to the control, and therefore, no positive values were possible. This was a shortcoming of the assessment methodology and led to a 'negative bias' in assessing the sociocultural dimension of SICS.

Table 2. Results of SICS analysis based on the developed assessment methodology [80]. Values were scored on a range from −1 to 1 for those experiments where data on all three dimensions were available (see [79]). Details on experiments can be found in [79]. Impact on sustainability was the average of environmental impact, economic impact, and sociocultural impact. Negative impacts are indicated by red and positive ones by green. More details are provided in Table S1.

Country	SICS Treatment	Environmental Impact	Economic Impact	Sociocultural Impact	Impact on Sustainability
Belgium	Wood chips	0.00	−0.93	−0.33	−0.38
Norway	Spring-sown cover crop/root mix	0.00	0.03	−0.26	−0.07
Hungary	N (maize 210, winter wheat 150, winter barley 120 kg/ha) + farmyard manure	0.34	−0.12	−0.13	0.06
Hungary	N fertilization (as above) + straw/stalk	0.37	0.38	0.60	0.44
Hungary	Minimum tillage + N (maize 180, winter wheat 160 kg/ha)	0.00	0.04	0.20	0.07
Switzerland	Controlled Uptake Long-Term Ammonium Nutrition (CULTAN) method	−0.10	−0.60	0.20	−0.16
Switzerland	Green manure, no pesticide	−0.15	−0.01	0.10	−0.03
Germany	Glyphosate + cover crops	0.00	−0.03	0.07	0.01
Romania	Rotation + mouldboard ploughing	0.24	0.31	−0.20	0.13
Italy	No-till, radish cover crop	0.00	0.07	0.00	0.02
Portugal	Conventional maize, Urban Sludge amendment	0.35	0.15	−0.56	0.02
Portugal	Maize with legume winter cover crop	0.11	0.03	−0.26	−0.03
Greece	Conversion from orange to avocado	0.03	0.76	0.00	0.24
Spain	Deficit irrigation with minimum tillage and pruning chips or temporal cover crops	0.30	−0.90	−0.03	−0.16
France	Early wheat sowing (Aug)	−0.08	−0.89	−0.20	−0.36
France	Sowing on the row of maize–buckwheat	−0.07	−0.33	0.10	−0.10
	average	0.08	−0.13	−0.05	−0.01
	median	0.00	0.01	−0.03	0.01
	# positive (>0.1)	6	4	3	3
	# negative (<−0.1)	1	6	7	4
	# no change (−0.1 to 0.1)	9	6	6	9

Detailed results of the evaluation of environmental, economic, and sociocultural dimensions were presented in [79]. For SICS for which data on all three dimensions were available, we calculated the impact on sustainability as the average of the impact on the three dimensions [80].

Finally, the study site results were upscaled to the European level using a storyline, simulation, and policy support process [81–83]. This process combined participation and modelling to better understand the impacts of SICS across Europe and to provide policy support to facilitate the uptake of SICS under different contexts and conditions. As part of the approach, an integrated assessment model (IAM) consisting of spatial, socioeconomic, and environmental simulation models (i.e., the AGMEMOD [84],

METRONAMICA [85], PESERA [86], dyna-QUEFTS [87], and MITERRA [88] models) was developed [81]. The IAM was used to simulate possible effects of four scenarios that captured diverse pathways for European agriculture until 2050 (Figure 4). These scenarios differed with regard to challenges to voluntary instruments and mandatory instruments. We used a combination of qualitative and quantitative techniques in a multi-actor approach to develop these scenarios in order to assess how agricultural practices could contribute to sustainable and profitable European agriculture and, finally, to discuss what is needed to enable adoption and implementation of these practices. In addition, for a range of 27 SICS, Europe-wide maps and modelling were combined with expert judgement from study site partners and their stakeholders to provide a SICS potential index based on the applicability, relevance, and impact of each SICS [82]. An interactive web-based tool was developed to help land users and decision makers select suitable SICS throughout Europe (imt.soilcare-project.eu; accessed on 13 April 2022) [83]. This tool allows users to compare different SICS with regard to various aspects, including IAM results and the SICS potential index.

Figure 4. Overview of scenario framing linked with scenario titles and motivating factors [82].

2.3. Concepts and Methodology Used to Study Adoption of SICS

In the last decade, there have been numerous policy initiatives at the European level that, directly or indirectly, promoted the adoption of beneficial agricultural practices [89,90]. Most recently, the European Green Deal (COM/2019/640 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN (accessed on 13 April 2022) and the new Soil Strategy (COM/2021/699 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699 (accessed on 13 April 2022)) set out the roadmap for making the European Union's economy more sustainable and identified several key actions that will be crucial in advancing land and soil protection in Europe. With this shift to more sustainable practices comes increasing pressure on farmers to change how they operate and adopt new techniques and practices. However, innovations associated with potential benefits to soil quality have not yet been adopted to their full potential and have, in some cases, even been abandoned, raising the question of why support for and adoption of these practices by European farmers is still weak.

Adoption of new or modified agricultural practices by farmers is a complex process that is governed not only by physical effectiveness and economics of agricultural practices but by a range of other factors, including individual, social, cultural, and policy-related factors [91]. These include internal factors, such as the farmer's own views on farming, the influence of peers and advisers, their perceived difficulties in implementing practices, and sociodemographic characteristics, and external factors, such as pedoclimatic conditions, markets, and policies [91,92]. Economics is an important factor and is often considered to be the main driver for adoption. However, overlooking some of the other factors may be

one of the main reasons why seemingly advantageous measures have not been adopted widely by farming communities (e.g., [93,94]). Factors influencing the adoption of sustainable farming practices in Europe range from the land managers' access to information, training, and technical advice [95], to the performance of a particular practice in terms of yield increase or reduction in production costs or work time [96,97], to aspects rooted in the social and cultural context or in the personality of the individual land user. Social factors include the underlying motives (e.g., social or personal rewards) and attitude towards risks [98]; personality traits such as openness to new experience or resistance to change; what land users perceive others expect from them; and land users' perceptions of the relative benefits, costs, and risks associated with a particular practice [97,99]. In addition, farming practices, e.g., conservation measures, must be compatible with the values of landowners [97], cultural constructions of 'good farming' [100,101], and farmers' sense of professional identity and aesthetic preferences [102]. Finally, social factors such as trust and acceptability also influence adoption [59]. The dynamics of trust (across space, time, social groups, and culture) can explain how innovations are adopted through social learning and collaborative learning processes. The speed and spatial scale at which trust can develop likely depends on the extent to which it is possible to find or develop shared values, converge towards compatible epistemologies, and find common interests that can transcend sociocultural, political, and economic differences. It should be noted that engagement processes work differently and can lead to different outcomes when they operate over different spatial and temporal scales [103] so that engagement processes should be adapted to local conditions.

To understand all the factors that influence adoption and take them into account, a multidisciplinary integrated approach is needed, including, e.g., soil science (physics, chemistry, and biology), agronomy, hydrology, ecology, climatology, economics, and social sciences. In addition, a variety of stakeholders should be involved, as multiple stakeholders influence the ways in which crops are produced. This makes adoption site-specific, as every area has its own unique combination of biophysical, sociocultural, economic, and policy factors, as well as its own set of stakeholders. Thus, adoption research necessitates the involvement of scientists and practitioners from multiple disciplines, as well as active involvement of stakeholders. For SoilCare, this contextual nature of sociocultural and political drivers meant, on the one hand, that a robust assessment of adoption factors could be performed only at the study-site scale, so the broader suitability of SICS across Europe was considered primarily based on biophysical and environmental characteristics. On the other hand, the adoption work could still offer insights into more general trends with respect to the typical factors that can influence the adoption of particular SICS.

The SoilCare research on the adoption of SICS focussed on understanding the reasons why SICS are being adopted or not adopted and how farmers can be encouraged through appropriate incentives to adopt suitable SICS. The methods applied addressed four types of factors affecting adoption:

- Biophysical factors, which followed from the evaluation of monitoring results [79] as well as from literature reviews [55,77]. This included the effects that SICS had on soil quality but also on crop yield. Results of the evaluation of monitoring of SICS were presented to stakeholders and were discussed with them;
- economic factors, which followed from a cost–benefit analysis of SICS implemented for monitoring [79] in combination with macroeconomic modelling using the AGMEMOD model [84]. Results of the economic analysis of SICS performed at the plot/farm scale were presented to, and discussed with, stakeholders;
- social factors, which were studied in a selection of study sites via work with farmers and agricultural stakeholders in the United Kingdom and Norway to understand their perceptions of causes of and potential solutions to soil degradation and how they perceived SICS in relation to alternative approaches to increasing the sustainability of cropping systems in Europe [104]. An assessment of the role of the farming

press and social media in decisions to adopt SICS and other sustainable agricultural practices was based on content analysis of media and interviews with U.K. farmers and agricultural advisers [105,106]. A wider analysis of social factors influencing adoption decisions, including an in-depth analysis of the role of social capital and trust, was based on literature review [91] and interviews with farmers and agricultural advisers in the United Kingdom and Hungary [107];

- policy factors, which were studied through analyses of soil-related agricultural and environmental policies at both the E.U. and study site levels, through workshops and interviews.

Adoption should be considered not only with regard to a range of factors but also at different scales, from the farm scale to the European scale, because operations and actors in the agricultural value chain stretch out over these scales in the supply, purchase, processing, and distribution of agricultural products. Furthermore, socioeconomic developments, such as changing public awareness of the importance of sustainable production and the consequences this has for the prices consumers and companies are willing to pay for sustainably produced food, have an influence on adoption.

The storyline, simulation, and policy support approach presented in Section 2.2 was used to assess the adoption potential of SICS at the European scale. By developing different scenarios or pathways for European agriculture using a combination of sociocultural, technological, economic, environmental, and political factors and drivers of change, the impact of (policy) actions on enhancing adoption of SICS was assessed under various current and future conditions to arrive to options that would be robust across scenarios or target specific factors/barriers and enablers within scenarios.

3. Key findings

3.1. Main Effects of SICS

Table 2 provides an overview of monitoring results from 11 countries, derived from [79], which contained details on the experiments. Overall, these results showed a small positive impact of SICS (when compared with the control) on environment (including soil quality), no effect on sustainability, and a small negative impact on economics and the sociocultural dimension. Some treatments showed both high and low values of impact scores on the dimensions of the sustainability assessment, which illustrated trade-offs in the performance of a SICS. Some treatments yielded only zero or negative impacts (e.g., early wheat sowing, FR), and other treatments gave positive impact scores in all dimensions (e.g., N fertilization with straw/stalk, HU).

3.1.1. Environmental Dimension

In general, the SoilCare field experiments were too short to show clear statistically significant effects on productivity (yield or relative yield), SOC, structure stability (water stable aggregates), infiltration rate (hydraulic conductivity), biological activity (earthworm counting), or soil bulk density. Hydraulic conductivity and bulk density have large spatial and temporal variability in the field, which made it difficult to detect significant differences without dramatically increasing the number of measurements. The study site in Poland illustrated this spatial variability well [108]. Overall, SICS showed a small but positive effect on soil properties and the environmental dimension (Table 2); 6 out of 16 experiments showed a positive impact of SICS, 1 experiment showed a negative impact, and 9 experiments showed no change. Although not significant from a statistical point of view, slight improvements were found for most of the experiments. In addition, stakeholders and scientists in many cases could visually detect and evaluate positive effects of SICS, in properties such as soil structure or infiltration, or negative effects, such as weed infestation.

In addition, the SoilCare monitoring results provided the following insights based on the evaluation of the environmental dimension for all SICS [79].

Tillage: For most experiments, reduced tillage and noninversion tillage had a positive effect on soil characteristics and did not lead to lower yields. The noninversion tillage in a Belgian experiment presented better physical characteristics (hydraulic conductivity and aggregate stability). The minimized tillage in a Hungarian LTE [109] also improved the aggregate stability and SOC content when compared with conventional ploughing and increased the plant available water content [110]. A Czech experiment [111] showed that zero tillage was difficult for heavy soils and root crops but significantly improved the topsoil SOC, bulk density and aggregate stability when compared with conventional ploughing. However, the increase in SOC did not affect the plant available water content [110]. Pest and weed control was a challenge in the Belgian experiments under strip tillage and significantly impacted plant growth and crop yield. Weed control was also a major issue in several no-tillage systems; this resulted in increasing use of herbicides.

Soil compaction: Subsoiling is a means to alleviating compaction [112] by breaking up the compaction of deeper soil layers. In a Romanian experiment, subsoiling was suggested to a depth of 60 cm every 3 to 4 years to improve the aggregate stability and hydraulic conductivity and reduce the soil bulk density while maintaining a good crop yield. A Swedish experiment on a naturally compacted soil found that mechanical subsoiling, with or without incorporation of organic materials, had a positive impact on root growth and rooting depth. In a U.K. experiment, different physical and biological methods for compaction alleviation were explored. Ploughing was the most effective method for opening up the soil structure and alleviating topsoil compaction, but no effect on crop yield was observed in the two years of study [113]. The results of an Italian experiment that used different crops and tillage methods to reduce soil compaction indicated a higher risk of crop failure and difficulties with weed control (requiring herbicides) under no-tillage systems. Nevertheless, reduced-tillage systems had the potential to increase farm environmental and agronomic sustainability according to the relative sustainability index, which was based on 11 physical chemical and biological properties [114].

Fertilizers and amendments: An LTE in Hungary [115] showed significant positive effects on yield and soil structure (water stable aggregates and bulk density) when incorporating crop residues into the soil or when applying farmyard manure. The SOC content and plant available water content were not significantly increased [110] despite the positive effects on yield and soil structure. A Belgian experiment compared adding woodchips, compost, and pig manure with a control (no additions). The C/N ratio of the amendments helped to explain the availability of nutrients for crops. In a Portuguese experiment, urban sludge from wastewater treatment plants increased SOC and soil nutrient contents and earthworm population without affecting the heavy metal concentration in the soil in the short term. In a Danish experiment [116], the use of manure helped to reduce the crop yield gap between organic cultivation treatments and conventional control treatment with mineral fertilizers and to reduce soil bulk density. A study in Italy [117] examined the effects of SICS with different crop residue management and concluded that crop residues reduced the need for fertilizers. The Controlled Uptake Long-Term Ammonium Nutrition (CULTAN) method in Switzerland reduced the risk of nitrate leaching.

Data from LTEs in Belgium, Denmark, the United Kingdom, and Hungary indicated that soil management influenced soil biota, which in turn influenced soil quality [118]. The fungal communities were found to be very variable across sites located in different soil types and climatic regions, and only fertilization showed a consistent effect on arbuscular mycorrhizal fungi and plant pathogenic fungi, whereas the responses to tillage, cover crops, and organic amendments were site, soil, and crop-species specific. A study in Poland [119] examined the effects of adding spent mushroom substrate and chicken manure to soils on soil fungal community composition and mycobiome diversity. Both increased the abundance of fungi and reduced the relative abundance of several potential crop pathogens. These results provided a novel insight into the fungal communities

associated with organic additives, which should be beneficial in the task of managing the soil mycobiome as well as crop protection and productivity. Both additives were also found to result in increased SOC [120].

Cover crops: Over the last decade, the increased use of cover crops between growing seasons has motivated the inclusion of this practice in the field experiments of many study sites. The benefits of cover crops are generally well accepted, and recent research has indicated that they can also enhance the availability of soil P and have positive effects on the soil microbial community [121–123] and earthworm abundance [116]. Positive effects were also illustrated by experiments in the study sites in Norway, Portugal, Denmark, France, Italy, and Germany [79]. However, because of global warming, which was visible in the results of the meteorological analyses for these study sites, the lack of freezing during recent winters meant that cover crops survived the winter. In that case, either herbicides or mechanical measures were required to kill them in spring. This is an important issue for further investigation. In the German experiment, the possible negative effect of glyphosate on soil quality was investigated by using different soil microbiological methods. An increase was found in ß-glucosidase activity (C-cycling enzyme) as a stress response of soil microorganisms after a period of seven days of application (unpublished data). Since no significant changes in microbial community composition occurred after the application of glyphosate in the field experiment, these effects were considered minor. Nevertheless, transport of glyphosate by preferential flow into deeper zones of soils might hinder the fast decay of this compound by bacterial glyphosate degraders [124]. Banning herbicides would require high-precision shallow tillage/mechanical weeding before seeding of the crops so as not to destroy the benefits of cover crops on soils again. Furthermore, mechanical weeding might mean more fuel use and GHG emissions.

In Greece and Spain, the tested cropping systems were vineyards, stone fruit, and olive orchards. In Crete (Greece), erosion reduction was the major challenge. Crete had historically high rainfall in October 2017 and some other heavy rainfall events afterwards. It was concluded that cover crops in vineyards and minimum tillage in olive orchards could reduce the erosion rates during extreme rainfall events and increase the earthworm density. The conversion of the traditional orange orchards to avocado cultivation resulted in a statistically significant reduction in erosion and increased SOC content and hydraulic conductivity [125]. Almería (southeast Spain), as the driest and hottest place in Europe, focused on water savings by deficit irrigation and erosion reduction with different soil cover or cultivation methods. The application of different combinations of irrigation led to water savings of up to 15%, but topsoil management did not cause significant differences in yield, fruit quality, or soil quality apart from an unexplained increase in the electrical conductivity when cover crops were used. [79].

3.1.2. Economic Impact (Profitability)

Table 2 indicates that the economic impact was positive for 4 out of 16 experiments, while it was negative for 6 and did not show change for the remaining 6. The average impact was −0.13, but the median impact was 0.01. Closer inspection of detailed data on costs and benefits (available for 15 SICS in Table S2) reveals that:

- For nine SICS, costs were higher than for the control; for five, they were lower; and for one, there was no change (defined as values between −25 and +25 EUR per ha). Hence, our hypothesis that SICS would reduce costs because of the lesser need for external inputs was not confirmed.
- For seven SICS, the benefits are higher than for the control; for two, there was no change compared with control; and for six, the benefits were lower.
- For seven SICS, the benefits minus the costs were higher than for the control; for seven, they were lower; and for one, there was no change.
- For 13 out of the 15 SICS for which detailed data were available, profitability was above 0.

This indicates that, at the field/farm level, short-term profitability was generally positive for the SICS (13 out of 15), but in half of the cases, it was lower for the SICS than for the control.

3.1.3. Sociocultural Impact

Table 2 indicates that for 3 out of 16 SICS, the sociocultural impact was positive; for 7, it was negative; and for 6, there was no change. The average impact was −0.04, and the median impact was −0.02. Analysis of data from 16 SICS showed (Table S3):

- Workload: Five SICS scored positive (required less work), six SICS scored negative (required more work), and for four SICS, there was no change.
- Perceived risk: 12 SICS were perceived to imply risks, and 3 were perceived to be riskless.
- Farmer reputation: Eight SICS scored positive (farmer implementing the SICS had a better reputation than farmer who did not), one scored negative (farmer had a worse reputation; the SICS in this case was the application of sewage sludge), and six registered no change.

This indicates that application of SICS had a positive impact on farmer reputation, as land users applying SICS were usually considered to be innovative. Workload did not show a clear trend, as for some SICS it was higher, while for others, it was lower. Many SICS are perceived to be associated with potential risks, most importantly the risk of crop failure and/or other economic risks (such as, e.g., high investment costs). The respondents often related the risk of crop failure to specific weather conditions such as prolonged dry spells or heavy rainfalls.

3.1.4. Main Results Upscaling SICS

Upscaling results included the potential for applying SICS across Europe as well as an assessment of the impact of SICS application under future uncertainty using the four developed scenarios (Figure 4). Figure 5 shows the SICS Potential Index for cover crops (for 2018) as an example result of the first type of upscaling activity. The figure shows that differences in climate, soil, and land use conditions resulted in differences in the applicability, relevance, and impact (on SOM, erosion, and yield) of cover crop use and hence the potential to apply them across Europe. Regarding the second type of upscaling activity, the results of the IAM indicated that over time (until 2050), in the different scenarios, different changes were expected in consumption, production and net exports, yield, gross margin, SOC, and erosion. This was due to, amongst other factors, growth in population, changes in diets, trade flows, climate change, technological changes, and changes in agricultural practices (i.e., through application of SICS). While some drivers were expected to result in impacts in the same direction in all scenarios (e.g., population growth was likely to lead to more consumption), other drivers could impact in very different ways. This was caused by regional differences such as, e.g., climate change impacting on yield levels and gross margins based on country-specific crop prices and location-specific biophysical conditions.

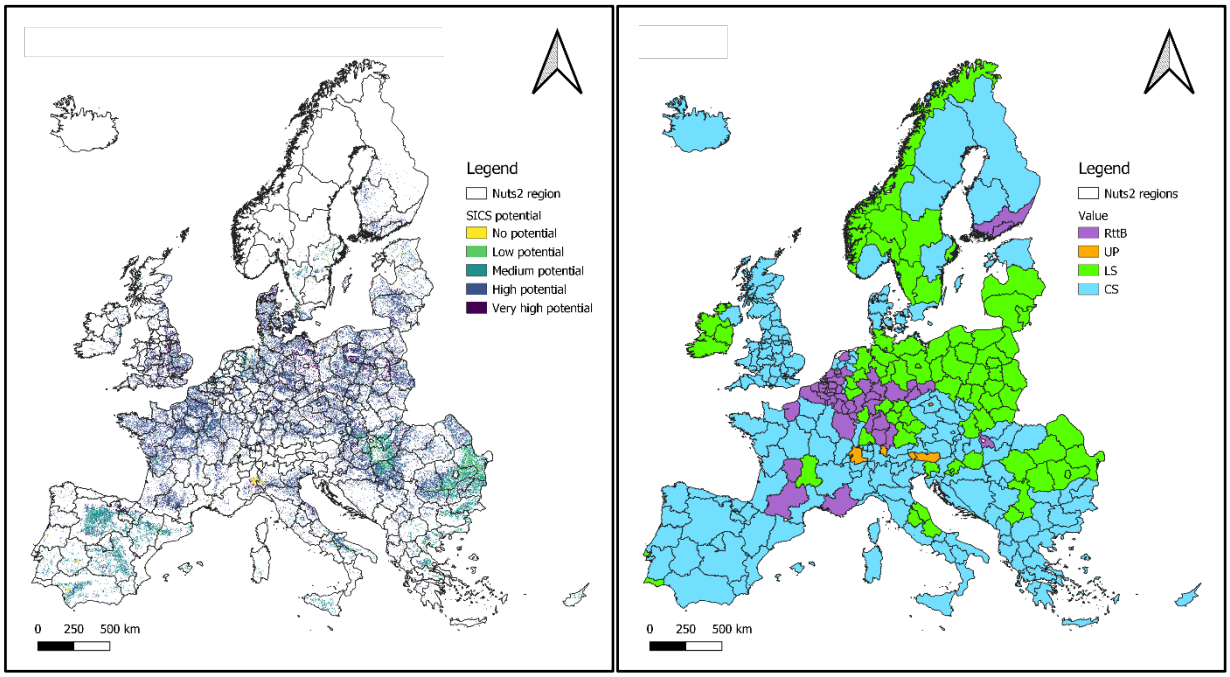

Figure 5. Examples of modelling results. Left: SICS potential index for cover crops (2018) [82]; right: scenarios leading to the highest yield increase in 2050 [81]. RttB = race to the bottom, UP = under pressure, LS = local and sustainable, CS = caring and sharing (see Figure 4).

As expected because of its formulation, the Caring and Sharing (CS) scenario, which assumed wide application of SICS (Figure 4), was likely to provide the best environmental impacts (i.e., increased, or stable SOC content and reduced erosion rates), and the Race to the Bottom scenario, assuming limited application, was likely to provide the worst.

An important finding, however, is that although the CS scenario in most regions led to highest yield impacts (Figure 5), the gross margin of SICS uptake under this scenario was negative in many NUTS-2 regions [81]. The most important factor contributing to this was the high implementation costs assumed when combinations of SICS were implemented. Despite sustainability being high on the agenda in the CS scenario, (financial) policy support would therefore likely be needed to enhance uptake of SICS. Alternatively, value added through additional products and services and valuation of environmental co-benefits could be a pathway to widespread SICS adoption.

The cost–benefit analysis showed a mixed spatial pattern of scenarios that had the highest gross margin across Europe. The reason for this was that the combination of drivers played out differently in different parts of Europe, indicating the complexity of the issue and the importance of understanding local dynamics. Using these scenarios for policy support also illustrated the importance of tailored/context-specific policy design/development, as selected options were often expected to have different performance under different scenarios.

3.2. Adoption of SICS

As illustrated in Table 3, there is a wide range of issues affecting adoption of sustainable soil management. Following this, country-specific issues stem from the fundamental E.U.-level factors listed below:

- **Sociocultural Factors:** A lack of awareness of soil in society and its framing as a resource to be exploited for humankind and economy engenders a disconnect between publics and impacts of agricultural production on soil. Further, mechanization creates distance between farmers and their fields and soil, making it difficult for farmers to see ecosystem changes. Some SoilCare stakeholders stressed ethical convictions

favouring ecological approaches to farming as an important force for change with respect to these issues.

- **Economic Factors:** The financially difficult transition period from conventional to organic or more sustainable soil management practices can prove too risky for many farmers to undertake, as yields can reduce during this period. Farmers therefore need funding to support them through this. Further, financial incentives from policy and public demand can motivate a change in practice. Global trade systems favouring monocultures also inhibit change, as power is accumulated in the retailers rather than the producers.
- **Institutional/Policy Factors:** Change via regulation was thought by SoilCare stakeholders to be both positive and negative. Possible inadvertent effects can be avoided by closely working with farmers. Currently, advisory services are seen as a tool for safeguarding business as usual and do not reflect scientific evidence for sustainable soil management. Regular training is needed for both farmers and advisers. Publics education and accessibility of sustainably produced food also needs prioritizing.

Table 3. Adoption factors in SoilCare study sites.

Sociocultural Factors	Economic Factors
Society's awareness and valuing of soil—Consumers need to better understand the impacts production methods have on soil for more informed purchasing decisions and increase willingness to pay prices reflecting costs of sustainable production *New generation of farmers open to change*—Habit made many farmers reluctant to change practices. However, there were also pioneers who want to try out new practices *Social factors*—Results reiterated the value of social learning from different peers and networks and the dynamics of trust and social acceptability it can engender [107]. Influencers and champions have a critical role to play in lending legitimacy to important sources of information	*High investment and/or implementation costs*—Change in practices involves high costs for, e.g., organic fertilizer, equipping machinery with the right tools, and purchase of new crops as well as additional seeds on top of main crop for cover crops *Holistic approaches and cobenefits to soil*—UK: changes in arable rotations due to weed and disease control have been mainstreamed and have coincidentally benefited the soil *Market pressures/demands*—BE: policy encourages farmers to plant cover crops and rotate crops, but because of the high demand, too many potatoes were grown; in addition, crop residues and organic materials have been used for biofuels and other bioproducts instead of being returned to the soil
Institutional/policy factors	**Knowledge and education**
Adverse effects of policy design—Policies were perceived to dictate practices that needed to be adopted regardless of feasibility/practicability, sometimes resulting in adverse behaviour, e.g., converting existing grassland to avoid the 'permanent grassland' status *Lack of coherence between legislation/conflicting objectives*—UK: targets and subsidies for increasing woodland areas for growing biofuel crops fail to specify that land must be suitable for these purposes; BE: because of the fragmentation in public services and departments, farmers often receive contradictory advice (Nitrates Directive versus CAP)	*Insufficient resources*—Advisory services need more resources for experimental and demonstration farms. Advice providers were often reliant on project funding, which has continuity problems *Adviser expertise and quality*—ES: quality of advice was heterogeneous, and advice was given on ad hoc basis; BE: physical and biological soil management was often neglected because of a focus on nutrients and fertilizers/manures; NO: quality of advice from NLR (independent membership organisation) is good; these people know a lot about soil and try to incorporate advice to enhance soil and environmental conditions when they can

4. Discussion and Conclusions

4.1. Evaluation of SICS

SoilCare provided scientific evidence on the potential of SICS at 16 study sites and Europe-wide. Although monitoring in study sites did not provide conclusive results in all

cases, it did show positive effects on most soil properties as well as a small positive impact on the environmental dimension. This was in line with the main results reported by meta-analyses such as those reviewed in [55]. No significant changes were observed for sustainability or for the economic dimension at the farm level. Nevertheless, most SICS were found to be profitable, since benefits were often higher than costs. However, in a small majority of cases, the profitability of the SICS was lower than for the control. The sociocultural dimension was slightly negative on average, mainly because SICS were perceived to be risky by farmers. The respondents often related the risk of crop failure to specific weather conditions, such as prolonged dry spells or heavy rainfalls. Indeed, it is known that some SICS are more sensitive to yearly variations than conventional practices, such as, for example, organic farming (e.g., [126–128]). On the other hand, weather conditions would in most cases also challenge the performance of the controls, but the risks associated with these practices were not assessed in our study. As described in Section 3.2, risks can also be higher during the transition period from conventional to more sustainable practices, although our economic data overall showed similar revenues for SICS and control. A final reason why SICS are perceived to be risky may have to do with uncertainty and risk aversion on the part of farmers, as switching from normal practices to SICS means a switch from familiar ways to something new. A repeated questionnaire after a few years of implementation of SICS might help to investigate whether risk perception of SICS changes over time.

It should be noted that our results were obtained at the plot/farm level and based on only 3 (max. 4 for some study sites) years of monitoring. This has several implications:

- Not all SICS may have reached their full potential within such a short period, and long-term monitoring is needed. In LTEs, several similar SICS proved to increase sustainability and crop yield when managed to optimize soil fertility [129]. Thus, LTEs provide useful information but cannot be used to directly compare with the exact SICS that were tested in SoilCare, as these SICS were selected within the project through interaction with stakeholders to cover specific local needs and preferences.
- Furthermore, specific conditions during the years of monitoring had an impact on the outcomes. For example, in 2018, droughts occurred at several study sites. Moreover, all the years had sometimes record-breaking high summer temperatures and less cold weather during the winter. Longer-term monitoring is needed to obtain reliable data on the effects of SICS.
- The economic analysis was conducted based on short-term SICS application, whereas the slow accrual of soil fertility enhancement and soil conservation effects are expected to lead to increasing yield impacts in the long term [130,131]. The short timeframe also carried, e.g., the risk that initial investments for implementation of SICS were given too much weight (though in our study we could not include equipment costs, which could be significant for some SICS) or the risk that workload was overestimated since farmers need time to find the most efficient ways for managing SICS. Furthermore, economic analysis should be based on the full rotation, which takes several years [132,133].
- Economic analysis should not be restricted to farm economics but should also consider other ecosystem services, both on-site (e.g., nutrient cycling, weed suppression, [134]) and off-site (e.g., sedimentation, [135]), to be able to assess societal costs and benefits of the application of SICS. Preference-based rather than cost-based valuation methods should be used to better capture this diverse set of impacts and offer credible policy support [136].
- As monitoring was conducted at the plot/farm scale, it did not study diversification. However, diversification could contribute to more sustainable agricultural production through, e.g., the reallocation of some farming resources/material, such as lands, equipment, and labour, to other fields; other social or natural services, including changes in productive goals; and switching to nonfarming activities at both spatial

and temporal scales [137]. In addition, diversification may alter soil chemical, physical, and/or biological properties, supporting large and sustainable production [138].

- Analysis of the social dimension was, by necessity, based on the views of farmers, and these might change over time as the farmers become more familiar with SICS. In addition, there may have been a bias in farmers participating in SoilCare experiments, as for the most part only farmers open to innovation took part in this work.

In addition, the assessment methodology for SICS that was applied may need further development and refinement. Both the assessment methodology and its application relied on expert opinion, not only with regard to the weights assigned to different parameters and to the environmental, economic, and sociocultural dimensions but with regard to the underlying concepts. For example, the economic dimension did not give very positive results for the SICS, which was at least partly due to the fact that more importance was attached to the relative difference between SICS and a control than to the difference between benefits and costs. As a result, SICS with a positive benefit/cost ratio scored negatively on the economic dimension because the control had a more positive benefit/cost ratio. This may actually reflect reality, as this meant that farmers would earn less by applying SICS, but the point here is to illustrate that assumptions made in the assessment methodology did have an impact on the outcome. Such assumptions are open to discussion and can be subject to revision as more data become available.

Furthermore, the outcome of the assessment was, of course, influenced by the input. Although this may seem trivial, it is not, as the input by necessity has to be a combination of different types of data (quantitative as well as qualitative) originating from different sources (including scientific experiments but also stakeholder perceptions), sometimes with gaps or limitations.

For all of these reasons, the results of the evaluation should not be seen as a final result, but rather as an indication that forms a starting point for discussion with stakeholders (from farmers to scientists and policy makers).

4.2. Adoption of SICS

SoilCare also delivered knowledge on how to promote the adoption of SICS to individual farmers, European institutions, member state authorities, and agricultural advisory services. The analyses carried out in SoilCare delivered increased insight into biophysical, economic, social, and political barriers to adoption, several of which corresponded to barriers already identified in [52] for conservation agriculture. SoilCare also provided solutions that could help to overcome such barriers. The results confirmed the crucial role of social factors such as trust in adoption and underlined the need for policies that support and enable a transition to more sustainable agricultural practices in a coherent way.

Historically, soil has been an overlooked component in studies on ecosystem service and policy decision making [139]. At a policy level, the removal of the proposed Soil Framework Directive (COM (2006) 232 final) in 2014 highlighted a need and an opportunity to think about soils differently [140]. The SoilCare project represents a short timeline when set against its objectives; however, it is also noteworthy that the role of soils transitioned to being at the heart of high-level ambitious European policies such as the European Green Deal and the CAP Farm-to-Fork and Biodiversity Strategies during the project lifetime. This was complemented by a focus on soil research and innovation in the European Joint Programme on soil and a mission in the area of soil health and food. E.U. policies to target soil and environmental objectives have been criticized for their lack of nuance to account for localized conditions in the past. In this regard, the SoilCare project has framed a methodology for SICS that reflects the key dimensions that must be considered in governance for local but also wider-scale dynamics. Although more work is required, the lessons learned, particularly in relation to those SICS that exhibited promise, should be further explored and leveraged under the new opportunities that now exist

within the policy, research, and innovation space. Table 4 provides an overview of policy recommendations resulting from SoilCare.

Table 4. Policy recommendations resulting from SoilCare, after [141].

Recommendation I: Define long-term ambitions and targets • Develop horizontal, holistic, long-term strategies for sustainable agriculture • Raise and clearly define the level of ambitions in existing policies • Define binding soil targets and promote sustainable practices through either dedicated soil policies or mainstreaming of soil objectives in existing and new environmental/sectoral policy instruments
Recommendation II: Increase coherence and exploit synergies between policies more effectively There are many different pieces of legislation that can work better together if coherence and integration between them is improved. In addition, stakeholders noted that some SICS might not align with existing policy objectives. At the E.U. and country levels, policy conflicts and synergies need to be carefully analysed and aligned to avoid discouraging a transition to sustainable farming.
Recommendation III: Design targeted economic instruments that facilitate a transition to sustainable practices and reward environmental benefits delivered The CAP should strive to be less prescriptive and avoid one-size-fits-all approaches, instead providing farmers with a general direction clearly defined by targets and empowering them to take steps towards these targets. There is a need to consider the different conditions in which farmers operate (e.g., differences in tenure), and measures need to be flexible enough to allow for regional differences. Priority should be given to farming techniques that are also means of food production and are both profitable and sustainable.
Recommendation IV: Strengthen existing and establish new opportunities for learning and knowledge exchange for farmers Strengthen capacity of Farm Advisory Services: These are valuable sources of information for farmers, but their independence and neutrality should be ensured. Advisers need to learn about new practices, their practical application and costs, and benefits to support farmers. Ref. [142] gave suggestions for achieving more effective advisory services. Inform farmers about new developments and insights: Dissemination of knowledge, awareness raising, and education are important components of policy interventions, and they should be used in parallel with economic and legislative instruments [143].
Recommendation V: Strengthen monitoring and enforcement At the E.U. level, there is a need to establish a clear, robust, and reliable monitoring and enforcement system for the CAP. At the country level, stronger monitoring and enforcement systems require the training of farm inspectors, who, like farmers, need to understand regulatory requirements and their practical implementation.

4.3. Sustainability and Profitability

Results obtained at the farm level indicated a small decrease in profitability and a small positive effect on the environmental dimension (Table 2). As discussed above, however, there is a need to consider larger temporal and spatial scales. This was done in the modelling approach, which was used to upscale results from the different study sites and integrate these results with factors operating at the European scale, such as policy development, macroeconomy, societal developments, and climate change. Several scenarios of possible developments with a time horizon of 2050 were simulated. Simulations showed that scenarios in which sustainability was given priority resulted in better soil quality and better environmental conditions. However, while SICS would be profitable to society in the long term, they may not always be profitable to farmers in the short term. As short-term benefit over conventional practice is a key point for farmers [63], and as modelling suggested that SICS outperformed control treatments in the longer term, some form of compensation and support to farmers would be required to stimulate adoption of SICS, for example, in the form of bridge payments.

4.4. Conclusions

The need for sustainable soil management is evident from the literature. Soils are critical for economic and environmental well-being because they provide a range of ecosystem services and form the basis for agricultural production. They are at the intersection of a broad range of agricultural and land use challenges. Soil management should aim at improving the quality and resilience of land and soil. Within the SoilCare project, the concept of soil-improving cropping systems (SICS) was developed and applied. SICS can play an important role in the transition towards more sustainable agricultural production that can also be profitable. In practice, the effectiveness of SICS is difficult to demonstrate within the lifespan of a single project, as results vary from year to year because of different conditions, such as different weather and price fluctuations of inputs and crops. Furthermore, many SICS are expected to reach their full potential only after a long time. SoilCare paved the way for further research on SICS by developing an assessment methodology for SICS, a database for SICS data, and a modelling approach for upscaling and scenario evaluation. In addition, SoilCare contributed to the understanding of adoption factors and provided a first assessment of a range of SICS. Whilst our work on adoption confirmed the role economic considerations play in the uptake of SICS, it also highlighted the influence of social factors, such as trust, and of knowledge. This underlines the need for policies that support and enable a transition to more sustainable agricultural practices in a coherent way.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land11060780/s1, Table S1: Results of environmental dimension, Table S2: Results of economic dimension, Table S3: Results of sociocultural dimension.

Author Contributions: Conceptualization: R.H., O.O., M.S.R., A.A., G.W., H.v.D., M.M., J.M., E.v.d.E., S.V. and F.A. (Falentijn Assinck); methodology: R.H., M.S.R., A.A., G.W., H.v.D., M.M., J.M., I.S.P., E.v.d.E., S.V., F.A. (Francisco Areal) and J.S.; software: I.S.P. and H.v.D.; validation: H.v.D., A.A., A.E., J.L., A.K., M.A.B., E.K., Z.T., M.H. (Moritz Hallama) and J.S.; investigation: A.A., A.E., J.L., A.K., M.A.B., E.K., Z.T., M.H. (Moritz Hallama), J.C., I.P., T.D. and J.S.; data curation: S.V., E.v.d.E., G.W., I.S.P. and H.v.D.; writing—original draft preparation: R.H., O.O., M.S.R., A.A., G.W., H.v.D., M.M., J.M. and J.E.B.; writing—review and editing: F.A. (Francisco Areal), M.H. (Marius Heinen), I.S.P., A.E., M.A.B., E.K., M.H. (Moritz Hallama), J.C., L.O., L.F., L.M., J.E.M.B. and J.S.; visualization: R.H., H.v.D., J.M. and C.-A.C. All authors have read and agreed to the published version of the manuscript.

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