land

MDPI

Article

A New Framework to Assess Sustainability of Soil Improving Cropping Systems in Europe

Abdallah Alaoui [1,*], Moritz Hallama [2], Roger Bär [3], Ioanna Panagea [4], Felicitas Bachmann [3], Carola Pekrun [5], Luuk Fleskens [6], Ellen Kandeler [2] and Rudi Hessel [7]

[1] Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland
[2] Soil Biology Department, Institute of Soil Science and Land Evaluation, University of Hohenheim, Emil-Wolff-Str. 27, 70599 Stuttgart, Germany; moritz.hallama@uni-hohenheim.de (M.H.); ellen.kandeler@uni-hohenheim.de (E.K.)
[3] Centre for Development and Environment (CDE), University of Bern, Mittelstrasse 43, 3012 Bern, Switzerland; roger.baer@unibe.ch (R.B.); felicitas.bachmann@unibe.ch (F.B.)
[4] Department of Earth and Environmental Sciences, KU Leuven, 3001 Leuven, Belgium; ioanna.panagea@kuleuven.be
[5] Agronomy Section, Institute of Applied Agriculture, Nuertingen-Geislingen University, Neckarsteige 6-10, 72622 Nürtingen, Germany; carola.pekrun@hfwu.de
[6] Soil Physics and Land Management Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands; luuk.fleskens@wur.nl
[7] Wageningen Environmental Research, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands; rudi.hessel@wur.nl
* Correspondence: abdallah.alaoui@giub.unibe.ch; Tel.: +41-31-684-89-22

Citation: Alaoui, A.; Hallama, M.; Bär, R.; Panagea, I.; Bachmann, F.; Pekrun, C.; Fleskens, L.; Kandeler, E.; Hessel, R. A New Framework to Assess Sustainability of Soil Improving Cropping Systems in Europe. *Land* **2022**, *11*, 729. https://doi.org/10.3390/land11050729

Academic Editor: Evan Kane

Received: 14 April 2022
Accepted: 10 May 2022
Published: 12 May 2022

Abstract: Assessing agricultural sustainability is one of the most challenging tasks related to expertise and support methodologies because it entails multidisciplinary aspects and builds on cultural and value-based elements. Thus, agricultural sustainability should be considered a social concept, reliable enough to support decision makers and policy development in a broad context. The aim of this manuscript was to develop a methodology for the assessment of the sustainability of soil improving cropping systems (*SICS*) in Europe. For this purpose, a decision tree based on weights (%) was chosen because it allows more flexibility. The methodology was tested with data from the SoilCare Horizon 2020 study site in Germany for the assessment of the impact of the integration of cover crops into the crop rotation. The effect on the environmental indicators was slightly positive, but most assessed properties did not change over the short course of the experiment. Farmers reported that the increase in workload was outweighed by a reputation gain for using cover crops. The incorporation of cover crops reduced slightly the profitability, due to the costs for seeds and establishment of cover crops. The proposed assessment methodology provides a comprehensive summary to assess the agricultural sustainability of *SICS*.

Keywords: sustainability framework; overall sustainability; costs and benefits; cover crops

1. Introduction

Assessing agricultural sustainability is one of the most complex exercises related to appraisal methodologies because it entails not only multidisciplinary aspects (environmental, economic and social dimensions), but also builds on cultural and value-based elements [1]. Thus, agricultural sustainability should be considered as a social concept that can be modified in response to the requirements of society as a whole and the individuals constituting this society [2,3].

According to the current definitions policy-oriented sustainability assessment is a methodology that can help decision- and policymakers decide what actions they should or should not take to make society more sustainable [4]. For this purpose, sustainability assessment practitioners have developed a large number of tools [5]. Finding the appropriate assessment instrument is critical to match theory with practice, and to have successful outcomes in improving sustainability. More specifically, although many methods exist for monitoring and evaluating the environmental dimension of agricultural management practices, no single method has been widely accepted for assessing it, perhaps due to the complexity and variability of agricultural systems [6]. Though the meanings and uses of the term sustainability remain diverse, it is now widely accepted that sustainability is the path to balancing social, economic, and environmental needs [7–9].

There is broad scientific agreement on the fact that sustainable agriculture is defined as the management and the use of the agricultural ecosystem in a way that allows reaching economic (e.g., income growth or economic stability), social (e.g., equity or the cover of basic needs), and ecological objectives (e.g., ecosystem protection or natural resources regeneration) [7,10]. These objectives need to be continuously evaluated with scientific criteria, acknowledging uncertainty and safety margins.

Many frameworks with various combinations of indicator sets aimed at describing farming and cropping systems exist, from simple ones to complex multi-dimensional assessment tools [11–13]. The choice of the indicators depends on the objective of the study. In many studies, indicators are chosen to characterise the sustainability of the system or the intensity of management and practices (i.e., land-use intensity) [14–16]. However, the collection of the data needed to implement such frameworks is tedious and time consuming, and thus simple and reliable indicators, based on data that are reasonably easy to obtain, are required [5].

A review study related to sustainable agriculture revealed that the social dimension is the most difficult to assess in a quantifiable way when compared to the environmental and economic dimensions due to its inherently more subjective nature [17,18]. Research looking into the social sustainability of farming systems deals with issues and indicators related to (subjective) well-being and quality of life of the farming population, working conditions (workload, working time), gender equality, on-farm and off-farm incomes, access to services (education, advisory services), social relations (family, community), social security, finding work meaningful, life satisfaction, physical and mental health, etc. [18–20]. Hence, socio-cultural acceptability is a prerequisite for the adoption of new agricultural practices.

In their review paper, Alaoui et al. [5] selected frameworks based on the following criteria: (1) are validated through a peer-review process, (2) consider a farm-level assessment, (3) cover universal agricultural sectors including livestock and arable farms, (4) include the three dimensions of sustainability, and (5) are suitable both for Europe and countries worldwide. Based on the selected criteria, the following frameworks were identified: RISE (Response-Inducing Sustainability Evaluation [21]), MASC (Multi-attribute Assessment of Sustainability of Cropping Systems [22]), LADA (Land Degradation Assessment in Drylands [3]), SMART (Sustainability Monitoring and Assessment RouTine, [23]), SAFA (Sustainability Assessment of Food and Agriculture systems [24]) and PG (Public Goods [25]).

The EU Horizon 2020 project SoilCare, aimed "to assess the potential of soil-improving cropping systems (*SICS*), to identify and test these *SICS* to determine their impacts on profitability and sustainability in Europe". This required an assessment framework based on an evaluation of environmental, sociocultural, and economic dimensions of crop production. The methodology needed to allow flexibility; it needed to be applicable to all study sites (SS) across Europe to allow comparison and upscaling and at the same time to be flexible enough to consider site-specific circumstances.

Taking into account the above considerations, none of the reviewed frameworks was suitable for SoilCare because they did not include the indicators needed to evaluate *SICS* and/or did not provide results to evaluate the key terms of SoilCare (such as sustainability, profitability, soil quality) in combination.

The main aim of this research was to develop a comprehensive methodology for assessing the overall sustainability of the farm with special attention to the benefits, drawbacks, profitability, and soil quality of the *SICS* as compared to the *control*-conventional system. To set up a tool for the assessment of the overall sustainability, we chose a decision tree based on weights (%). This is because it allows simple aggregation to assess the three dimensions of sustainability and provides flexibility [22].

In this manuscript, we provide the general concept of the assessment tool developed to calculate sustainability of the *SICS* under consideration. We provide information on the indicators, their weighting factors, their threshold values, and their scores. An application with data from the German SoilCare study site is provided to explain how the tool is used for conservation agricultural techniques and serves as a first critical evaluation to document lessons learned. In this study, we assess the sustainability of the farm/field where the *SICS* is implemented.

2. Materials and Methods

2.1. Assessment Tool

For the evaluation of the overall sustainability of a farm and to facilitate the assessment of the performance of cropping systems three dimensions of sustainability were considered, i.e., environmental, sociocultural and economic. A decision tree was chosen for the aggregation. It breaks the sustainability assessment decisional issue down into simpler units that comprise quantitative as well as qualitative elementary criteria to rate cropping systems. Such aggregation is needed as the data for the three dimensions include various kinds of quantitative and qualitative data, obtained in different ways, including monitoring and questionnaires [22].

Within the decision tree, weights (%) were assigned to adjust the relative importance of the different indicators used within the three dimensions of sustainability. These weighting factor values were established from expert knowledge based on the literature review and can be modified to fit specific conditions and decision makers [5].

In the SoilCare project, the study sites selected to test the sustainability impact of *SICS* were grouped into 4 key topics to improve sustainability, namely, compaction, soil-improving crops, fertilization/amendments, and soil cultivation. The experiments implemented in the SoilCare project were short-term since the project was a 5-year project. To assess the sustainability of a given farm using the tool developed here, input data is needed. The tool calculates sustainability by assigning a higher score to the key topic considered in comparison to the others. This was the reason why we developed a new tool for the assessment of sustainability.

For the assessment of the sustainability of a farm or a field, we have selected plots with the *SICS* and plots without (*controls*) that best characterise the farm or field under consideration. The assessment was carried out by comparing the *SICS* plot with the *control* plot. Figure 1 provides an overview of the three dimensions considered and the related properties. For future use, the users can adapt the weighing to their specific case. This flexibility would help improve the assessment tool for various purposes.

2.1.1. Environmental Dimension

- Monitoring variables

To assess the sustainability of a farm, in situ measurements of the variables were carried out. For this purpose, a monitoring plan was established to harmonize the monitoring including instructions on the treatment replication, randomization, and sampling in which each experiment within a field/location is composed of 3 blocks (corresponding to 3 replicates). Each block contains two experimental units or plots where sampling is carried out for composite or undisturbed samples [26].

- Selection of the indicators and weights

Based on a literature review [5] and considering the *SICS*-related key topics in the SoilCare project, a list of variables for the evaluation of the environmental dimension of the implemented systems was established. Each key topic is defined by a set of indicators with high weight, e.g., soil compaction is assessed by bulk density and penetration resistance with a value of 0.20, and by infiltration capacity and aggregate stability with weight values of 0.15 and 0.10, respectively (refer to the grey boxes in Table 1).

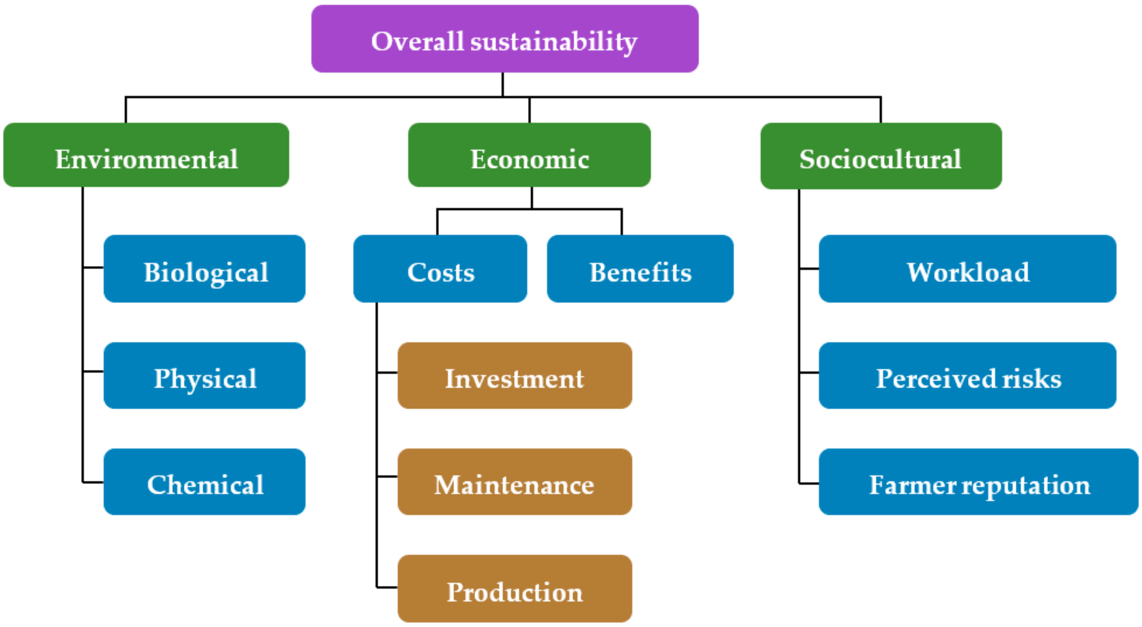

Figure 1. Structure of the aggregation of sustainability dimensions and assessment units.

Table 1. Weighing factors attributed to variables as related to the four key topics (soil cultivation, soil fertilization, soil-improving crops, and soil compaction).

Variable	Weight			
	Soil Cultivation	**Fertilisation**	**Soil Improving Crops**	**Compaction**
Infiltration capacity	0.05	0.01	0.05	0.15
Aggregate Stability	0	0.01	0.05	0.10
Bulk Density	0.08	0.01	0.05	0.20
Penetration Resistance	0	0	0	0.20
Mineral Nitrogen	0.05	0.22	0.05	0.05
SOC	0.05	0.30	0.05	0.05
pH	0.02	0.05	0.05	0.05
Earthworm Density	0.05	0.05	0.05	0.05
Crop Yield	0.20	0.05	0.10	0.05
Yield Quality	0.10	0.10	0.10	0.05
Crop Cover Characteristics	0.25	0.05	0.10	0.05
Pests	0.05	0.05	0.20	0
Root Diseases	0.05	0.05	0.10	0
Weed	0.05	0.05	0.05	0

The selection of variables and their assigned weights was based on the literature review [5] and is presented in Table 1. For more explanation, refer to File S1.

The assessment tool was designed to assess the change in the environmental dimension resulting from the implementation of the *SICS* compared to the *control* cropping system. Prior to inputting data into the assessment tool, the quantitative change of each variable as measured/estimated in the field is transformed into a qualitative score: positive change, no change, or negative change. For more details, refer to the "Metadata sheet" in File S1 using a statistically based approach.

In this tool, an additional option suggests the appropriate methods to be used for the evaluation of the variables listed in Table 1. The aim was to harmonize the methods across all study sites (refer to File S1, input datasheet). Based on the type of method used, the accuracy of the evaluation is evaluated.

- Statistical analysis

To quantify the difference between the variables of soil with the *SICS* and the ones of the *control*, a statistical approach was used. Mixed-effects models were used to estimate if statistically significant differences exist between the *SICS* and related *control* treatments. Mixed effect models were chosen as they allow a larger variety of designs and implementations [27] enabling a better identification and interpretation of interactions and repeated measurements. The statistical data analysis was performed using-R-Studio, R version 3.6.1 [28]. Differences between treatments or dates were analyzed using the full factorial statement "Treatment x Date", or the factor "Treatment" for variables with repeated measurements and only once measured variables, respectively. The experimental design structure effect (block, whole plot, main-plot, etc.) was introduced in all models as a random effect, using the statement "1 | structure" (in the German case study this was 1 | Block). The model's optimum fixed structure was selected for the best fit attaining the lowest value of Akaike's Information Criterion (AIC) using a maximum likelihood function (ML). A visual inspection was performed of the residuals' Q-Q plots and the normalised residuals' plots against the fitted values. The final models were fitted using REML estimation. Estimated marginal means by factors were computed by the least square method and contrasted by the Tukey group comparison method ($p < 0.05$).

The comparison between the variables of *SICS* and the ones of the *control* used for scoring the impact of *SICS* was scored by attributing a value of "1" for the statistically significant positive change (PC) (*SICS* is better than the *control*), "0" for no statistically significant change (NoC) and "−1" for statistically significant negative change (NC) (*control* is better than *SICS*).

2.1.2. Sociocultural Dimension

In contrast to the environmental indicators, most factors that determine the sociocultural acceptability of a *SICS* cannot be easily measured or quantified, which is due to their inherently subjective nature. Therefore, a qualitative approach was applied, and a short questionnaire (summarized in Table 2) was used to grasp the land users' assessment of the tested *SICS* in terms of three key topics: changes in workload, perceived risks, and influence on farmers' reputation.

Three requirements for *SICS* to be socially/culturally acceptable were identified on the basis of a literature review.

- Requirement 1 (Workload): *SICS* should not result in a considerable increase in workload, especially in periods where labour demand is already high.

In agriculture, working hours are generally long, considerably longer than in other professions. Therefore, it is not surprising that farmers are sensitive to an increase in workload, especially when it occurs during periods in which labour input is already high, e.g., in spring (field preparation and sowing) or summer respective autumn (harvesting) [29]. Additionally, an increase in workload not only means long working days, but also leads to higher production costs [29,30].

- Requirement 2 (Risk): In the perception of farmers, a *SICS* should not be a (too) risky practice.

A survey from north-eastern Germany showed that associated risks are among the main drivers when decisions are made to adopt new conservation measures [29]. Trujillo-Barrera et al. [31] concluded from their in-depth interviews with Dutch hog farmers that perceived risk is a barrier to the adoption of sustainable production practices.

- Requirement 3 (Reputation): Applying a *SICS* should not impair the farmer's reputation.

Much evidence exists [29,32–34], that farmers base their decision to adopt or reject conservation practices not exclusively on economic, agronomic, and ecological grounds. To be adopted, practices need to be compatible with land owners' values, and perceptions as to what makes a good farmer, or an aesthetic agricultural landscape (e.g., keeping fields nice and tidy).

Within each requirement, different questions were asked. The possible combinations of the responses and their output scores are reported in the "Metadata sheet" of File S1.

To calculate the final score of the sociocultural dimension, a specific weight was attributed to each requirement listed above (Table 2).

Table 2. Variables considered in the sociocultural dimension based on a questionnaire completed by the land user and their weighing factors.

Topic	Weight	Variable	Range of Answers
1. Workload	0.4	1.1. Increase/decrease in workload	Strongly increased, slightly increased, remained the same, slightly decreased, strongly decreased
		1.2. Workload increase during already existing work peaks	Yes/no
2. Perceived risks	0.4	2.1. Health risk 2.2. Economic risk 2.3. Risk of crop failure 2.4. Risk of conflicts 2.5. Other risk	Yes/no Yes/no Yes/no Yes/no Yes/no
3. Farmer's reputation	0.2	3.1. The (positive/negative) effect *SICS* application has on the reputation of the farmer	Strongly improved, slightly improved, remained the same, slightly worsened, strongly worsened

Given the fact that the two topics of risk perception and workload increase are both crucial for the adoption or rejection of new farming practices, they both have double weight compared to the topic of farmer reputation. In addition, the effect on a farmer's reputation is much more difficult to grasp and verify. Therefore, it was deemed appropriate to give this topic less weight in the assessment.

Study site researchers conducted the interviews at the end of the growing season with those farmers involved in the *SICS* trials. The questionnaire was kept as simple as possible, in order to avoid any limitations related to the implementation of the questionnaire, such as an adequately trained audit team, long duration for the training and implementation.

2.1.3. Assessment of the Economic Dimension

The economic dimension was assessed by evaluating the costs and benefits of the farm using a spreadsheet formatted questionnaire to ensure ease of use. This questionnaire, adapted from [35], contained the different types of costs, such as investment costs, maintenance costs, production costs, and benefits related to both the *control* and the *SICS* fields. Details on costs and benefits should refer to the same area/unit that can be defined in the Overview worksheet (refer to File S2 for more details). A summary of the costs and benefits is directly calculated and provided at the end of the questionnaire to allow the comparison between the *control* and the *SICS*. The details of each cost category are described below.

Investment costs: The assessor should list all one-off investment costs, structured according to the activities and inventorying labour, agricultural inputs, construction material, wood, earth, and other costs.

An activity refers to a defined task needed to establish the *SICS* and may consist of multiple inputs:

- Labour costs indicate total person days, either paid or voluntary.
- Equipment includes tools, machine hours, etc. Cost calculation for machine hours should be based on hiring costs–even if the machinery is owned by the land user.

- Agricultural inputs include seeds, seedling, fertilizer, biocides, compost/manure, etc. and indicate costs and quantities needed.
- Construction material includes stones, wood, earth, sand, etc. and indicate costs and quantities needed.

Maintenance costs: List of maintenance/recurrent activities and their associated costs for the *SICS* and the *control* cropping. It contains the same cost categories as listed for the investment costs above.

Production costs: List of changes pertaining to activities or inputs related to activities that have changed as a consequence of introducing a *SICS* (or a crop). Recurrent costs related to the technology itself should be recorded under maintenance costs.

Benefits: The benefits are considered at the farm level and consequently are defined as "on-site benefits". They can include: (i) Products harvested (cash and food crops, timber, fuelwood, fruits and nuts, animal fodder, etc.), (ii) Grazing/browsing, (iii) Recreation/tourism, (iv) Subsidies (e.g., for agri-environmental measures), and (v) Protection against natural hazards.

Calculation: The cost–benefit score represents the difference between the weighted (see below) relative change in benefits and in costs. A positive score means an improved cost–benefit ratio, a negative score means an impaired cost–benefit ratio. The score was calculated as follows:

$$Cost\ –Benefit\ score = \left(\Delta \mathrm{RC}_{benefits} \times Benefit\ weight\right) - (\Delta \mathrm{RC}_{costs} \times Cost\ weight) \quad (1)$$

With $\Delta \mathrm{RC}_{benefits}$ = Relative change in benefits, calculated as follows:

$$\Delta \mathrm{RC}_{benefits} = \frac{\sum Costs_{SICS}}{\sum Costs_{Control}} \quad (2)$$

$\Delta \mathrm{RC}_{costs}$ = Relative change in costs, calculated as follows:

$$\Delta \mathrm{RC}_{Costs} = \frac{\sum Benefits_{SICS}}{\sum Benefits_{Control}} \quad (3)$$

The type of costs for both *SICS* and *Control* are: Investment costs + Maintenance costs + production costs.

The benefits of both *SICS* and *Control* include all benefits listed in File S2 and are calculated as follows: Products harvested (cash and food crops, timber, fuelwood, fruits and nuts, animal fodder, etc., +Grazing/browsing + Recreation/tourism + Subsidies (e.g., for agri-environmental measures) + Protection against natural hazards.

In both cases (i.e., change in benefits and change in costs) the relative change has been capped to +/−100%. At the cost end, the positive extreme is theoretically solid as it means that costs involved with the *control* system can be reduced to 0 and that 0 means a perfect (+1) score. A doubling of the cost (and anything above) is regarded as the most negative outcome (−1). At the benefit side, a score of −1 is attributed to any decrease.

The *Benefit weight* and *Cost weight* account for the amplitude of changes in benefits and cost. The *Benefit weight* represents the ratio between the absolute difference in benefits as compared to the absolute difference in costs. The *Cost weight* is the counterpart of the *Benefit weight* and represents the ratio between the absolute difference in costs as compared to the absolute difference in benefits. The weights are calculated as follows:

$$Benefit\ weight = \frac{|Benefit_{SICS} - Benefit_{Control}|}{|Costs_{SICS} - Costs_{Control}| + |Benefit_{SICS} - Benefit_{Control}|} \quad (4)$$

$$Cost\ weight = 1 - Benefit\ weight \quad (5)$$

This allows us to appropriately consider cases with minimal absolute changes at the cost side but large changes at the benefit side, or vice versa. For instance, the doubling of cost from EUR 10 to EUR 20 will have double the weight (0.66) compared to a doubling of benefits from EUR 5 to EUR 10 (0.33).

2.2. The Case Study

In the SoilCare project, panel meetings including scientists, farmers and other stakeholders identified a number of threats to soil quality and fertility and proposed management techniques for the mitigation of these threats [36]. At the study site in Germany, the stakeholder panel suggested focusing on conservation agriculture and to investigate, among other techniques, specifically cover crop management. Therefore, a field experiment was set up at a research farm in Tachenhausen, Germany (48.649800° N, 9.387500° E, 330 m a.s.l.). In the present study, the assessment methodology was applied to the comparison between cover cropping and bare fallow treatments.

The soil is heavy, and loess derived, with a very fine sandy loam texture. The soil profile is characterized as Cambisol (IUSS Working Group WRB, 2015) with four horizons and with a ploughing pan at 40 cm. The climate is temperate with a mean annual temperature of 8.8 °C and 809.3 mm precipitation (monitoring weather station Tachenhausen HfWU, 150 m from the site, 1961–1990). The field has a history of conventional agriculture, with a crop rotation consisting mainly of cereals and sugar beet and winter oilseed rape as alternate break crops. The crop rotation for the experiment was spring barley (2018)–cover crop mixture/bare fallow–silage maize (2019)–spring barley (2020). The main crop for the 2019 cropping season was Zea mays (var. Figaro) sown on 6 May 2019 with 10 plants m−2 and harvested on 17 September 2019.

The experimental layout was a randomized complete block design with eightreplicates with plots of 2.4 × 3 m. The treatments included bare fallow and cover cropped plots. Originally, the field experiment was set up as a full factorial experiment, including also two herbicide treatments. However, as no significant interaction between the cover crop and herbicide treatments could be detected, the measurements could be averaged over the two cover crop treatments. For establishment of the field experiment, a commercial cover crop mixture consisting of 55% Vicia sativa, 20% Trifolium alexandrinum, 16% Phacelia tanacetifolia and 9% Helianthus annus was sown at 25 kg ha^{-1} in rows of 20 cm in the beginning of August. The field was tilled with a rotary harrow in a depth of 10 cm shortly before sowing the cover crops in a regime of non-inversion tillage. Mineral fertilizer was applied in 2018 at the rates of 90 kg ha^{-1} N, 17.5 kg ha^{-1} P, 53.1 kg ha^{-1} K, 8.1 kg ha^{-1} Mg and 20 kg ha^{-1} S. The maize in 2019 was not given any fertilizer. The following spring barley received mineral N-fertilizer at a rate of 89 kg ha^{-1} on 17 April 2020. Herbicides were applied as necessary.

The sampling and measurement of the indicators of the assessment methodology was carried out in spring after the cover crop in 2018–2019 following a monitoring plan with standardized methods for biological, physical and chemical properties of soils [26]. In the case study of Germany, the economic assessment was made possible by taking the values from publicly available tables of agricultural economics. For the calculation of the cost–benefit analysis, a sequence similar to the field experiment consisting of cereal-cover crop-silage-maize-cereal was used, but with winter wheat instead of spring barley. The sociocultural dimension was assessed by conducting semi-structured interviews based on the abovementioned questionnaires with five different farmers and a consultant of the public extension service of the region.

3. Results

3.1. Environmental Dimension

The assessment methodology was applied at the study site in Germany to compare the *SICS* integrating cover crops with the *control* treatment with bare fallow over winter. The environmental performance of the *SICS*, measured as the response of selected soil quality indicators, showed mixed results. Some indicators improved with cover crops (i.e., bulk density and soil cover) or showed a positive trend (number of earthworms) (Table 3). On the contrary, water-stable aggregates and infiltration were higher in the fallow plots, while weeds, tended to be lower than in the cover crop treatments. Mineral nitrogen tended to be lower under cover crops. Most of the other soil quality indicators showed no variation. This slight improvement indicates the positive effect of certain cover crop species on soil quality, especially on soil structure expressed by the reduced bulk density/increase in total porosity [37]. The resulting figures are presented in Supplementary Material File S3, the error bars represent the SE of the model.

Table 3. Impact of cover crops on the variables at least two years after the implementation.

Indicators	Impact of *SICS*	Score	Weight In *SICS*
Infiltration	No change	0	0.05
Aggregate stability	Negative change	−1	0.05
Bulk density	Positive change	+1	0.05
Penetration resistance	No data	0	0.00
Mineral nitrogen	No change	0	0.05
SOC	No change	0	0.05
pH	No change	0	0.05
Earthworm density	No change	0	0.05
Crop yield	No change	0	0.10
Yield quality	No change	0	0.10
Crop cover characteristics	Positive change	+1	0.10
Pests	No data	0	0.20
Root diseases	No data	0	0.10
Weed diseases	No change	0	0.05

Concerning the key topic addressed here, namely soil improving crops, there was a slight increase with an impact index of 0.10 (Table 4).

Table 4. Outcomes of the assessment of the environmental dimension with regard to the key topics.

Properties	Impact Index
Soil cultivation	0.33
Fertilisation	0.05
Soil improving crops	0.10
Compaction	0.15
Environmental dimension	0.18

3.2. Economic Dimension

In order to assess the economic dimension, the benefits of *SICS* were calculated in relation to the costs for the crop sequence of three years. Since the cereal straw was left on the field, the benefit is based on the pure grain yields, respective silage maize yield multiplied by the average market price in the respective year.

When comparing the benefits with the costs for both *control* and *SICS*, there is a loss in both cases (File S2), but less loss for the *control* than for the *SICS*.

The benefit of the *SICS* is higher than that of the *control* (Table 5). The cause of the loss is due to the higher costs for cover crop seeds and sowing that outweigh the slight increase in benefits (yield).

Table 5. Impact index of the economic dimension of *SICS* as compared to *control* considered in the CSS of Germany.

Cropping System	Impact Index
Cost	0.09
Benefits	0.06
Economic dimension	−0.03

3.3. Sociocultural Dimension

The assessment of the sociocultural dimension shows slight positive impact due to the improvement of farmer reputation, although the moderate increase in the workload due to the short time window left after harvest to perform sowing reduces the perceived overall benefit for the farmers (Table 6). The problem with the workload at harvest time could be mitigated by using the technique of harvest–sowing, but this is only possible in some combinations of main and cover crop.

Table 6. Assessment of the changes of the sociocultural dimension with cover crops as soil improving cropping system. The Impact index was calculated using the responses of practitioners in structured interviews at the study region in Germany.

Sociocultural Data	Impact Index
Workload	−0.33
Perceived risks	0.00
Farmer reputation	1.00
Sociocultural dimension	0.07

3.4. Overall Sustainability

The field study in Germany provides an example of the application of the tool (Table 7). In this case, the environmental and the sociocultural dimension improved slightly under cover cropping (*SICS*) compared to bare fallow (*control*). The economic dimension showed a negative scoring, because of a slight increase in costs. Further assessment in the coming years is necessary to confirm these results.

Table 7. Synthesis of the impact of applied *SICS*.

	Impact of Applied SICS
Sociocultural dimension	0.07
Economic dimension	−0.03
Environmental dimension	0.18
Overall sustainability	0.08

4. Discussion and Recommendations

4.1. Outcomes of the CSS of Germany

In order to evaluate the applicability of the assessment tool, it was applied to the dataset resulting from a field experiment at the German study site comparing cover crops and bare fallow as agricultural practices in a common crop rotation with cereals and silage maize. The proposed set of soil quality indicators was used to assess the environmental dimension. The effects on the economic dimension were evaluated by assessing the costs and benefits of the two systems, while the sociocultural dimension was studied using structured interviews with farmers. Generally, statistically observable effects of the *SICS* treatment on the measured soil properties in the field experiment were limited to a few indicators. Reports of positive effects of cover cropping on main crop yield and soil quality are abundant in the literature, but results vary [38,39]. The costs of the *SICS* with the inclusion of cover crops were slightly higher than in the conventional treatment, resulting in a slightly negative score of the economic dimension. The farmers that were interviewed for the assessment of the sociocultural dimension had consistently a positive opinion of cover crops, but also acknowledged management difficulties and a certain dependence on a favourable climate for cover crop establishment and performance.

Regarding the environmental dimension, the positive effect of cover crops on soil cover in spring was significant. Especially under conservation tillage management, cover crop litter constitutes a protective layer on the soil surface and provides important benefits for the agroecosystem, such as erosion protection, reduced evaporation and habitat for soil fauna [40]. Cover cropping had also a positive effect on bulk density, which is related to pore connectivity. As compaction is an increasingly acknowledged soil threat [41], cover crops provide an interesting opportunity to increase porosity, especially in systems with no or decreased mechanical soil loosening [42]. A previous study showed that cover crops reduced soil penetration resistance or compaction by 0–29% (average, 5%). They improve wet aggregate stability by 0–95% (average, 16%) and cumulative infiltration by 0–190% (average, 43%) [43]. In our case, soil biological properties tended to improve, with earthworm numbers showing a positive trend with cover crops although not significant (data not shown here), as well as the potential extracellular activity of β-glucosidase, an enzyme involved in the breakdown of cellulose (not shown). These results clearly showed that the micro-habitat provides more substrate and energy for microbial life under cover crops [38,44]. While most measured soil chemical attributes were not changed.

Despite these positive changes with cover crops, the *SICS* seemed to have also undesired effects on some soil variables: aggregate stability decreased significantly while bulk density decreases (or increase in total porosity). This last observation can be attributed to the dominance of the structural porosity created by earthworms. The unexpected decrease in aggregate stability indicates that positive effects of cover crops on different aspects of soil structure might require time and multiple growing cycles to develop [45]. More on the management side, weed pressure tended to be higher in the cover cropped plots compared to the bare fallow due probably to missing herbicide application, although weed suppression is another expected benefit from cover cropping. Maximising the cover crop biomass and an optimized termination and residue management can improve the weed-suppression capacity of cover crops [46]. The obtained scoring of the environmental dimension of the assessment methodology provided a quite accurate resume of the slight improvement of soil quality with cover crops compared to the bare fallow *control*, but with an uneven response of the different soil quality indicators.

Similarly, the farmers' rather positive opinion about cover crops was reflected by the improvement of the sociocultural dimension. The modest increase in workload was greatly offset by the improved reputation. This underscores the importance of prestige for decision making for practitioners [47], especially since the farmers in the region are increasingly worried about their public image, some of them even mentioned feeling attacked by media. The farmers also acknowledged potential positive benefits of the cover crops being especially interesting when considering the necessary adaption to climate change [48].

The slight negative scoring of the economic dimension matches the reality, as the adoption of *SICS* and other sustainable farming techniques frequently implies higher production and maintenance costs which are not covered economically due to the inability of the market to integrate externalities into pricing [49]. Potential benefits of cover crops were not included in the economic assessment, such as SOC increase, erosion reduction, N input by leguminous cover crops or an increased biodiversity. Nor could external benefits for society be included, such as reduced sediment runoff, C sequestration and positive effects on water quality or landscape, among others [50]. The complexity of management techniques based on (agro-)ecosystem functions means they frequently require a substantial amount of experience to yield satisfying results. Even worse, although management can alleviate many reasons for the underperformance of *SICS*, in some cases significant trade-offs between environmental performance and productivity remain and call for a paradigm shift [51]. Until then, in absence of effective market mechanisms, potential losses can be only compensated by increasing the subsidies for environmentally friendly farming practices.

The overall scoring of the SoilCare assessment methodology of cover cropping is therefore possibly partially biased by an overly negative score of the economic dimension, but seems to provide an acceptable resume of the effects of the adoption of this *SICS* for the sustainability of the system. When evaluating the assessment methodology in workshops at the German study site, the stakeholders provided a heterogeneous rating of the assessment methodology and made some suggestions that could likely improve the applicability and power of the tool.

Regarding the measured soil properties, some farmers suggested to include methods of visual assessment of soil structure, e.g., as in a shovel test, as this method is easy to perform for practitioners and it gives relevant information for practitioners [52]. Participants with a more academic background suggested the measurement of greenhouse gases to cover this important aspect of sustainability. Another possibility would be to integrate methods to assess the soil microbial community into the tool. Creamer et al. [53] explain in detail how soil life could be integrated in the concept of multifunctionality of agricultural ecosystems. It is clear that the selection of adequate methods for judging soil microbiological properties is context dependent. The authors give in their article three different possible contexts where soil microbiological properties could have an additional value: Mechanistically understanding of multifunctionality, optimising sustainable land management and soil quality monitoring over time. Further investigations are needed to include all the above aspects in the here presented tool.

4.2. Strengths and Challenges of the Assessment Tool

This paper describes a new assessment tool to assess the overall sustainability of soil-improving cropping systems illustrated by an example from Germany. An overview of results from SoilCare study sites obtained with the tool under various conditions within SoilCare is provided in [36]. Therefore, from the outset, our intention was to develop a practical and flexible tool to assess the overall sustainability that can be adapted for other purposes and contexts.

In our assessment methodology, we included environmental/soil quality, economic and socio-cultural aspects in order to take into account all factors that are relevant for the success of *SICS*. Nevertheless, it should be realised that our assessment remains a simplification of reality. To be able to develop an assessment methodology for *SICS* that could be used in SoilCare, some assumptions were necessary, and some limitations exist:

- Overall Sustainability assessed in this study has been defined within the three dimensions, environmental, sociocultural, and economic dimensions. The last dimension was restricted to economic benefits to the farmer during the assessment period considered in this study and does not take into account the benefits at larger spatial and temporal scales, e.g., benefits to society, off-site effects, long-term benefits. In reality, an agricultural system is sustainable when the trade-offs between the objectives considered for public evaluation of its performance, economic objectives, social objectives, and ecological objectives reach acceptable values for society as a whole [1].
- An economic assessment at farm level should include the whole rotation that is used, which was not always possible, as rotations are often longer than the 3 years of monitoring that was possible in SoilCare.
- Another limitation of the method, partially solved by considering rental costs, was the lack of detailed costs and benefits related to the equipment that should include depreciation costs occurring at longer time scale than the one considered in this study as well as the use of such equipment for other purposes than the ones related to the *SICS* considered here.
- In general, the SoilCare experiments were too short to show significant effects on the overall sustainability, e.g., soil organic carbon content, mineral nitrogen, pH, earthworm density) (Table 3). Some benefits of the *SICS* may require a longer time period to become detectable [54,55]. Besides, hydraulic conductivity and bulk density have a large spatial and temporal variability in the field, which makes it more difficult to detect significant differences without increasing dramatically the number of measurements [36].
- It should be kept in mind that monitoring was carried out for 2–4 years, and that specific conditions during the years of monitoring can have an impact on the outcomes. For example, the weather conditions during the short-term experiments were quite

specific, especially in 2018 occurred droughts at several study-sites, resulting in a drastic decrease in yield [41]. Moreover, all the years had high, sometimes record-breaking, temperatures.

- Considering the existing distortions of the market and the large dependence of European agriculture on subsidies, it could be debated whether the weight given to the economic dimension in the calculation of the overall sustainability score is biased by ideology instead of a true interest in the well-being of future generations. This societal benefit effect can be captured by an extension of the indicators and extensive data collection. The semi-quantitative nature of the sustainability index would allow for an extension considering the direction of the impact of *SICS* (positive, no change, negative) on different ecosystem services for society even if valuation is not possible.

5. Conclusions

The aim of this paper was to establish a tool for the assessment of the sustainability of the *SICS* at the farm/field scale. For this purpose, a decision tree based on weights (%) was chosen because it allows simple aggregation to assess the three dimensions of sustainability, namely, environmental, economic and sociocultural, and provides flexibility. The decision tree allowed us to set up a comprehensive and standardized methodology that could be further improved and used for different purposes. The methodology was tested with data from the SoilCare Horizon 2020 study site of Tachenhausen, Germany, for the assessment of the effect of integration of cover crops into the crop rotation. The effect on the environmental indicators was slightly positive, but most assessed properties did not change during the short time of implementation (two crop seasons). Regarding the social dimension, farmers reported that the increase in workload was outweighed by an improved reputation for using cover crops. Regarding the economic dimension, the incorporation of cover crops reduced slightly the profitability, due to the costs for seeds and establishment of cover crops, which were greater than the increased income from higher yields. Further development and refinement by considering various pedo-climatic and land management conditions, as well as long-term assessments, are needed to strengthen the predictions.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land11050729/s1, File S1: Excel Tool for the evaluation of the sustainability, File S2: Excel Tool to assess economic dimension, File S3: Results of the statistical analysis–study site in Tachenhausen, Germany.

Author Contributions: Conceptualization: A.A., R.H. and M.H.; methodology: A.A., R.B., F.B., I.P., R.H., M.H. and L.F.; data acquisition: C.P., E.K., M.H. and A.A.; data analysis: I.P., A.A., F.B. and C.P.; writing—review—editing: A.A., M.H., R.B., F.B., I.P., R.H., L.F. and E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 677407 (SoilCare project). RH also received funding from Dutch Ministry of LNV, via Kennis Basis programma 34, project KB-34-008-005.

Institutional Review Board Statement: Not applicable in this study.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Supplementary Material.

Acknowledgments: We thank the stakeholders in the SoilCare study sites. Without their collaboration this research would not have been possible.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sala, S.; Ciuffo, B.; Nijkamp, P. A systematic framework for sustainability assessment. *Ecol. Econ.* **2015**, *119*, 314–325. [CrossRef]
2. Dufour, D.L. Use of Tropical Rainforests by Native Amazonians. *Bioscience* **2009**, *40*, 652–659. [CrossRef]
3. Nachtergaele, F.; Biancalani, R.; Bunning, S.; George, H. Land Degradation Assessment: The LADA approach. In Proceedings of the 19th World Congress of Soil Science, Brisbane, Australia, 1–6 August 2010; pp. 72–75.
4. Devuyst, D. Linking impact assessment and sustainable development at the local level: The introduction of sustainability assessment systems. *Sustain. Dev.* **2000**, *8*, 67–78. [CrossRef]
5. Alaoui, A.; Barão, L.; Ferreira, C.S.; Hessel, R. Assessment of sustainability in agricultural areas: A review of available indicators, frameworks and approaches. *Land* **2022**, *11*, 537. [CrossRef]
6. Glover, J.D.; Reganold, J.P.; Andrews, P.K. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. *Agric. Ecosyst. Environ.* **2000**, *80*, 29–45. [CrossRef]
7. Gomez-Limon, J.; Riesgo, L. Alternative approaches to the construction of a composite indicator of agricultural sustainability: An application to irrigated agriculture in the Duero basin in Spain. *J. Environ. Manag.* **2009**, *90*, 3345–3362. [CrossRef]
8. Binder, C.R.; Feola, G.; Steinberger, J.K. Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environ. Impact Assess. Rev.* **2010**, *30*, 71–81. [CrossRef]
9. Bitsch, V. Sustainability as innovation: Challenges and perspectives in measurement and implementation. In *Diffusion and Transfer of Knowledge in Agriculture*; Huyghe, C., Bergeret, P., Svedin, U., Eds.; Matière à Débattre et Decider: Quae, France, 2016; Chapter 2.
10. Van Cauwenbergh, N.; Biala, K.; Bielders, C.; Brouckaert, V.; Franchois, L.; Garcia Cidad, V.; Hermy, M.; Mathijs, E.; Muys, B.; Reijnders, J.; et al. SAFE-A hierarchical framework for assessing the sustainability of agricultural systems. *Agric. Ecosyst. Environ.* **2007**, *120*, 229–242. [CrossRef]
11. Bockstaller, C.; Guichard, L.; Makowski, D.; Aveline, A.; Girardin, P.; Plantureux, S. Agri-environmental indicators to assess cropping and farming systems. A review. *Agron. Sustain. Dev.* **2008**, *28*, 139–149. [CrossRef]
12. Bockstaller, C.; Feschet, P.; Angevin, F. Issues in evaluating sustainability of farming systems with indicators. *Oilseeds Fats Crops Lipids* **2015**, *22*, D102. [CrossRef]
13. Pelzer, E.; Fortino, G.; Bockstaller, C.; Angevin, F.; Lamine, C.; Moonen, C.; Vasileiadis, V.; Guérin, D.; Guichard, L.; Reau, R.; et al. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. *Ecol. Indic.* **2012**, *18*, 171–182. [CrossRef]
14. Bechini, L.; Castoldi, N. On-Farm Monitoring of Economic and Environmental Performances of Cropping Systems: Results of a 2-Year Study at the Field Scale in Northern Italy. *Ecol. Indic.* **2009**, *9*, 1096–1113. [CrossRef]
15. Gaudino, S.; Reidsma, P.; Kanellopoulos, A.; Sacco, D.; van Ittersum, M.K. Integrated assessment of the EU's greening reform and feed self-sufficiency scenarios on dairy farms in Piemonte, Italy. *Agriculture* **2018**, *8*, 137. [CrossRef]
16. Smith, A.; Snapp, S.; Chikowo, R.; Thorne, P.; Bekunda, M.; Glover, J. Measuring sustainable intensification in smallholder agroecosystems: A review. *Glob. Food Secur.* **2017**, *12*, 127–138. [CrossRef]
17. Bond, A.J.; Morrison-Saunders, A.; Pope, J. Sustainability assessmenet: The state of the art. *Impact Assess. Proj. Apprais.* **2012**, *301*, 53–62. [CrossRef]
18. Röös, E.; Fischer, K.; Tidåker, P.; Nordström Källström, H. How well is farmers' social situation captured by sustainability assessment tools? A Swedish case study. *Int. J. Sustain. Dev. World Ecol.* **2019**, *26*, 268–281. [CrossRef]
19. Lynch, J.; Donnellan, T.; Finn, J.A.; Dillon, E.; Ryan, M. Potential development of Irish agricultural sustainability indicators for current and future policy evaluation needs. *J. Environ. Manag.* **2019**, *230*, 434–445. [CrossRef]
20. Mottet, A.; Bicksler, A.; Lucantoni, D.; De Rosa, F.; Scherf, B.; Scopel, E.; Lopez-Ridaura, S.; Gemmill-Herren, B.; Bezner Kerr, R.; Sourisseau, J.M.; et al. Assessing transitions to sustainable agricultural and food systems: A tool for agroecology performance evaluation (TAPE). *Front. Sustain. Food Syst.* **2020**, 252. [CrossRef]
21. Häni, F.; Braga, F.; Stämpfli, A.; Keller, T.; Fischer, M.; Porsche, H. RISE, a tool for holistic sustainability assessment at the farm level. *Int. Food Agribus. Manag. Rev.* **2003**, *6*, 78–90. [CrossRef]
22. Sadok, W.; Angevin, F.; Bergez, J.E.; Bockstaller, C.; Colomb, B.; Guichard, L.; Reau, R.; Messéan, A.; Doré, T. MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agron. Sustain. Dev.* **2009**, *29*, 447–461. [CrossRef]
23. Landert, J.; Pfeifer, C.; Carolus, J.; Schwarz, G.; Albanito, F.; Muller, A.; Smith, P.; Sanders, J.; Schader, C.; Vanni, F.; et al. Assessing agro-ecological practices using a combination of three sustainability assessment tools. *Landbauforschung* **2020**, *70*, 129–144. [CrossRef]
24. *FAO Safa Guidelines—Sustainability Assessment of Food and Agriculture Systems*; FAO: Rome, Italy, 2014; ISBN 9789251084854.
25. Gerrard, C.L.; Smith, L.G.; Pearce, B.; Padel, S.; Hitchings, R.; Measures, M.; Cooper, N. Farming for Food and Water Security. In *Farming for Food and Water Security*; Springe: Dordrecht, The Netherlands, 2012; Volume 10, pp. 1–22, ISBN 978-94-007-4499-8.
26. Alaoui, A.; Schwilch, G.; Bachmann, F.; Panagea, I.; Diels, J.; Wyseure, G.; Hessel, R. Deliverable 4.2. Monitoring Plan for Study Sites. SoilCare Project 2019, Report. Available online: https://www.soilcare-project.eu/ (accessed on 10 April 2022).
27. Smith, A.; Cullis, B.; Thompson, R. The analysis of crop cultivar breeding and evaluation trials: An overview of current mixed model approaches. *J. Agric. Sci.* **2005**, *143*, 449–462. [CrossRef]
28. RStudio Team. *RStudio: Integrated Development Environment for R*; RStudio, Inc.: Boston, MA, USA, 2016.

29. Sattler, C.; Nagel, U.J. Factors affecting farmers' acceptance of conservation measures—A case study from north-eastern Germany. *Land Use Policy* **2010**, *27*, 70–77. [CrossRef]
30. Fantappiè, M.; Lorenzetti, R.; De Meo, I.; Costantini, E.A.C. How to improve the adoption of soil conservation practices? Suggestions from farmers' perception in western Sicily. *J. Rural. Stud.* **2020**, *73*, 186–202. [CrossRef]
31. Trujillo-Barrera, A.; Pennings, J.M.E.; Hofenk, D. Understanding producers' motives for adopting sustainable practices: The role of expected rewards, risk perception and risk tolerance. *Eur. Rev. Agric. Econ.* **2016**, *43*, 359–382. [CrossRef]
32. Schneider, F.; Ledermann, T.; Fry, P.; Rist, S. Soil conservation in Swiss agriculture—Approaching abstract and symbolic meanings in farmers' life-worlds. *Land Use Policy* **2010**, *27*, 332–339. [CrossRef]
33. Schneider, F.; Rist, S. The significance of aesthetics for the adoption of no-tillage farming. *Agrar. Schweiz* **2012**, *3*, 216–223.
34. Sutherland, L.A.; Darnhofer, I. Of organic farmers and 'good farmers': Changing habitus in rural England. *J. Rural. Stud.* **2012**, *28*, 232–240. [CrossRef]
35. Fleskens, L.; Gaaff, M.; Verzandvoort, S.; Irvine, B. Model Assessments of the Cost- Effectiveness of Prevention/ Remediation/ Restoration Measures for All CASE STUDY Areas. RECARE Deliverable 7.2. 2018. Available online: https://www.recare-hub.eu/images/WP7/RECARE_REPORT_29_D72_final.pdf (accessed on 10 April 2022).
36. Hessel, R.; Wyseure, G.; Panagea, I.; Alaoui, A.; Reed, M.S. Soil Improving cropping systems for sustainable and profitable farming in Europe. *Land* 2022, *submitted*.
37. Hallama, M.; Pekrun, C.; Pilz, S.; Jarosch, K.A.; Frąc, M.; Uksa, M.; Marhan, S.; Kandeler, E. Interactions between cover crops and soil microorganisms increase phosphorus availability in conservation agriculture. *Plant Soil* **2021**, *463*, 307–328. [CrossRef]
38. Maltais-Landry, G.; Scow, K.; Brennan, E.; Vitousek, P. Long-term effects of compost and cover crops on soil phosphorus in two California agroecosystems. *Soil Sci. Soc. Am. J.* **2015**, *79*, 688–697. [CrossRef]
39. Cardoso, D.P.; Silva, M.L.N.; de Carvalho, G.J.; de Freitas, D.A.F.; Avanzi, J.C. Potential of cover plant species in reconditioning of physical and chemical properties of soil. *Revista Brasileirade Ciencias Agrarias* **2013**, *8*, 375–382. [CrossRef]
40. Junge, S.M.; Storch, J.; Finckh, M.R.; Schmidt, J.H. Developing Organic Minimum Tillage Farming Systems for Central and Northern European Conditions. In *No-Till Farming Systems for Sustainable Agriculture: Challenges and Opportunities*; Dang, Y.P., Dalal, R.C., Menzies, N.W., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 173–192, ISBN 978-3-030-46409-7.
41. Piccoli, I.; Sartori, F.; Polese, R.; Berti, A. Crop yield after 5decades of contrasting residue management. *Nutr. Cycl. Agroecosystems* **2020**, *117*, 231–241. [CrossRef]
42. Bacq-Labreuil, A.; Crawford, J.; Mooney, S.J.; Neal, A.L.; Ritz, K. Cover crop species have contrasting influence upon soil structural genesis and microbial community phenotype. *Sci. Rep.* **2019**, *9*, 7473. [CrossRef]
43. Blanco-Canqui, H.; Ruis, S.J. Cover crop impacts on soil physical properties: A review. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1527–1586. [CrossRef]
44. Hallama, M.; Pekrun, C.; Mayer-Gruner, P.; Uksa, M.; Abdullaeva, Y.; Pilz, S.; Schloter, M.; Lambers, H.; Kandeler, E. The Role of Microbes in the Increase of Organic Phosphorus Availability in the Rhizosheath of Cover Crops. *Plant Soil* **2022**. [CrossRef]
45. Brennan, E.B.; Acosta-Martinez, V. Cover Cropping Frequency Is the Main Driver of Soil Microbial Changes during Six Years of Organic Vegetable Production. *Soil Biol. Biochem.* **2017**, *109*, 188–204. [CrossRef]
46. Osipitan, O.A.; Dille, J.A.; Assefa, Y.; Radicetti, E.; Ayeni, A.; Knezevic, S.Z. Impact of Cover Crop Management on Level of Weed Suppression: A Meta-Analysis. *Crop Sci.* **2019**, *59*, 833–842. [CrossRef]
47. Mills, J.; Ingram, J.; Dibari, C.; Merante, P.; Karaczun, Z.; Molnar, A.; Sánchez, B.; Iglesias, A.; Ghaley, B.B. Barriers to and opportunities for the uptake of soil carbon management practices in European sustainable agricultural production. *Agroecol. Sustain. Food Syst.* **2020**, *44*, 1185–1211. [CrossRef]
48. Kaye, J.P.; Quemada, M. Using cover crops to mitigate and adapt to climate change. A review. *Agron. Sustain. Dev.* **2017**, *37*, 4. [CrossRef]
49. Bergtold, J.S.; Ramsey, S.; Maddy, L.; Williams, J.R. A Review of Economic Considerations for Cover Crops as a Conservation Practice. Renew. *Agric. Food Syst.* **2019**, *34*, 62–76. [CrossRef]
50. Blanco-Canqui, H.; Shaver, T.M.; Lindquist, J.L.; Shapiro, C.A.; Elmore, R.W.; Francis, C.A.; Hergert, G.W. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agron. J.* **2015**, *107*, 2449–2474. [CrossRef]
51. Wittwer, R.; Bender, S.; Hartman, K.; Hydbom, S.; Lima, R.; Loaiza, V.; Nemecek, T.; Oehl, F.; Olsson, P.; Petchey, O.; et al. Organic and Conservation Agriculture Promote Ecosystem Multifunctionality. *Sci. Adv.* **2021**, *7*, eabg6995. [CrossRef] [PubMed]
52. Alaoui, A.; Barão, L.; Ferreira, C.S.; Schwilch, G.; Basch, G.; Garcia-Orenes, F.; Morugan, A.; Mataix-Solera, J.; Kosmas, C.; Glavan, M.; et al. Visual assessment of the impact of agricultural management practices on soil quality. *Agron. J.* **2020**, *112*, 2608–2623. [CrossRef]
53. Creamer, R.E.; Barel, J.M.; Bongiorno, G.; Zwetsloot, M.J. The Life of Soils: Integrating the Who and How of Multifunctionality. *Soil Biol. Biochem.* **2022**, *166*, 108561. [CrossRef]
54. Kandeler, E.; Tscherko, D.; Spiegel, H. Long-term monitoring of microbial biomass, N-mineralisation and enzyme activities of a Chernozem under different tillage management. *Biol. Fertil. Soils* **1999**, *28*, 343–351. [CrossRef]
55. Kandeler, E.; Stemmer, M.; Klimanek, E.M. Response of soil microbial biomass, urease and xylanase within particle size fractions to long-term soil management. *Soil Biol. Biochem.* **1999**, *31*, 261–273. [CrossRef]