Critical review of soil quality indicators

with respect to their sensitivity to indicate soil functions and soil threats and interactions with management as well as reliability and simplicity of measurement

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Report number: 09
Deliverable: D3.2
Report type: Report
Issue date: December 2016
Project partner: ISRIC, FiBL

www.iSQAPER-project.eu

DOCUMENT SUMMARY	
Project Information	
Project Title	Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience
Project Acronym	iSQAPER
Call identifier	The EU Framework Programme for Research and Innovation Horizon 2020: SFS-4-2014 Soil quality and function
Grant agreement no:	635750
Starting date	1-5-2015
End date	30-4-2020
Project duration	60 months
Web site address	www.isqaper-project.eu
Project coordination	Wageningen University
EU project representative & coordinator	Prof. Dr. C.J. Ritsema
Project Scientific Coordinator	Dr. L. Fleskens
EU project officer	Ms Arantza Uriarte Iraola
Deliverable Information	
Deliverable title	Critical review of soil quality indicators
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Delivery Number	D3.2
Work package	3
WP lead	FiBL
Nature	Public
Dissemination	Report
Editor	L. Fleskens
Report due date	November, 2016
Report publish date	December, 2016
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Critical review of soil quality indicators with respect to their sensitivity to indicate soil functions and soil threats and interactions with management as well as reliability and simplicity of measurement

Deliverable 3.2 of

iSQAPER
Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience

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December 2016

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Executive summary

This report is Deliverable (3.2) of the EU-funded project '*Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience*' (iSQAPER).

The aims are to analyse effects of selected agricultural management practices and farming systems on soil quality indicators, and assess their sensitivity to soil threats with regard to soil function in major pedo-climatic zones of Europe and China. For this study, six key indicators (*i.e.*, yield, soil organic matter/carbon (SOM/SOC), pH, aggregate stability, water holding capacity, and earthworms) were evaluated for five paired practices: organic matter addition versus no organic matter input, no-tillage versus conventional tillage, crop rotation versus monoculture, irrigation versus non-irrigation, and organic agriculture versus conventional agriculture. Thereby the "standard practice" was referred to as a reference, *e.g*. conventional tillage, the use of "innovative practice" such as the use of no tillage as "improved practice".

For this analyses, we have collated data of 30 long-term experiments from iSQAPER project partners in Europe and China. These data were complemented with analytical data from additional 42 long-term experiments across China. Further we collected over 900 publications and reports using various web-based search engines. These materials and data were subsequently screened for their relevance to the above-mentioned aims of WP3 of the iSQAPER project. We used a reference manager to store the evidence presented in the literature (378 references) into a literature review database (LR-database).

Trends of the chosen indicators under the long-term experiments were analysed; response ratios were calculated for each indicator under a paired practice for the literature data in the LR-database as well as in the LTEs, for example, soil organic carbon (SOC) content under no-tillage was divided by SOC content under conventional tillage. In total, some 1044 observations were analysed for the chosen indicators under the paired practices. The number of observations was biased, *i.e.* more data were available for yield, SOM/SOC and pH; and much less for water holding capacity and earthworms which were supplemented from the long-term experiments.

Descriptive statistics for the indicators under the paired practices were analysed. In order to restrict the influence of data outliers, medians rather than means were used to present ratio distributions and visualised in flower petal diagrams for each paired practice (Figures ES-1-5): a value of 1 or close to 1 indicates no change or no difference (blue line) in the diagrams; a value > 1 indicates 'positive' change (increase) due to the improved practice versus the reference practice, and a value < 1 'negative' change (decrease); magnitudes of the trend depend on the median values. For most indicators, a median > 1 is considered favourable from a soil quality perspective. For pH results have to be interpreted more cautiously - dependent on pH of the reference and soil type - also in view of the log scale. Colours for the flower petals are assigned in R scripts as: dark grey, if number of observation is less than 2; otherwise other colours are assigned if number of observation is equal or more than 2: orange, when median is less than or

equal to 1; light green, when median is larger than 1 and less than 1.5; dark green, when median is larger than 1.5.

Main findings:

Organic matter addition versus no organic matter input

Organic matter (OM) addition favourably affected all the indicators under consideration as shown in Figure ES-1. The most favourable effect was reported for earthworm numbers, followed by SOM/SOC, yield and soil aggregate stability. OM addition enhanced also soil water holding capacity. For pH, effects depended on soil type, for example OM input favourably may affect the pH of acidic soils.

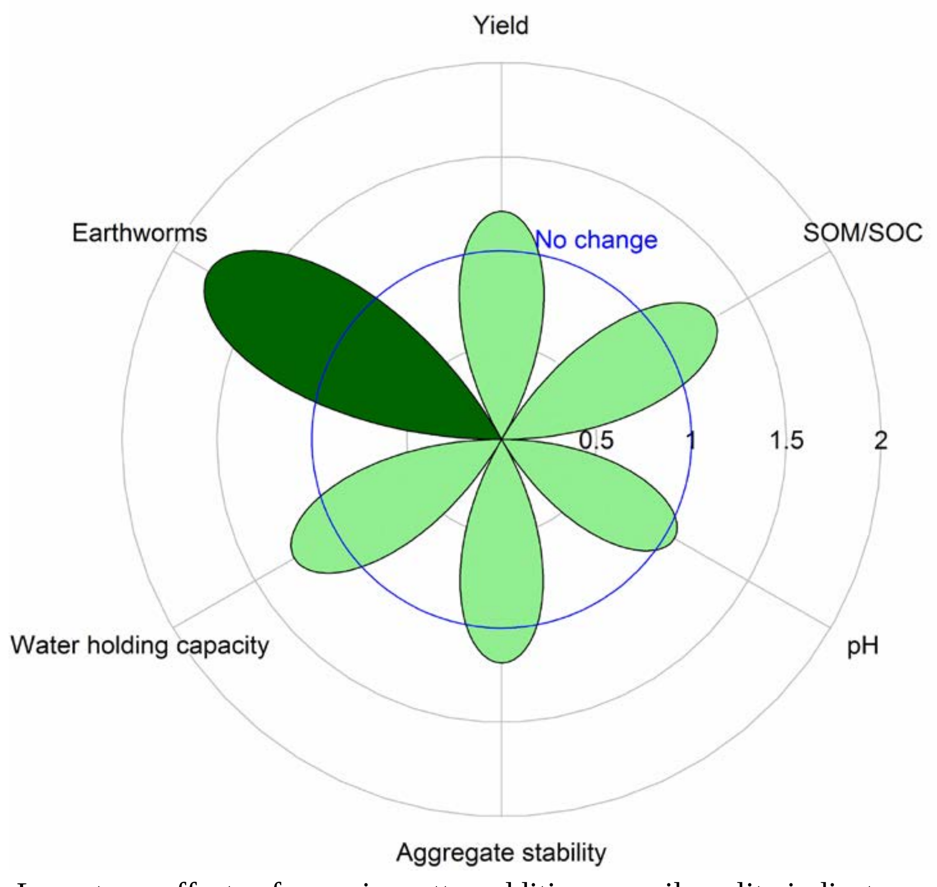


Figure ES-1. Long-term effects of organic matter addition on soil quality indicators compared to no organic matter input, expressed by a median of ratios (see text for details). For size and colours of petals, see section 2.5.

No-tillage versus conventional tillage

There was no clear trend in effect of no-tillage (NT) on soil pH. NT generally led to increased aggregate stability and greater SOM content in upper soil horizons. Compounded, these effects were reflected in a greater water holding capacity. However, the magnitude of the relative effects varied *e.g.* with soil texture. No-tillage practices enhanced earthworm populations, but not always where herbicides or pesticides were needed to combat weeds and pests. Overall, in this review, yield slightly decreased under NT (Figure ES-2).

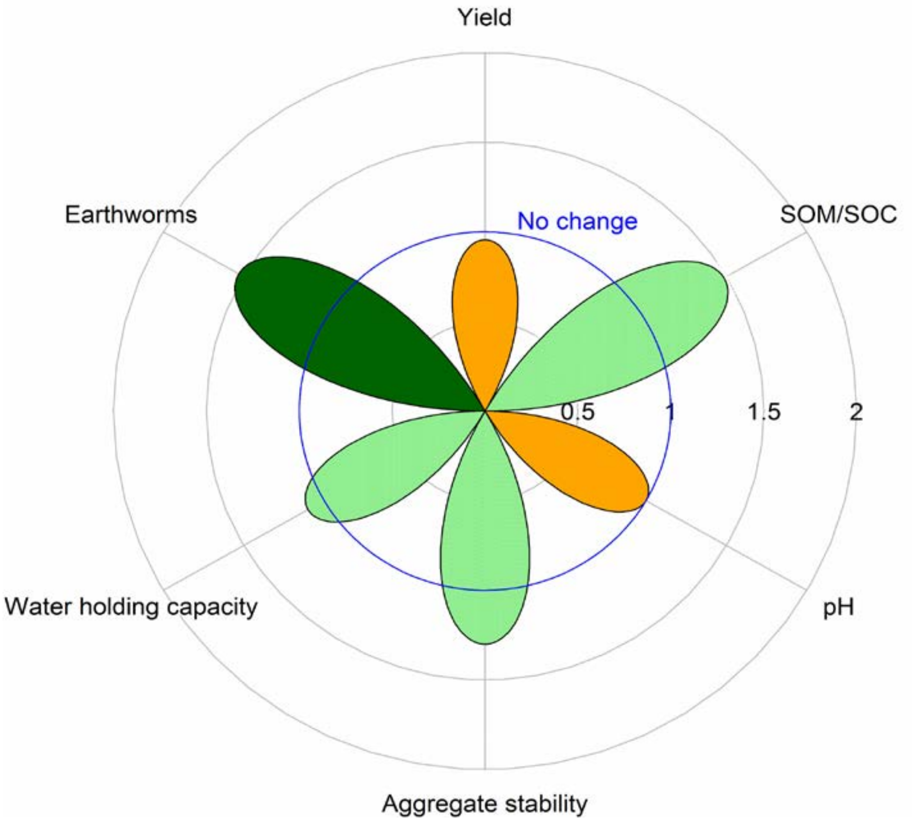


Figure ES-2. Long-term effects of no-tillage on soil quality indicators compared to conventional tillage, expressed by a median of ratios.

Crop rotation versus monoculture

Crop rotation had a positive effect on SOM/SOC content and yield; overall, crop rotation had little impact on soil pH, aggregate stability and water holding capacity - depending on the type of intercrop. Mixed, *i.e.*, positive, negative or no effects on earthworm numbers were observed - depending on the type of intercrop; whereas rotation of arable crops only could have adverse effects, rotation with ley very positively influenced population numbers; overall result was unfavourable (Figure ES-3).

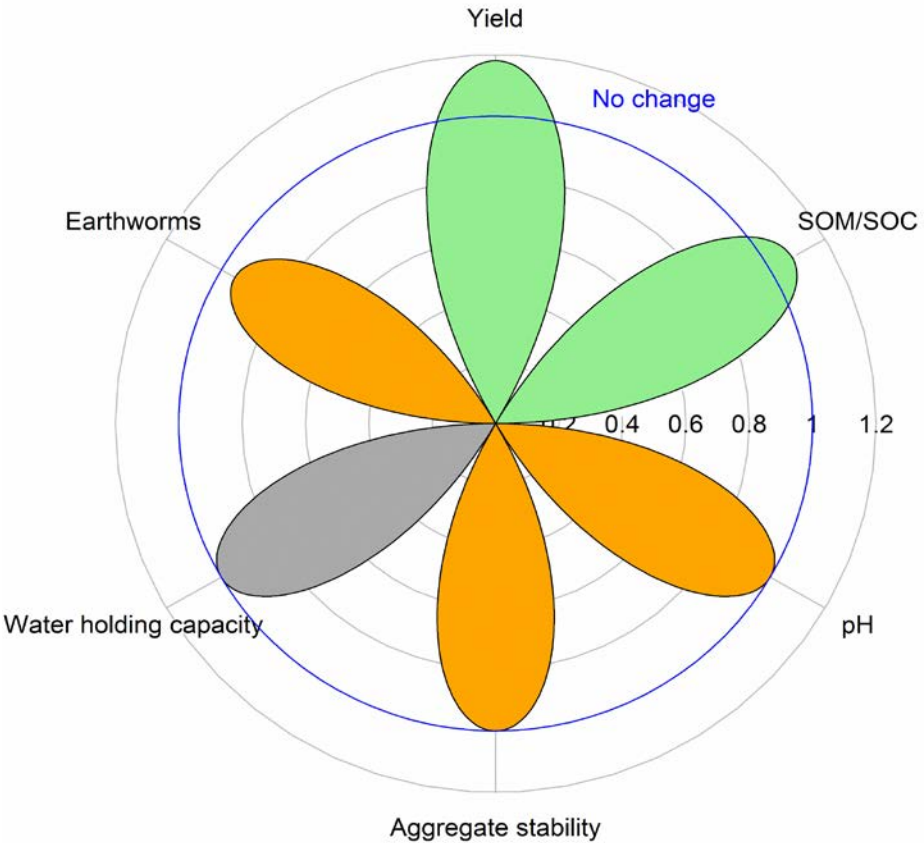


Figure ES-3. Long-term effects of crop rotation on soil quality indicators compared to monoculture, expressed by a median of ratios.

Irrigation versus rain-fed farming

Relatively few studies were available for this assessment. Figure ES-4 shows impacts of irrigation on the selected soil quality indicators: irrigation increased earthworm populations, aggregate stability and SOM/SOC. However, no clear trends were observed for soil pH and water holding capacity as such effects were strongly dependent on soil type, amendments used, and quality of irrigation water.

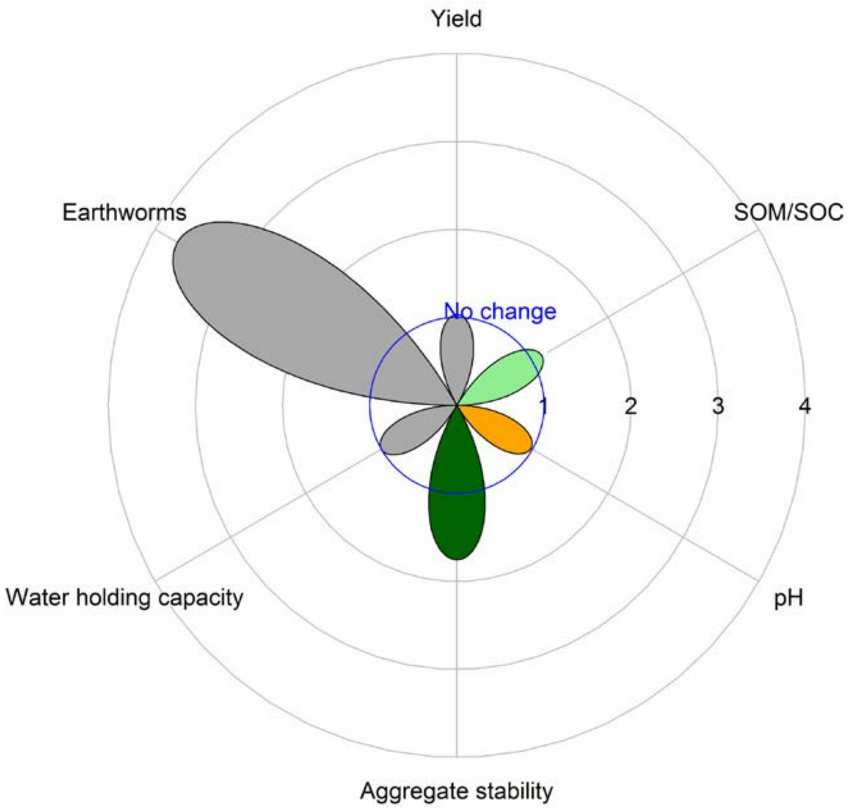


Figure ES-4. Long-term effects of irrigation on soil quality indicators compared to rain-fed agriculture, expressed by a median of ratios.

Organic versus conventional agriculture

A clear positive trend was observed for earthworm abundance under organic agriculture. Further, organic agriculture generally resulted in increased aggregate stability and greater SOM/SOC content. Overall, no clear trend was found for pH and water holding capacity; a decrease in yield was observed in this review (Figure ES-5).

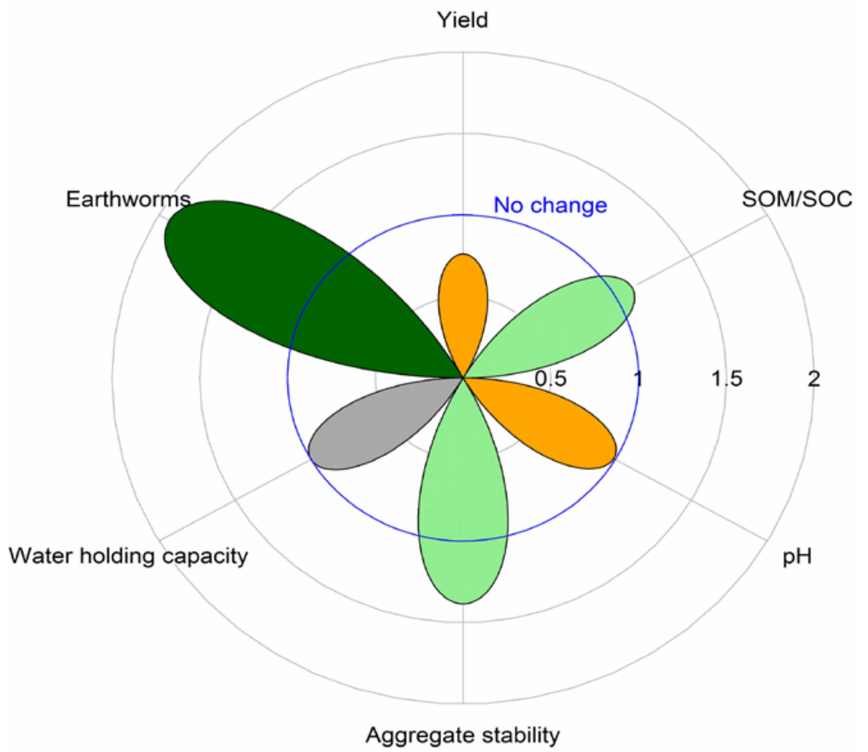


Figure ES-5. Long-term effects of organic agriculture on soil quality indicators compared to conventional agriculture, expressed by a median of ratios.

Suitability of the chosen soil indicators as a measure for soil functions

Table ES-1 shows expert-based assessment of linkages between selected soil quality indicators (this report) and soil functions (FAO). √: Suitable as direct indicator; (√): Suitable within certain limits, as indirect indicator.

Table ES-1. Linkages between soil quality indicators and soil functions (expert-based assessment).

SQ indicators / Soil functions	SOM/SOC	Soil pH	Aggregate stability	WHC	Earthworms	Yield
Provision of food, fibre and fuel	√	√	√	√	√	√
Carbon sequestration	√	√	√	√	√	(√)
Water purification and soil contaminant reduction	√	√	√	√		√
Climate regulation	√	(√)	√	√	√	(√)
Nutrient cycling	√	√	(√)	(√)	√	(√)
Habitat for organisms	√	(√)	√	√	√	
Flood regulation	√		√	√		

Source of pharmaceuticals and genetic resources		(√)			(√)	
Foundation for human infrastructure	(√)		(√)	(√)		
Provision of construction materials			(√)			
Cultural heritage		(√)		(√)		

Soil quality is best assessed by soil properties that are neither so stable as to be insensitive to management, nor so easily changed as to give little indication of long-term alterations. The indicators discussed in this review reflected long-term changes of experiments of the iSQAPER partner countries and the literature reports - most of whose were also based on long-term trails. As such, overall, these indicators are suitable measures for the corresponding soil functions. Although no clear trend in soil pH was observed for most practices, except for organic matter input, pH is still considered a useful parameter for evaluation of overall soil quality as it is a measure for changes in soil acidity hence crop growth. Acid soils are more directly adjusted by liming, and alkaline soils by sulphur in specific cases. Concerning SOC, it may be important to consider long-term changes in pool sizes in relation to the desired ecosystem services (*e.g.* crop production versus carbon sequestration relating to climate change mitigation/adaptation).

Sensitivity of the soil indicators to soil threats

Table ES-2 summarizes expert-based assessment on linkages of the soil quality indicators and soil threats under consideration. Only SOM/SOC and yield are good measures for the considered threats. None of the indicators appears to be suitable for soil sealing. The usefulness of the indicators varies depending on the nature of the threat, for example, soil pH can be a suitable indicator for acidification and salinisation. There is no universal set of indicators for either all soil threats or an individual threat; soil properties or soil quality indicators are indicators among other indicators biophysical (climate, water, vegetation and so on), economic and social-cultural.

Table ES-2. Relationship between soil quality indicators and soil threats (expert-based assessment).

SQ indicators / Soil threats	SOM/SOC	Soil pH	Aggregate stability	WHC	Earthworms	Yield
*SOM decline	√					√
*Acidification	√	√				√
*Erosion (by water and wind)	√		√	√		√
**Nutrient loss	√		√			√
Soil sealing						
**Salinisation	√	√	√		√	√

**Desertification	√		√			√
*Soil biodiversity loss	√		√		√	
*Compaction		√	√	√		√
**Pollution	√	√				√

*These are the threats considered in the current study caused by unsustainable agricultural practices.
**For loss of soil nutrients (available and total soil nutrients), salinization (electrical conductivity) and pollution (toxic elements and compounds), there are more specific, direct indictors are not considered here.

Reliability and simplicity of measurement

Ease of measurement is a prerequisite for a soil quality indicator in almost all soil quality concepts and reliability is also an important consideration. The chosen soil indicators were frequently used in concept and assessment of soil quality and they were measured consistently in the iSQAPER LTEs as well as the LR-database except for earthworm; therefore they are reliable. The indicators were sampled and measured mostly in labs; field measurements were rarely reported in both the LTEs and LR-database. The methods for the indicator measurements varied, *e.g.*, for SOC, Walkley-Black, Tiurin's method, dry combustion at 600°C with a Leco-RC 412 analyser and so on were used; A reference measurement (lab) would be needed to compare results obtained from these methods to assess accuracy of the measurements or reliability. Overall soil biological indicators and their measurement were observed much less than soil chemical and physical properties; these will be enhanced in upcoming EC LUCAS soil survey (2018).

Possible limitations

Trends for the indicators and their relative changes under the paired practices were determined based on the collected long-term experiment data, analytical data from the 42 LTEs in China, and reviewed studies. As such it is possible that some important works may not have been considered in this short desk study.

Conclusions and recommendations

All the discussed management practices affect soil quality indicators reviewed in this report, but they do this in various ways. Overall, there are clear trends and relative changes in the six indicators as affected by the five paired practices. However, the magnitude of the trends and direction of change vary with crop species, climate zone and soil type.

Earthworm appears to be the most sensitive indicator for all the discussed management practices; however, its magnitude of the trends and direction of change vary with climate zone, soil type and crop species; SOC/SOM responds positively to all the practices after 23 years (on average in this study) in comparison to the references. Water holding capacity, aggregate stability and yield are less sensitive to the practices and pH appears to be the most insensitive indicator.

Five paired practices were analysed for their impacts on soil quality indicator trends and relative changes against a reference (control) practice. However, influences of irrigation on soil pH is not clear as it is strongly dependent on soil type and quality of irrigation water.

Some of the practices are investigated as a rather ‘general’ category such as organic matter input. However, there are various types of organic matters, such as farmyard manure, compost, green manure, crop residue, or slurry. Application of such diverse materials will have different effects on soil quality indicators. Although such aspects were documented in the LR-database and text, they could not be included explicitly in the synthesis. For this, a full scale metadata analysis would be required, which was beyond the scope of this study.

Some management practices had negative effects on biophysical properties, for example, levels were lower under organic farming as compared to conventional farming, and to a less extent, no-till; but there are also positive aspects under organic farming such as higher marketing price and reduced environmental damage. Therefore, to evaluate whether it is judicious to convert conventional farming to organic farming, socio-economic aspects have to be considered in combination with the biophysical impact.

Results presented in this review could be used as a reference or input in other iSQAPER work packages, especially WP 4 on the development of a soil quality-based mobile phone app (SQAPP).

It should be noted that farmers often know very well which specific soil parameters are most relevant for their particular situation. Therefore, the view of land managers should be taken into account when evaluating various sets of indicators for soil quality. This would require a transdisciplinary and participatory approach.

Acronyms

CT	Conventional Tillage
EC	European Commission
FYM	Farmyard Manure
iSQAPER	European Commission funded project 'Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience'
LTE	Long-term Experiment
NT	No Tillage
POC	Particulate Organic Matter
SOC	Soil Organic Carbon
RR	Response Ratios
SOM	Soil Organic Matter
SQAPP	Soil Quality Application (iSQAPER mobile phone app)
SSSA	Soil Science Society of America
TOC	Total Organic Carbon
UAA	Utilised Agricultural Area
WHC	Water Holding Capacity
WP	Work Package

1 Introduction

1.1 The iSQAPER project

Increasingly, soil is recognized as a non-renewable resource because, once degraded, the restoration of its productivity is an extremely slow process. Given the importance of soils for crop and livestock production as well as for providing wider ecosystem services for local and global societies, maintaining the soil in good condition is of vital importance.
To manage the use of agricultural soils well, decision-makers need science-based, easy to apply and cost-effective tools to assess soil quality and function. The most important aims of the iSQAPER project are to:

- Integrate existing soil quality related information;
- Synthesize the evidence for agricultural management effects provided by long-term field experiments;
- Derive and identify innovative soil quality indicators that can be integrated into an easy-to-use interactive soil quality assessment tool;
- Develop, with input from a variety of stakeholders, a multilingual Soil Quality Application (SQAPP) for in-field soil quality assessment and monitoring;
- Test, refine, and roll out SQAPP across Europe and China as a new standard for holistic assessment of agricultural soil quality;
- Use a trans-disciplinary, multi-actor approach to validate and support SQAPP.

Nine work packages (WPs) were conceived in the iSQAPER project. WP3 was to critically review soil quality indicator systems all over the world, and analyse the identified long-term European and Chinese field experiments to identify the best subset of measurements to be used to develop an aggregate index of agricultural soil quality underpinning soil-based ecosystem services and development of SQAPP: i) conducting a critical review of existing concepts of soil quality indicators; ii) documenting existing field trials across various pedo-climatic zones in Europe and China so as to compile a database of research results, identify the most cost-effective indicators, in terms of sensitivity to indicate soil threats, soil functions and land potential, and identify knowledge gaps; iii) assessing how soil type, climatic zone, topography and crop and land management interact to affect indicators of soil quality; and iv) screening and evaluating a range of newly developed indicators of soil quality in long-term experiments.

1.2 The challenge of assessing soil quality

There is not one single indicator to assess soil quality. A combination of soil chemical, physical and biological parameters, yield *etc*. is required. Basically, there is no lack of indicators; the challenge is to select the most promising ones. But which are those?
Agronomists have always relied on a knowledge of chemical, physical and biological properties of soils to assess capacity of sites to support agricultural production. Assessing soil properties has recently expanded because of growing public interest in determining consequences of agricultural management practices on soil quality relative to sustainability of ecosystem functions and

services including productivity. The concept of soil quality includes assessment of soil properties and processes as they relate to ability of soil to function effectively as a component of a healthy ecosystem. Specific functions and subsequent values provided by ecosystems are variable and rely on numerous soil physical, chemical, and biological properties and processes, which can differ across spatial and temporal scales.
Choice of a standard set of specific properties as indicators of soil quality can be complex and vary among agricultural systems and management purposes. Indices of soil quality which incorporate soil chemical, physical, and biological properties will be most readily adopted if they are easily measured and inexpensive, measure changes in soil function, encompass chemical, biological, and physical properties, are accessible to many users and applicable to field conditions, and are sensitive to variations in climate and management.

1.3 Scope of this report

Bünemann *et al*. (2016) has reviewed concepts and indicators of sol quality all over the world within the iSQAPER project(WP3.1). They discussed strengths and weaknesses of existing concepts, proposed a novel concept framework for soil quality assessment in various pedo-climatic zones in Europe and China. This study as part of WP3.2 aims to analyse effects of agricultural management practices on soil functioning and health, as expressed here by key soil quality indicators, in the major pedo-climatic zones of Europe and China. It also analyses how far the selected soil quality indicators can be related to soil threats, such as erosion or salinisation.

The title of the review contains the word ‘critical’, because there is not *one* indicator alone which could cover soil quality. And even the set selected for the present study may not be suitable to help evaluating all soil functions, and soil threats (in particular sealing and nutrient loss was not targeted in this study).

The report has been written by soil professionals for other professionals in the field of land and soil. Nevertheless we have taken care to make essential parts understandable for the interested laymen. Our main results are extracted in an executive summary, and easy-to-understand ‘flower petal’ graphs are used to summarise and visualise the rather large knowledge base behind this report.

Within the iSQAPER project, our findings will support the development of a soil quality-based mobile phone application (SQAPP) for in-field soil quality assessment and monitoring in Work Package 4 (WP4) of the iSQAPER project:

1) Help users to identify promising soil quality indicators;
2) Illustrate how the results can be used in the future in other iSQAPER work packages;
3) Explain possible restrictions: assessment restricted to farmland; only selected (common) agricultural measures analysed; *etc*.

2 Methods

2.1 Pre-selection of soil quality indicators

We have chosen major indicators of soil quality to be reviewed based mainly on the following considerations:

- Changes in soil quality and fertility are long-term developments and significant effects often do not happen within less than ten years; hence, long-term experiments are of critical importance!
- Focus on “dynamic” over “static” indicators as only the former can reflect changes within reasonable time and spans (10-20 years?).
- Most indicators are soil and site specific (*e.g.* SOC-soil organic carbon and pH), so it is important that experiments have been done under comparable conditions (*e.g.* LTEs with split-plot design, or at least with neighbouring parcels).
- Important to distinguish between short-term, seasonal effects and long-term changes in soil quality indicators.
- Indicators are suitable/required for covering potential changes in soil functions and soil threats.
- Selection of soil quality indicators was based on data available through iSQAPER long-term experiments as well as workload and time constraints.
- Potential novel soil biological indicators that will be carried out within iSQAPER by a PhD student.
- It is important not only to identify the most appropriate bio-physical indicators but also to ensure that farmers and land managers can understand and relate to them to support on-farm management decisions.

Based on the above considerations and outcome of the iSQAPER WP 3.1 (Deliverable 3.1 by Bünemann *et al*., 2016) , we focussed on six indicators in this report: Yield, soil organic matter/soil organic carbon, pH, aggregate stability (soil structure), water holding capacity, and earthworms (number). Details on sampling and measurement were captured as part of the connected LR database.

Yield
Although not a soil property, crop yield provides a good indication of soil quality and is of most concern to farmers. Yield (productivity) is also an important ecosystem service.

Soil organic matter/soil organic carbon
Soil organic matter/carbon plays a central role in the maintenance of soil fertility and other soil functions. Its environmental and economic relevance is based on the capacity of soil organic matter (SOM) to limit physical damage and to improve nutrient availability. Judicious soil management leading to increased SOM levels can help mitigate climate change through increased sequestration of ‘soil organic carbon’ (SOC) (UNEP, 2012).

pH

Soil pH is an important, and easily measured, soil quality indicator. It is a measure of soil acidity, which controls nutrient availability to crops. If soil pH is too high, nutrients such as phosphorus, copper, manganese, iron and boron become unavailable to crops. If pH is too low, potassium, phosphorus, calcium, magnesium and molybdenum become unavailable. Unavailability of nutrients limits crop yields and quality. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Microbial biomass and activity of soils is closely correlated to pH, whereby fungi tolerate lower pH than bacteria. Most crops grow preferably in soil pH around 6.2-6.8, and generally, as SOM content increase, crops can tolerate lower soil pH (Moebius-Clune *et al*., 2016).

Aggregate stability/soil structure

A soil aggregate is defined as a 'naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates' (Martin *et al.*, 1955). It is used as an indicator of soil structure (Six *et al.*, 2000) which is a key factor in the functioning of soil, its ability to support plant and animal life, and regulate environmental quality with particular emphasis on soil carbon sequestration and water holding capacity. Aggregation results from the rearrangement, flocculation and cementation of particles (Duiker *et al*., 2003). It is mediated by soil organic carbon (SOC), biota, ionic bridging, clay and carbonates, and complex interactions of these aggregants can be synergistic or disruptive to aggregation (Bronick and Lal, 2005).

Resistance of soil aggregates to physical stress determines soil conduciveness for germination and rooting of crops (Lynch and Bragg, 1985; Angers and Carson, 1998), ability of carbon storage through physical protection of organic molecules (Jastrow and Miller, 1997), crusting and erosion (Le Bissonnais, 1996). SOM is preferentially held in micro-aggregates (Williams and Petticrew, 2009), soil erosion and nutrient loss depend primarily upon micro-aggregates mobilization and fragmentation of macro-aggregates (Mbagwu and Bazzoffi, 1998; Six *et al*., 2004; Green *et al*., 2005; Kuhn, 2007). Aggregate stability is therefore a good indicator of general soil quality. In general, as soil aggregation increases, soil structure and soil tilth improve (Abiven *et al*., 2009). However, it is known that conventionally cultivated soils tend to have decreased aggregate stability (Barthés and Roose, 2002).

Water holding capacity

Soil water holding capacity is defined as the amount of water that a given soil can hold, and is an important determinant of crop production. Soil texture, mineralogy and content of organic matter are key components that determine soil water holding capacity.

Earthworms

Earthworms can increase soil porosity and improve soil structure; they can increase mineralization of SOM in the short-term by altering physical protection within aggregates and enhance microbial activity and nutrient cycling; using earthworm services in cropping systems

has potential to boost agricultural sustainability (Bertrand *et al*., 2015). Earthworm abundance is considered a useful biological indicator of soil quality (Bünemann *et al*., 2016).

2.2 Selection of agricultural management practices

Based on 1) practices described in iSQAPER LTE documentation, 2) practices commonly selected in previous EU projects, 3) agreement reached in iSQAPER WP3 group and with project coordination team; we have chosen five management practices *i.e.*, organic matter addition, no-tillage, crop rotation, irrigation and organic agriculture in this study and taken no organic matter input, conventional tillage, monoculture, non-irrigation and conventional farming as references (baseline), respectively.

2.3 Collection and harmonisation of long-term experiment (LTE) data

Long-term field experiments are indispensable for assessing effects of agricultural management practices on changes in soil quality indicators. Within the iSQAPER project, data for 30 long-term experiments (LTEs) have been collected. These represent data from our 13 project partners in Europe and China. The earliest LTE began in 1964 in Estonia. Most experiments are still ongoing except those for Braila (Romania) and Vitaqua (Spain). The average duration of the LTEs is 20 years.

Information collated at each LTE includes: location, climate, land use (history), soil information, trial factors, management systems, assessments done, sample storage and analysis, and related publications. Details are provided in Caspari and Bai (2015). The corresponding data are analysed and discussed in this report.

The LTE data collected from the Chinese partners (6 LTEs) were complemented with analytical data from additional 42 LTEs across China covering over 30 years and various management practices (Xu *et al* 2015a, 2015b). We also considered sources from EU-funded projects, *e.g.*, TILMAN-ORG (data provided by FiBL, Cooper *et al.*, 2016). In total data of 65 LTEs were analysed.

2.4 Literature review

Over 900 papers and reports have been collected using various search engines including Google Scholar, ScienceDirect, ISI Web of Science, ResearchGate, ResearcherID, Scopus, AuthorID, ORCiD, Scholarmate, and Academia.edu. Duplicate titles were removed from the analyses. Publications in Chinese were found using the China Knowledge Resource Integrated (CNKI) database. We used Mendelay.com software, a reference manager, to register key elements of the various publications.

Subsequently, key elements of the selected studies (some 400 references) were entered into a literature database in MS Excel (LR-database). We calculated the ratio for each indicator under a paired practice, for example soil organic carbon content under crop rotation is divided by soil organic carbon content under monoculture for each long-term experiment.

2.5 Data analysis and visualization

The effects of management practices on selected soil quality indicators were examined on the basis of both the iSQAPER LTE data and the literature review evidence.

Trends of the chosen indicators under the long-term experiments were analysed; response ratios were calculated for each indicator under a paired practice for the literature data in the LR-database as well as in the LTEs, for example, soil organic carbon (SOC) content under no-tillage was divided by SOC content under conventional tillage. In total, some 1044 observations were analysed for the chosen indicators under the paired practices. The number of observations was biased, *i.e.* more data were available for yield, SOM/SOC and pH; and much less for water holding capacity and earthworms which were supplemented from the long-term experiments.

Descriptive statistics for the indicators under the paired practices were analysed. To restrict influence of data outliers, medians rather than means were used to present ratio distributions and draw 'flower petal' diagrams for each paired management practice in sections 3.2.1 to 3.2.5. A value of 1 or close to 1 indicates no change or no difference (blue line) in the diagrams; a value > 1 indicates 'positive' change (increase) due to "improved practice" versus reference practice, and a value < 1 'negative' change (decrease); the extents depend on the median values. For most indicators, a median > 1 is considered favourable from a soil quality perspective. For pH results have to be interpreted more cautiously - dependent on pH of reference and soil type - also in view of the log scale.

All analyses including the flower petal diagrams were performed using R scripts.

Colours for the flower petals are assigned in R scripts as follows: dark grey, if number of observations is less than 2; otherwise other colours are assigned if number of observation is equal or more than 2:

- orange, when median is ≤ 1;
- light green, when median is > 1 and < 1.5; and
- dark green, when median is > 1.5.

3 Results

3.1 Impact of land and soil management on soil quality indicators

3.1.1 Organic matter additions

Long-term effects of organic matter additions on soils are well documented, but findings are ambiguous. Several reviews have reported a positive influence of organic matter additions on soil organic carbon (SOC) content, water holding capacity, and aggregate stability of soils (Khaleel *et al*., 1981; Haynes, 1998; Abiven *et al*, 2009). Other reviews have shown that addition of organic manures to soil has a positive effect on earthworm populations (Haynes *et al.*, 1998). The effects depend on rate applied, nature of organic matter addition, soil type as well as climate variables (Albiach *et al.*, 2001; Tejada and Gonzalez, 2003). Further, the sampling period can influence the pH, earthworm population, and soil aggregate stability (D'Hose *et al*., 2014a).

The major limitations to assess the impact of organic matter additions on targeted soil quality indicators were:

- Limited availability of data for some of the indicators.
- Difficulty of comparing experimental results in view of the high variability of methods, years of application, time and type of sampling, as well as duration of the experiments.

Nonetheless, the below trends could be distilled from the present analyses.

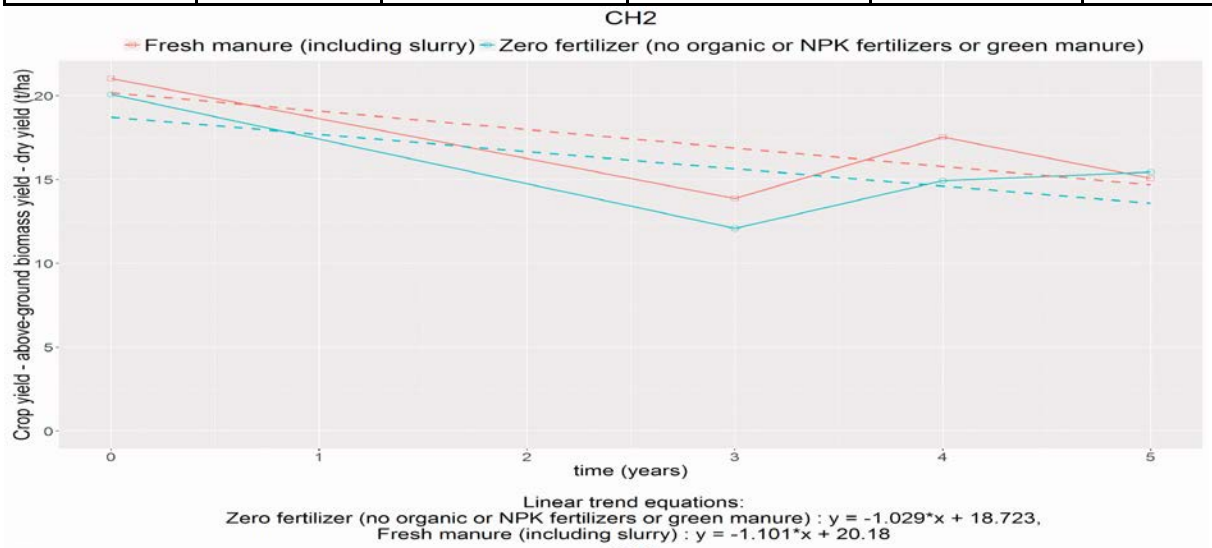
Yield

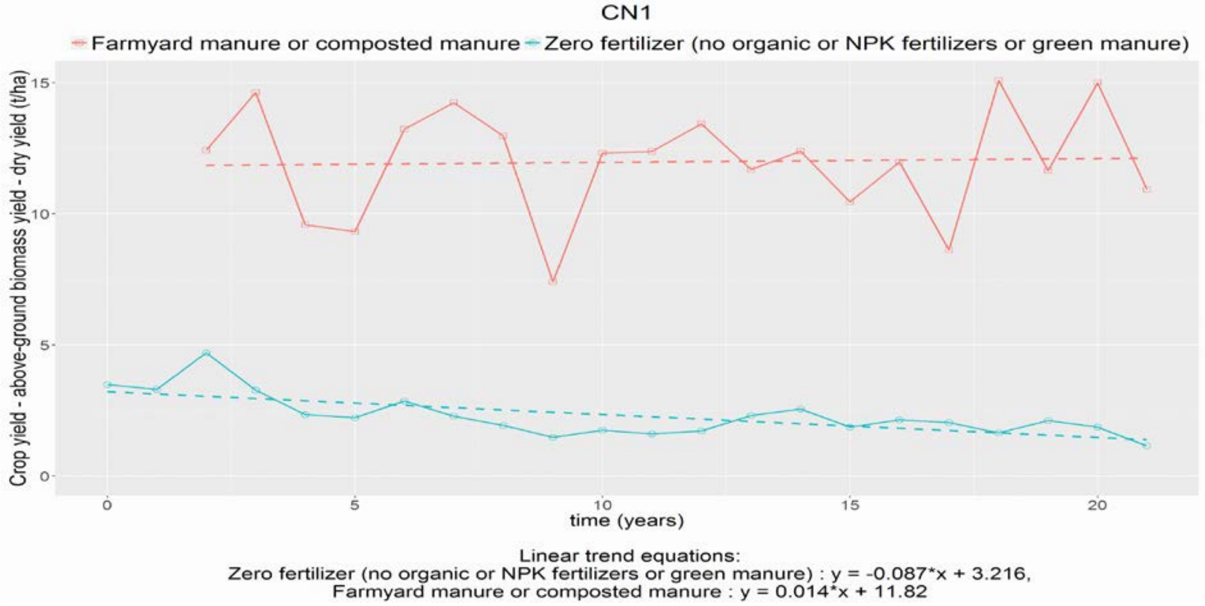
Most studies showed a positive trend in yield after addition of manure or organic matter, but the yield varies depending on types of crop.

Our review shows that the amount and type of organic matter added and frequency of application are key factors that influence yield (*e.g.,* Diacono *et al*., 2010; Tejada *et al*., 2008). According to Diacono *et al* (2010), organic amendments combined with mineral fertilizers seem to enhance crop yield more than application of only compost and organic amendments. This trend has been confirmed by 42 LTEs in China (Xu *et al*., (2015a, 2015b). Similar trends were also observed from the iSQAPER LTEs with most of the ratios (manured/unmanured) greater than 1 (Table OM-01, Figure OM-01).

Table OM-01. Yield changes under manured and unmanured trials within iSQAPER LTEs.

Trial name	Country	Response	Unmanured	Manured	Ratio
Aesch trial (CH2)	Switzerland	Dry yield above-ground (t ha^{-1})	Treatment 1: 20.08 (2010) 14.94 (2014) 15.45 (2015)	Treatment 3: 21.03 (2010) 17.54 (2014) 15.07 (2015)	1.05 (2010) 1.17 (2014) 0.98 (2015)
Therwil DOK trial (CH2)	Switzerland	Dry yield above-ground (t ha^{-1})	Treatment 1: 10.46 (2006) 6.76 (2012)	Treatment 3: 20.16 (2006) 10.4 (2012)	1.93 (2006) 1.49 (2012)
Qiyang red soil fertility LTE (CN1)	China	Dry yield above-ground (t ha^{-1})	Treatment 2: 4.70 (1993) 1.14 (2012)	Treatment 12: 12.43 (1993) 10.93 (2012)	2.64 (1993) 9.59 (2012)
Tillorg (SI1)	Slovenia	Crop yield - air-dry seeds yield (t ha^{-1})	Treatment 1: 0.5 (2001) 4.4 (2009)	Treatment 2: 0.8 (2001) 7.3 (2009)	1.60 (2001) 1.66 (2009)





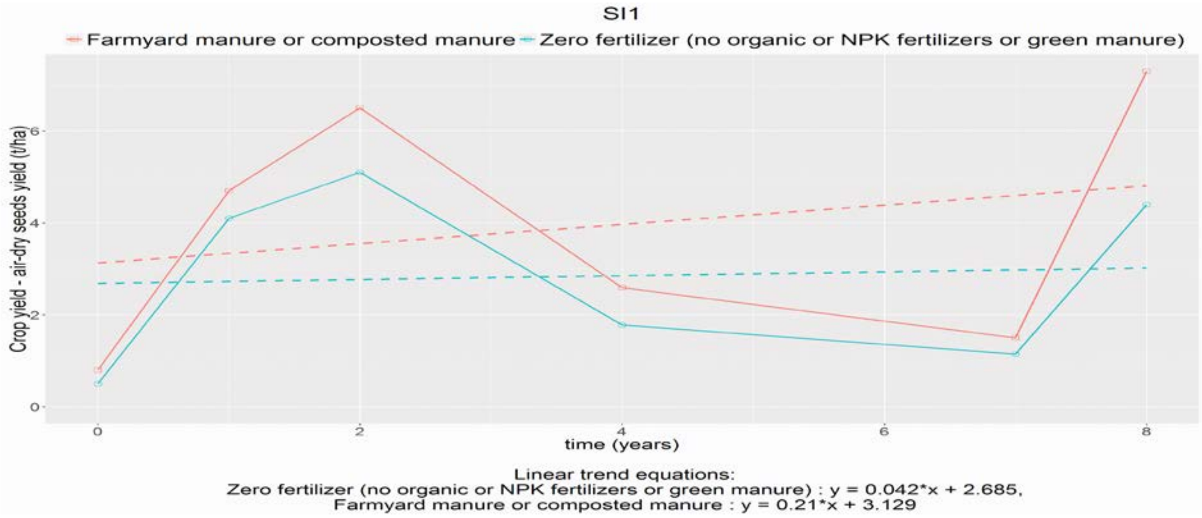


Figure OM-1. Trends in yield under manured and unmanured trials within iSQAPER LTEs (top: Aesch trial (CH2) in Switzerland, middle: Qiyang (CN1) in China, bottom: Tillorg (SI1) in Slovenia).

Overall impact evaluation: a very positive effect of organic input on yield, + +.

SOM/SOC

Increase of SOC content through organic matter additions has been well documented. The question is how much organic matter (OM) needs to be added? And what is the relationship between OM addition and build-up of SOC contents? How is the non-linear relationship influenced by other soil factors?

It is expected in general that an increase in soil organic carbon content will happen after application of organic matter additions, generally with a proportional response due the rate of application (Larney *et al*, 2012). But the relationship between organic matter applications rates and increase in SOC contents is not so simple (Khaleel *et al*., 1981; Xu *et al*., 2015a). Figure OM-02 shows SOC increase, as a result of a long-term application of several organic materials, *i.e.* municipal solid waste (MSW) compost, farmyard manure (FYM), organic manure, composted farmyard manure and cattle manure and slurry, ranging from 24 to 92% Diacono and Montemurro, 2010).

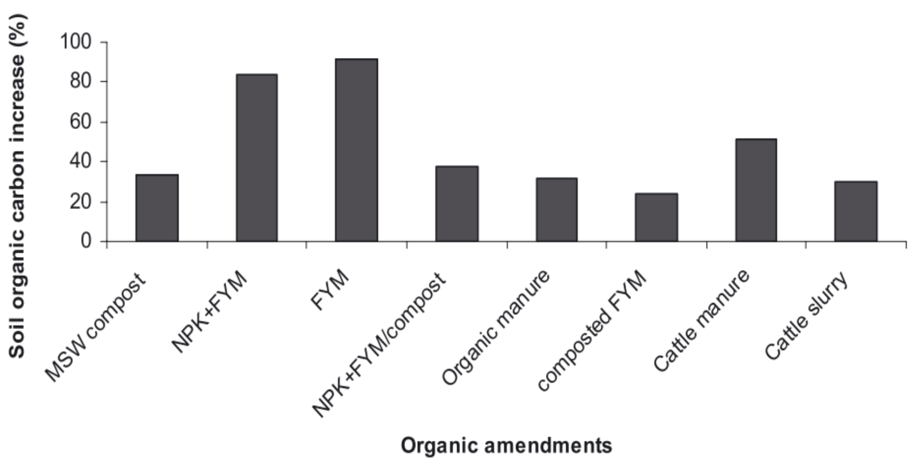


Figure OM-02. Increase in SOC after different long-term organic amendments. (Source: Diacono and Montemurro, 2010).

Studies with application of pig slurry, however, found no significant increment in SOC in amended soils as opposed to non-amended soils (Plaza *et al.*, 2002).
Frequency of application is another important factor. In conventional arable systems, which promote organic matter decomposition, SOC content begins to decline as soon as manure applications cease (Haynes *et al.*, 1998). Long-term experiments are necessary for monitoring and explaining SOC changes after addition of organic and inorganic materials, such as the often cited Rothamsted experiments (Reeves *et al*, 1997), see Figure OM-03 for example.

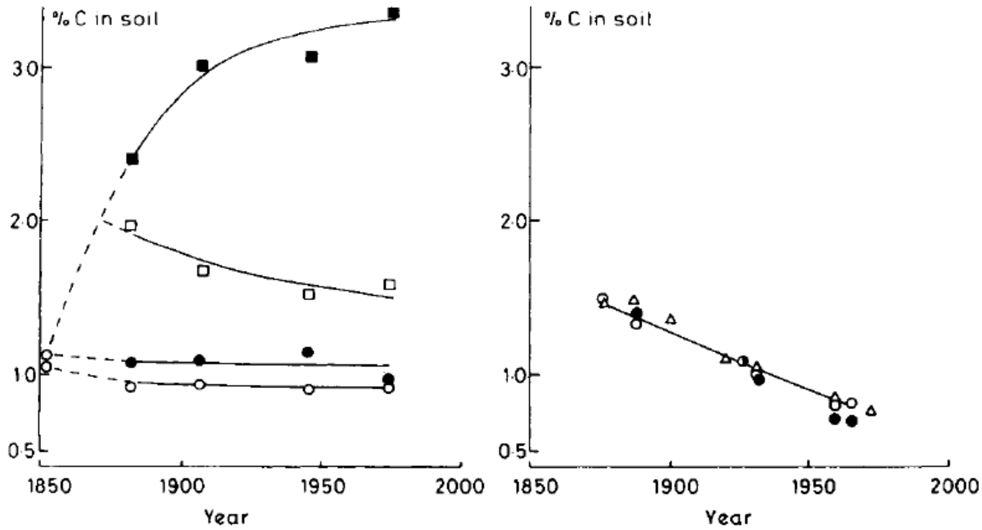


Figure OM-03. Changes in soil C content with time under all-arable cropping systems on a silty clay loam at Rothamsted (left), and a sandy loam at Woburn (right). Rothamsted: Barley grown each year, annual treatments since 1852: ○ unmanured; ● NPK fertilizers, 48 kg N ha^{-1}; ■ FYM 35 t ha^{-1}; □ FYM 1852-71, none since. Woburn: Cereals grown each year: ○ unmanured; ● NPK fertilizers; Δ A manured four-course rotation (Jenkinson and Johnston, 1977) (Source: Christensen and Johnston, 1997).

The iSQAPER project LTE data show that organic matter additions increased SOC content in the top soil layer as compared to unmanured treatments (Table OM-02, Figure OM-04).

Table OM-02. SOC changes under manured and unmanured trials within iSQAPER LTEs.

Trial name	Country	Response	Unmanured	Manured	Ratio
Aesch trial (since 2010)	Switzerland	Topsoil carbon content (%)	Treatment 1: 1.62 (2010) 1.61 (2012)	Treatment 3: 1.64 (2010) 1.72 (2012)	1.01 (2010) 1.07 (2012)
Therwil (since 1978) DOK trial	Switzerland	Topsoil carbon content (%)	Treatment 1: 1.02 (2006) 0.99 (2010)	Treatment 3: 1.49 (2006) 1.39 (2010)	1.46 (2006) 1.40 (2010)

Qiyang red soil fertility long-term experiment (since 1990) (CN1)	China	Topsoil carbon content (%)	Treatment 2: 0.92 (1992) 0.71 (2012)	Treatment 12: 1.04 (1992) 1.33 (2012)	1.13 (1992) 1.87 (2012)
Org-Conv system experiment (since 2008)	Estonia	Topsoil carbon content (%) - winter wheat - barley - potato - pea	Treatment M0: 1.48 (2012) 1.55 (2012) 1.57 (2012) 1.53 (2012)	Treatment M1: 1.68 (2012) 1.63 (2012) 1.65 (2012) 1.64 (2012)	1.13 (2012) 1.05 (2012) 1.05 (2012) 1.07 (2012)
Tillorg (since 1999)	Slovenia	Topsoil carbon content (%)	Treatment 1B: 2.20 (2004) 2.07 (2012)	Treatment 1C: 2.37 (2004) 2.22 (2012)	1.07 (2010) 1.07 (2012)

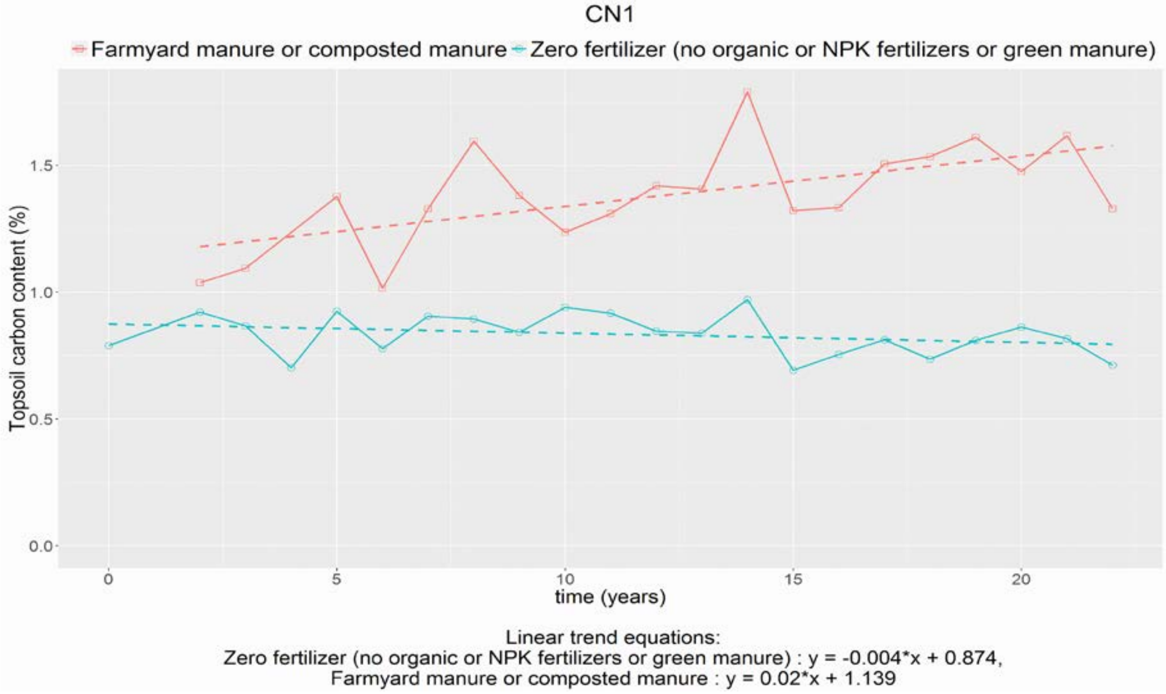


Figure OM-04. SOM/SOC trends under manured and unmanured trials within iSQAPER LTE site CN1 (Qiyang, China).

Similar trends have been found in other experiments:

- For the Askov long-term fertilization experiments in Denmark manure fertilizer increased SOC content by 23% vis a vis non-manured soils (Reeves, 1997).
- In the EU CATCH-C project, tested organic manures, *i.e.*, compost, farmyard manure and slurry application, increased SOC contents by 37%, 23% and 21%, respectively in the upper 10 cm and tended to increase with the duration of experiments (> 10 years compared to < 10 years, see Spiegel *et al*., 2015).

Xu *et al*. (2015a, 2015b) reported changes in soil properties (SOM/SOC, pH, bulk density, aggregate stability, water holding capacity, micro-biological diversity and abundances, plant-available N, P, K) over 30-year long-term experiments from 42 sites under various management practices; the experiments have been treated in a standard way: inorganic fertilizers (control, N, P, K, NP, NK, PK, NPK), organic matter (OM) inputs (crop residues, animal manure, green

manure) and defined combinations of inorganic and organic fertilizers (control, N plus OM, NP plus OM, NPK plus OM). They found that:

1) No fertilizer application (control): SOC contents declined on average by 0.13 t ha^{-1} y^{-1} in the black soil area in NE China (7.4% - 12.7%) and S China (10.6% - 18.1%); reduced on average by 0.03 t ha^{-1} y^{-1} in dry NW China and areas lacking irrigation in the Yangtze River Basin. The SOC content remained stable in the N China Plain and areas with irrigation and two rice cropping in the Yangtze River Basin.

2) N, P, K application: the SOC content increased in most regions of China, on average by 0.30 t ha^{-1} y^{-1} in the N China Plain (50%-68%) and non-irrigated areas in the Yangtze River Basin (8.6% - 23.5%); increased by 0.11 t ha^{-1} y^{-1} or 7.8% - 41.2%, in areas under irrigated two-rice cropping in the Yangtze River Basin; the SOC remained the same in NE China and red soil regions in S China;

3) N, P, K plus organic matter inputs: the SOC content increased significantly in all areas: 0.27 to 2.24 t ha^{-1} y^{-1} (average 0.69 t ha^{-1} y^{-1}) in NW China and N China Plain; on average 0.52 t ha^{-1} y^{-1} in the dry red soil region in S China and in the irrigated rice cultivation in the Yangtze River basin and 0.44 t ha^{-1} y^{-1} in NE China.

4) Return of crop straw to soils played a key role in increasing the SOC content: 0.49 t ha^{-1} y^{-1} in the Yangtze River basin, 0.41 t ha^{-1} y^{-1} in the N China Plain, and 0.23 t ha^{-1} y^{-1} in the NW China and the red soil region in S China.

5) There is a significant positive correlation between increase in the SOC content and amount of organic matter input (Figure OM-05); conversion rate of the organic matter input into SOC content was on average 16% nation-wide; however, it varied regionally 25.7% in NW China, 22% in the black soil region in NE China, 13.3% on the N China Plain, and 9.9% in the red soil region of S China.

6) Summarizing, Xu *et al*. (2015a, 2015b) **conclude that under current cultivated land management practices, to maintain at least a moderate level of soil fertility, straw application of 7.5-12 t ha^{-1} y^{-1}, or equivalent, to the soil is needed to restore the initial SOC content.**

7) There is a highly positive correlation between SOM content and yield under current management practices: on average an increase of 1 g kg^{-1} C could increase corn yield by 988 kg ha^{-1} and wheat yield by 957 kg ha^{-1} in N China; in S China, corn yield increase by 596 kg ha^{-1}, wheat yield 192 kg ha^{-1} and rice yield 613 kg ha^{-1}. There were upper threshold values for SOC content for above which crop yields did not improve: 18.5 g kg^{-1} in the black soil region in NE China, 11.4-12.9 g kg^{-1} in NW china, 9.2 g kg^{-1} in the N China Plain; conversely, such threshold values were not observed for the red soil region in S China nor the Yangtze River basin. Above the reported threshold values for SOC, crop yields could not be significantly increased.

8) If a target yield, *i.e.*, 90% of the maximum yield (corn and wheat), is set, and the demand of the corresponding SOC content is known some inferences can be made. Based on the above correlations between organic matter input, increase of SOC contents and

corresponding crop yield increases, addition of organic materials to current SOC contents, *e.g.*, by 10%, can be estimated.

To maintain medium- or high-level soil fertility, the following amounts of dry organic materials are needed (t ha^{-1} y^{-1}):

Region	Soil fertility level	
	Medium	High
NE China	3 - 5	13 - 31
NW China	9 - 20	19 - 49
S China	5 - 12	-
Yangtze River Basin	5 - 16	-

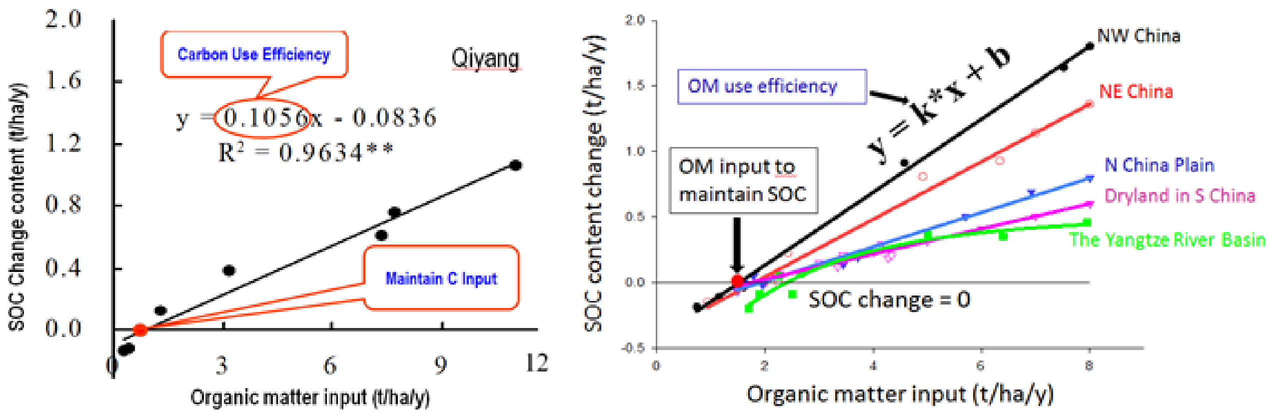


Figure OM-5. Relationships between SOC content and organic input in different regions of China (Adopted from Xu *et al*. 2016, personal communication).

Han *et al*. (2016) conducted a global meta-analysis of SOC changes under unbalanced application of chemical fertilizers (UCF), balanced application of chemical fertilizers (CF), chemical fertilizers with straw application (CFS), and chemical fertilizers with manure application (CFM) and found that topsoil organic C increased by 0.9 g kg^{-1}, 1.7 g kg^{-1}, 2.0 g kg^{-1} and 3.5 g kg^{-1} under UCF, CF, CFS and CFM, respectively. The C sequestration durations were estimated as 28–73 years under CFS and 26–117 years under CFM but with high variability across climatic regions. At least 2.0 Mg ha^{-1} y^{-1} C input is needed to maintain the SOC in ~85% cases; they highlighted a great C sequestration potential of applying CF, and adopting CFS and CFM is highly important for either improving or maintaining current SOC stocks across all agro–ecosystems. Additional references have been entered into the literature database for further statistical analysis in the synthesis section 3.2.

Overall impact evaluation: a very positive effect of organic material input on SOC content, + +.

pH

Effects of organic matter addition on changes in soil pH are not widely documented. Whalen *et al*. (2000) found that application of cattle manure to an acid soil had an immediate effect of soil pH, resulting a higher pH on the amended soil *vis á vis* the non-manured treatment. Haynes *et al*. (2001) reviewed studies on how soil pH was affected by organic matter addition, and reported that overall the soil pH increased when organic matter was added it had a shorter response period in comparison to the other indicators reviewed in this review. Soil type and buffering capacity influence pH change; application of 20 t ha^{-1} y^{-1} of dry organic matter could lead to an pH increase of 0.2-0.6 units; input of 40-50 t ha^{-1} y^{-1} could result in a pH increase of 0.8-1.5 units. Schjønning *et al*. (1994) found that pH declined slightly when organic matter is added to the soil. Slight increases in soil pH under organic material addition were observed in the iSQAPER LTEs data (Table OM-03 and Figure OM-06). The EU CATCH-C project found that compost addition caused a significant increase in soil pH (Catch-C, 2015).

Table OM-03. Soil pH (water) changes under manured and unmanured trials within iSQAPER LTEs.

Trial name	Country	Response	Unmanured	Manured	Ratio
Aesch trial since 2010	Switzerland	soil pH (-)	Treatment 1: 7.43 (2010)	Treatment 3: 7.37 (2010)	0.99 (2010)
Therwil since 1978 DOK trial	Switzerland	soil pH (-)	Treatment 1: 5.70 (2006) 5.95 (2012)	Treatment 3: 6.78 (2006) 6.69 (2012)	1.19 (2006) 1.12 (2012)
Qiyang red soil fertility long-term experiment since 1990	China	soil pH (-)	Treatment 2: 6.68 (1993) 5.64 (2011)	Treatment 12: 6.7 (1992) 6.50 (2011)	1.00 (1992) 1.15 (2011)
Zhifangggou since 1985	China	soil pH (-)	Treatment pre: 8.65 (Before 1989)	Treatment 1: 8.54 (2004) 8.56 (2012)	0.99 (pre-2004) 0.99 (pre-2012)
Org-Conv system experiment since 2008	Estonia	soil pH (-) - winter wheat - barley - potato - pea	Treatment M0: 5.83 (2014) 6.01 (2014) 5.96 (2014) 5.95 (2014)	Treatment M2: 6.10 (2014) 5.91 (2014) 6.04 (2014) 6.00 (2014)	1.04 (2014) 0.98 (2014) 1.01 (2014) 1.01 (2014)
Tillorg	Slovenia	soil pH (-)	Treatment 1: 6.63 (2004) 6.42 (2012)	Treatment 2: 6.70 (2004) 6.49 (2012)	1.01 (2004) 1.01 (2012)

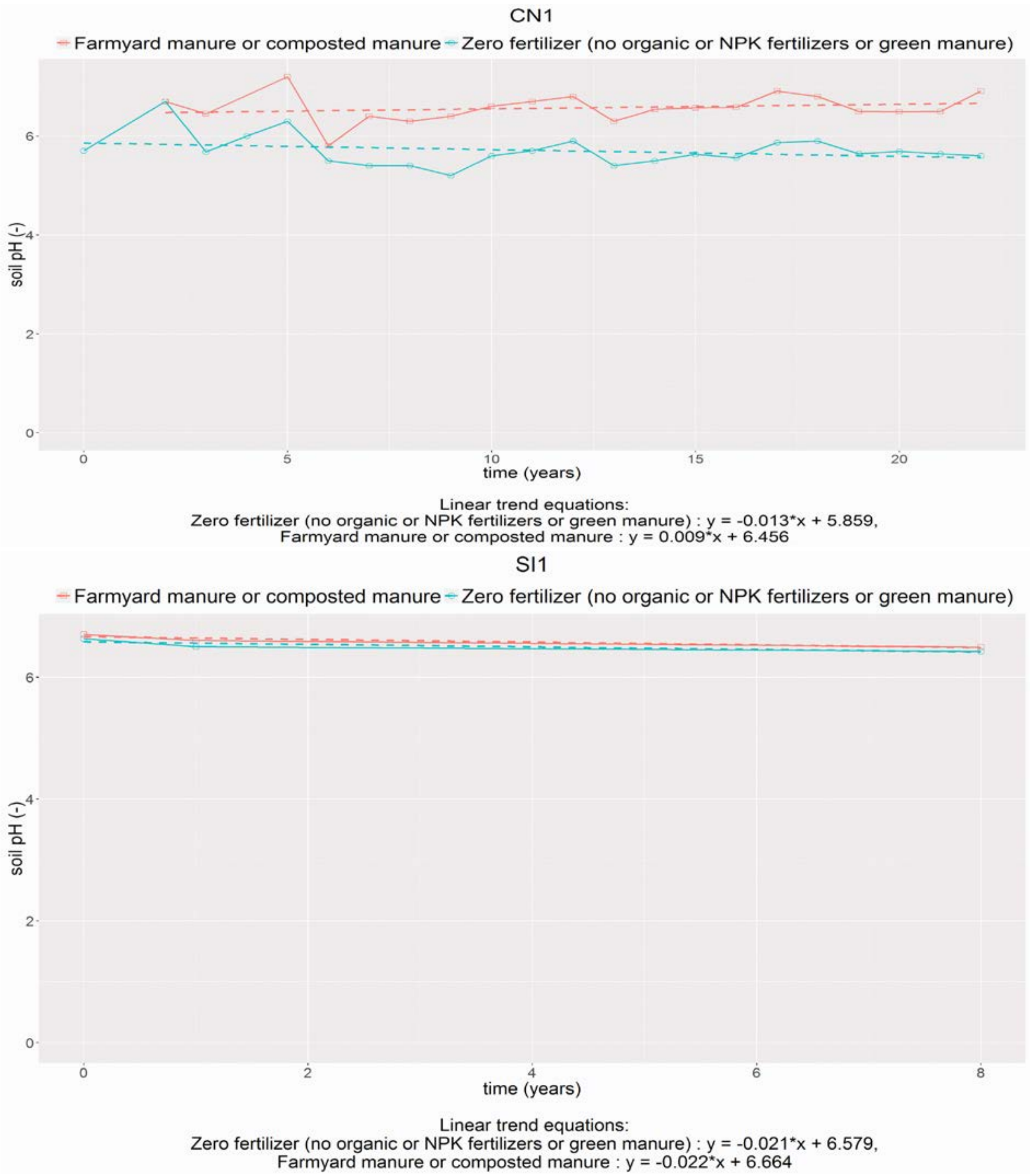


Figure OM-6. Trends in soil pH under manured and unmanured trials for iSQAPER LTE sites CN1 (Qiyang, China) and SI1 (Tillorg, Slovenia)

Overall impact evaluation: OM addition slightly increases soil pH, +.

Aggregate stability/Soil structure

Aggregate stability is influenced by different soil properties of which organic matter content is a major factor (Abiven *et al*., 2009). There is a high and positive correlation between SOC content and soil aggregate stability (Darwish *et al*., 1995; Haynes and Naidu, 1998b). Organic matter additions can increase SOC content thereby enhancing aggregation. However, depending on the organic matter (quality and quantity) addition and experimental conditions, contradictory results can be observed in different studies (Albiach *et al*., 2001).

Abiven *et al* (2009) found that soil aggregate stability can be influenced by many factors, including texture, clay, mineralogy, cation content, aluminium and iron oxides as well as climatic conditions, agricultural management practices and rates of organic addition decomposition; results were classified according to their magnitude which was calculated as the ratio between a measured parameter (in this case aggregate stability) for soil with organic input and the value reported for the control soil (no organic addition), based on 16 field experiments (the review also includes controlled experiments). Abiven *et al* (2009) found that organic input increased aggregate stability by a ratio of 1.1 (18 year and 3 year experiment with manure application) to 5.2 (3 year experiment with de-inking paper sludge as organic input); after 37 year of fresh manure application, aggregate stability increased by a ratio of 1.1 to 2.3.

Addition of legumes to pastures did not change the aggregate size distribution but increased the stability of aggregates against slaking in eastern Colombian savannas (Gijsman and Thomas, 1995). Guidi *et al* (1988) found that there was no significant change of soil aggregate stability after the application of up to 300 kg N ha^{-1} as manure or compost for a short term experiment (2 years).

In the iSQAPER project LTEs, a decline in aggregate stability under green manure amendment was observed in Estonia (Table OM-04 and Figure OM-07).

Table OM-04. Changes in aggregate stability under manured and unmanured trials within iSQAPER LTEs.

Country	Response	Year	Time	Zero fertilizer (no organic or NPK fertilizers or green manure)/ Potato	Green manure only/Potato	Ratio
Estonia	Water stable soil aggregates (WSA), %	2012	0	64.81	64.81	1
Estonia	Water stable soil aggregates (WSA), %	2013	1	62.05	61.42	0.99
Estonia	Water stable soil aggregates (WSA), %	2014	2	64.36	51.67	0.8
Estonia	Water stable soil aggregates (WSA), %	2015	3	53.75	53.81	1

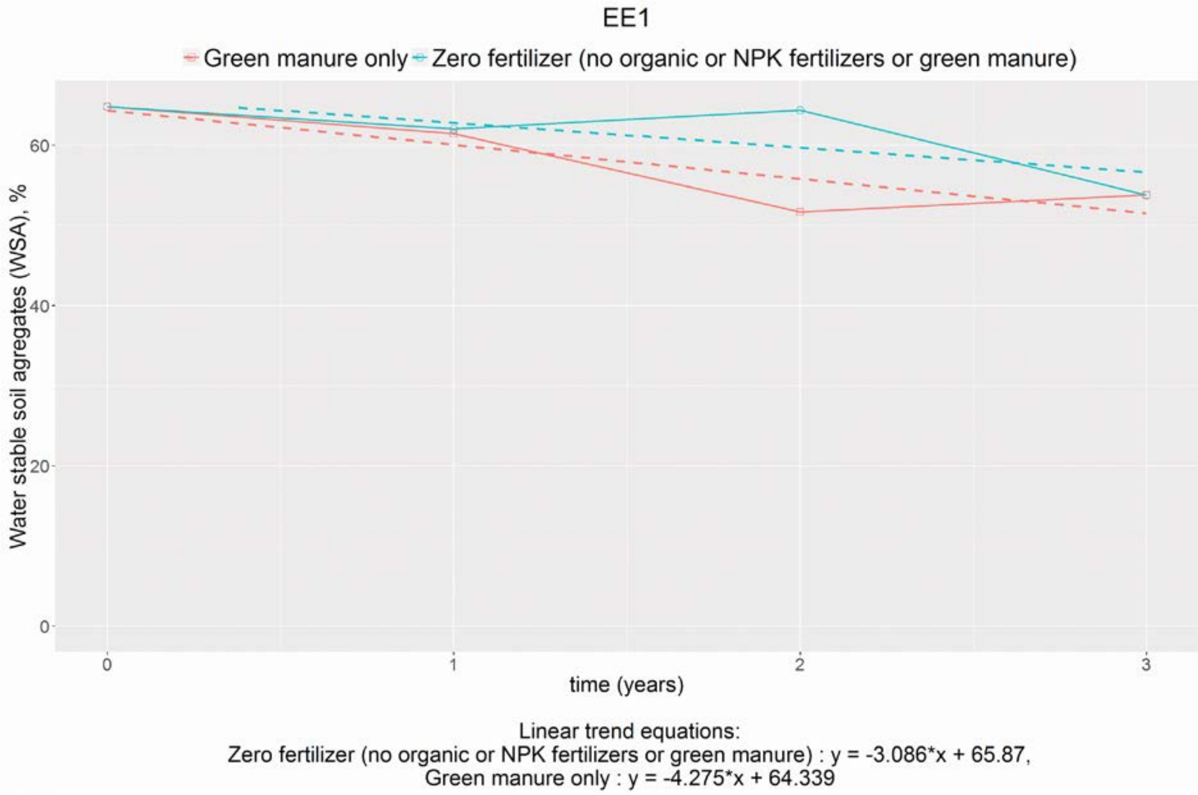


Figure OM-07. Trends in aggregate stability under manured and unmanured trials for iSQAPER LTE site EE1 (Org-Conv system experiment, Estonia).

A positive effect of organic matter additions on soil aggregate stability was found in the CATCH-C (2015) project, in particular for application of sludge and fresh manure.

Overall impact evaluation: a positive effect of organic input on soil aggregate stability, +.

Water holding capacity

Khaleel *et al.* (1981) reported that an increment of SOC due to addition of organic matter led to an increase in water holding capacity. This finding is corroborated by the iSQAPER LTE data (Table OM-05).

Table OM-05. Changes in water holding capacity under manured and unmanured trials by iSQAPER LTEs.

Trial name	Country	Response	Unmanured	Manured	Ratio
Org-Conv system experiment *since 2008*	Estonia	Max. water holding capacity (%) - winter wheat - barley - potato - pea	Treatment M0: 28.09 (2013) 26.95 (2013) 26.19 (2013) 24.87 (2013)	Treatment M2: 30.63 (2013) 28.81 (2013) 30.00 (2013) 29.42 (2013)	 1.09 1.06 1.14 1.18

Overall impact evaluation: a positive effect of organic input on WHC, +.

Earthworms

Bertrand *et al*. (2015) found that earthworm communities increased, in terms of abundance and/or species diversity, when organic matter was added into soils: in plots supplied with different types of compost, more individuals per square metre were found than in unamended plots. The increase was driven by different variables including application rate (Haynes and Naidu, 1998), nature of organic amendments and their quality (Bertrand *et al*., 2015). Andersen (1980) applied different rates of farmyard manure and slurry to Danish test sites and found an increase in earthworm numbers in the manured plots compared to the control plots. D'Hose *et al*. (2014b) found that additions of farmyard manure increased the number of earthworms per square metre more than compost input did; they also indicated that soil texture could be a factor influencing earthworms abundance.

Results from the literature review are in agreement with those of the long-term experiments. In the "classical experiments" in Rothamsted, application of dung, fish meal and other organic fertilizers increased earthworm population (Edwards, 1980). Similarly, the CATCH-C project reported a significant increase in the amount of earthworms for all organic amendments. Overall, farmyard manure and animal slurry application has a positive effect on earthworms abundance as does compost compared to no organic material input (Table OM-06).

Table OM-06. Earthworm numbers under different organic amendments (from the Catch-C Project Deliverable D3.344).

Organic amendment	n	min	max	mean	stdev	skewness	kurtosis	normality test	t-test
COMP	29	8	238	75	73	1.04	0.49	0.065ns	0.005**
FYM	7	58	569	320	255	-0.08	-3.2	0.141ns	0.027*
S	6	-6	591	283	266	-0.01	-2.69	0.200ns	0.048*

COMP: compost application; FYM: farmyard manure application; S: animal slurry application

In the iSQAPER LTEs earthworms abundance was more than double under organic input than that under no-organic application (Table OM-07).

Table OM-07. Soil earthworms under manured and unmanured trials within iSQAPER LTEs.

Trial name	Country	Response	Unmanured	Manured	Ratio
Org-Conv system experiment *since 2008*	Estonia	Earthworm abundance (individual m^{-2}) - winter wheat - barley - potato - pea	Treatment M0: 13.75 (2013) 8.12 (2013) 10.62 (2013) 20.62 (2013)	Treatment M2: 38.75 (2013) 18.12 (2013) 39.37 (2013) 56.87 (2013)	 2.81 2.23 3.70 2.75

Alternatively, Riley *et al*.(2008) found that some organic additions, such as slurry, may be toxic for earthworms; this issue could be addressed by law or regulations (Emmerling *et al*., 2010).

Overall impact evaluation: a very positive effect of organic input on earthworms, + +.

3.1.2 Tillage practices

Tillage is widely used for loosening and homogenising the topsoil, suppressing weeds/pests, management of residues, incorporating and mixing of substances such as fertilizers, manures and seeds, and levelling or ridging of the land in order maintain the soil in suitable physical condition for crop production. Consequently, a change or difference in tillage practices can result in changes in biological, chemical and physical properties of soil, resulting in changes in functional quality of the soil (Chan, 2001; Islam *et al*., 2000) as well as the soil's capacity to provide ecosystem services (Funk *et al*., 2015; Palm *et al*., 2014). However, how will all these interacting factors and processes ultimately affect soil quality and functioning? In addition, how will such effects change with climate change, socio-economic drivers, and duration of the various tillage practices? When comparing system performance measures between tillage systems, as illustrated in Figure NT-01, it is important to be aware of the significant and numerous factors involved in tillage performance (Morris *et al.*, 2010). Such confounding effects should ideally be 'teased out' during analysis of long-term (paired) data sets. Importantly, the view of land managers should be taken into account when evaluating various sets of indicators for soil quality (Lima *et al*., 2013; Palm *et al*., 2014).

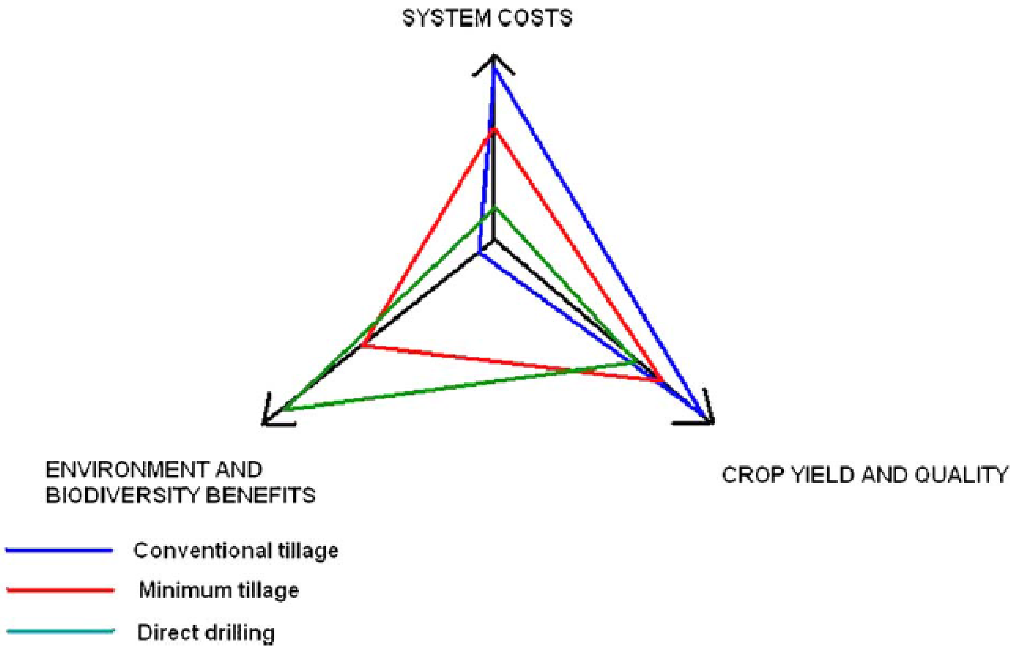


Figure NT-01. Performance measures relating to the different tillage systems (Source: Morris *et al*., 2010).

Conventional tillage (CT) or full-inversion tillage (FIT) involves disking, ploughing and other methods of tilling up crop residue left behind after harvest (Figure NT-02). Alternatively, conservation tillage or no-till (NT) is focussed on limited disturbance (*i.e*. non-inversion) of the soil. The objective of NT practices is to promote a better cohesion between soil aggregates, decrease soil organic matter mineralisation, and allow the development of soil biota (Scopel *et al*., 2013).

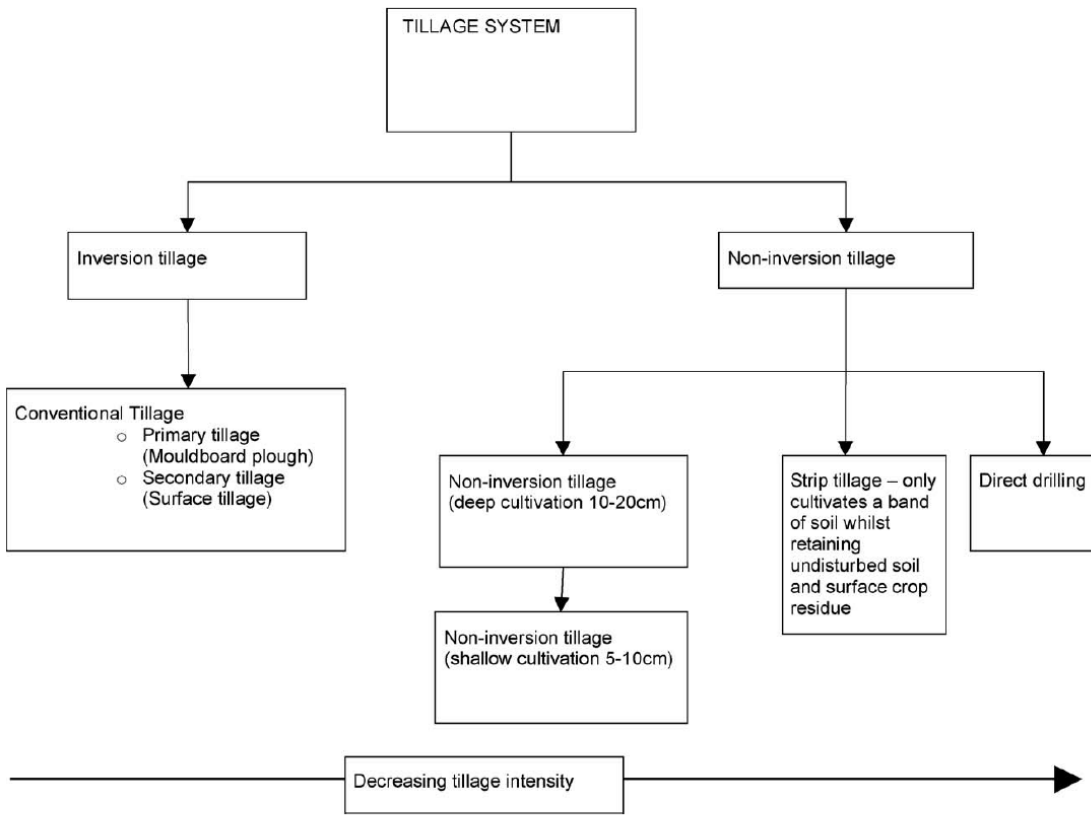


Figure NT-02: Classification of tillage systems in relation to tillage intensity (Source: Morris *et al*., 2010)

Conservation tillage practices include zero tillage (no-till), reduced (minimum) tillage, mulch tillage, ridge tillage and contour tillage (Busari *et al*., 2015). No -illage (NT) comprises land cultivation with little or no soil surface disturbance, the only disturbance being during planting. Minimum tillage implies a reduced level of soil manipulation that involves ploughing using primary tillage implements. In mulch tillage, the soil is prepared or tilled in such a manner that the plant residues or other materials are left to cover the surface to a maximum extent. In ridge tillage, crops are planted in rows either along both sides or on top of the ridges; the ridges are prepared at the start the cropping season. Contour tillage refers to tillage at right angles to the direction of the slope (Busari *et al*., 2015). Conservation agriculture has been promoted as a way to reduce production costs, soil erosion and soil fertility degradation under both tropical and temperate conditions (Palm *et al*., 2014; Scopel *et al*., 2013).

Soil quality or condition is best assessed by soil properties that are neither so permanent as to be insensitive to management, nor so easily changeable as to give little indication of long-term alterations (Bertrand *et al*., 2015; Islam *et al*., 2000; Pittelkow *et al*., 2015; Scopel *et al*., 2013). It is clear that soil tillage can affect soil quality, hence soil functioning, in various ways depending on the agro-system under consideration. Tillage may cause mechanical changes in soil structure with concomitant changes in, for example, soil structure, aeration, organic carbon content, bulk density, water holding capacity, and soil hydraulic properties (Strudley *et al*., 2008). Such changes, in turn, will affect chemical movement and plant growth.

Yield

The experimental comparison of CT and NT systems on crop yields has received much attention across the world (*e.g.* Holland, 2004; Palm *et al*., 2014; Scopel *et al*., 2013; Soane *et al*., 2012; Strudley *et al*., 2008; Zhang *et al*., 2009). Soane *et al* (2012) reviewed no-till application in various countries in Europe (Table NT-01); the ratio of the average yield recorded under NT and CT is 0.96.

Although no-till suggests merely the absence of tillage, in reality several components need to be applied to a conservation agriculture system to guarantee similar or higher yields and better environmental performance than with conventional tillage systems (Derpsch *et al*., 2014). Most recently and comprehensively, Pittelkow *et al*. (2015) evaluated the influence of various crop and environmental variables on NT versus CT yields. Their state-of-the-art global meta-data analysis, considered data from 678 peer-reviewed publications, representing 6005 paired observations, and covering 50 crops and 63 countries. Side-by-side or so-called ‘paired’ yield comparisons were restricted to studies comparing CT to NT practices in the absence of other cropping system modifications. Cooper *et al* (2016) found that reducing tillage intensity in organic systems reduced crop yields by an average of 7.6 % compared to deep inversion tillage with no significant reduction in yield compared to shallow inversion tillage; shallow noninversion tillage resulted in non-significant reductions in yield relative to deep inversion; whereas deep non-inversion tillage resulted in the largest yield reduction, of 11.6 %; using inversion tillage to only a shallow depth resulted in minimal reductions in yield, of 5.5 %, but significantly higher soil C stocks and better weed control.

Pittelkow *et al*. (2015) found that crop category was the most important factor influencing the overall yield response to NT followed by aridity index, residue management, no-till duration, and Nitrogen application rate. Responses varied with and between crop types (Figure NT-03). NT yields were similar to conventional tillage yields for oilseed, cotton, and legume crop categories. When considering cereal crops, the negative impacts of NT on yield were smallest for wheat (−2.6%) and largest for rice (−7.5%) and maize (−7.6%). According to Pittelkow *et al*. (2015), NT systems performed best under rainfed conditions in dry climates, with yields often being equal to or higher than for CT (Figure NT-04). Further, they observed that yields in the first 1–2 years following NT implementation decreased for all crops except oilseeds and cotton, but matched CT tillage yields after 3–10 years except for maize and wheat in humid climates. Overall, no-till yields were reduced by 12% without N fertilizer addition and 4% with inorganic N addition (Pittelkow *et al*., 2015) for the considered paired observations.

Ploughed yield ($t\ ha^{-1}$)	No-till as % of ploughed
4.3	95
4.3	100
5.89	61
6.38	91
4.95	66
5.38	34
5.17	99
6.26	95
4.25	88
4.89	91
2.44	89
4.13	96
5.52	101
4.36	83
8.57	83
4.79	91
8.80	99
8.40	105
7.79	92
8.37	102
8.59	102
7.82	101
2.62	103
0.87	108
3.50	100
1.00	200
2.22	103
1.73	98
1.89	113

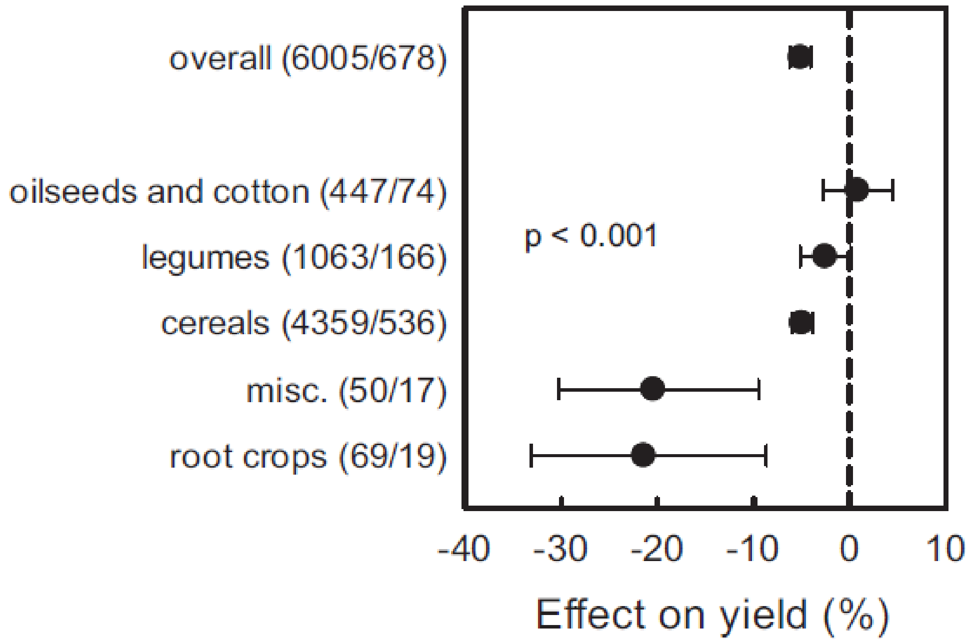


Figure NT-03. Yield impacts of no-tillage relative to conventional tillage for different crop categories. The misc(ellaneous) category included broccoli, coffee, cucumber, lettuce, mustard leaf, pepper, squash, tobacco, tomato, and watermelon. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals (Source: Pittelkow *at al.* 2015).

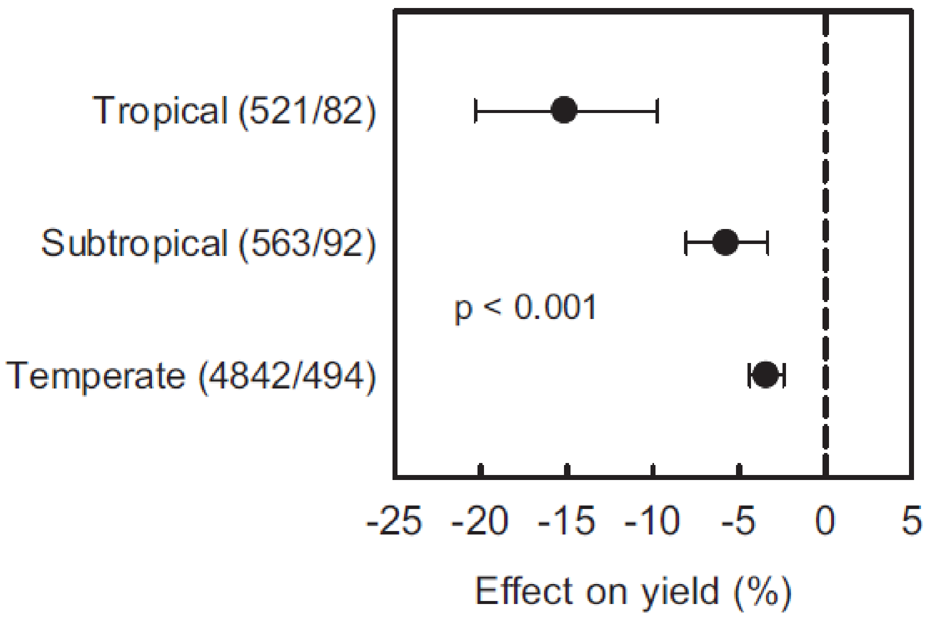


Figure NT-04. Yield impacts of no-till relative to conventional tillage in tropical, subtropical, and temperate latitudes. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals (Source: Pittelkow *at al*. 2015).

For Ontario, the average 20-year maize grain for CT was 6.5 t ha^{-1} or 5.3% greater than NT tillage and 1.4% greater than ridge tillage. Although there was profound year to year variation in yield during the experiment as a result of weather conditions, there was no obvious yield trend due to the maturation of the soils under the no-tillage treatment (Drury *et al*., 2004). In general, the maize grain yields were similar across all three tillage treatments in moist years when yields were above 6 t ha^{-1}. However, in 1991 and 1993 when yields were reduced by severe July and August droughts, conventional tillage substantially outperformed conservation tillage.

For a thorough inter-comparison of results from various locations worldwide, however, no-tillage research should be standardised (Derpsch *et al*., 2014). Interestingly, aspects such as slope, soil type and stoniness are seldom taken into account explicitly as possible determinants of soil quality. However, research carried out in the UK between 1998 and 2002 showed that yields were affected when comparing different tillage systems on light, medium and heavy soils (Knight, 2004, as cited in Morris *et al*., 2010). The authors found that direct drilling gave 25–40% lower yields in two out of three years compared to non-inversion or conventional tillage on a clay soil. However, non-inversion tillage was found to give the highest yields in all years on the light chalk soil (Knight, 2004). Cannell *et al*. (1994) reported that in long-term tillage experiments (over 10 years) yields in winter cereals have been similar between non-inversion and conventional tillage systems, but yields of spring-sown cereals have sometimes been lower after direct drilling than compared to ploughing. Higher mineralization and/or leaching rate could explain the reduction in organic C and total N under tilled plot due to soil structure deterioration following tillage (Busari *et al*., 2015). As such, importantly, the view of land managers should be taken into account when evaluating various sets of indicators for soil quality (Lima *et al*., 2013). Finally, Derpsch *et al*. (2014) contend that standardization of research methodologies in no-tillage/conservation agriculture systems is needed, based on a thorough description of the whole system so that results from different researchers and regions of the world can be compared logically and consistently.

The iSQAPER LTEs (Table NT-02-1, Table NT-02-2, Table NT-02-3 and Figures NT-05 and NT-06) show that, overall, NT tillage treatments resulted in lower yields compared to conventional tillage.

Table NT-02-1. Effects of tillage practices on crop yields as derived from the iSQAPER long-term experiments at Keszthely (HU3), Hungry.

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25cm depth)	No tillage	Ratio
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1964	0	17.22	22.32	1.3
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1974	10	24.18	14.65	0.61
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1984	20	8.22	14.93	1.82
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1994	30	3.49	2.5	0.72
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	2004	40	14.03	18.39	1.31

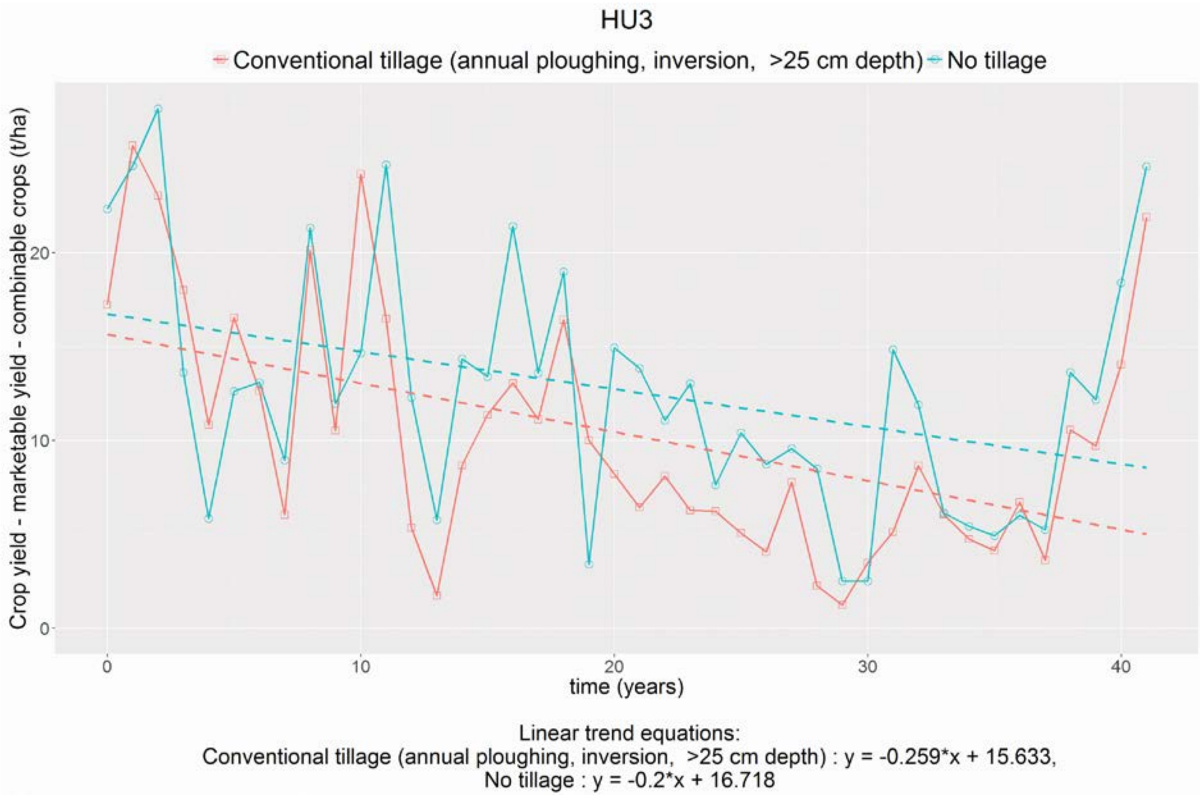


Figure NT-05. Yield trends under different tillage practices from the iSQAPER long-term experiment at Keszthely (HU3), Hungary.

Table NT-02-2. Effects of tillage practices on crop yields as derived from the iSQAPER long-term experiments at Keszthely (HU4), Hungry.

Trial name	Country	Response	Year	Time	Conventional tillage	Minimum tillage	Ratio
Tillage in maize-wheat bi-culture (Keszthely)	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1974	1	3.89	3.4	0.87
Tillage in maize-wheat bi-culture (Keszthely)	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1983	10	2.19	1.81	0.83
Tillage in maize-wheat bi-culture (Keszthely)	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1993	20	2.36	1.91	0.81
Tillage in maize-wheat bi-culture (Keszthely)	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	2003	30	2.07	1.32	0.64

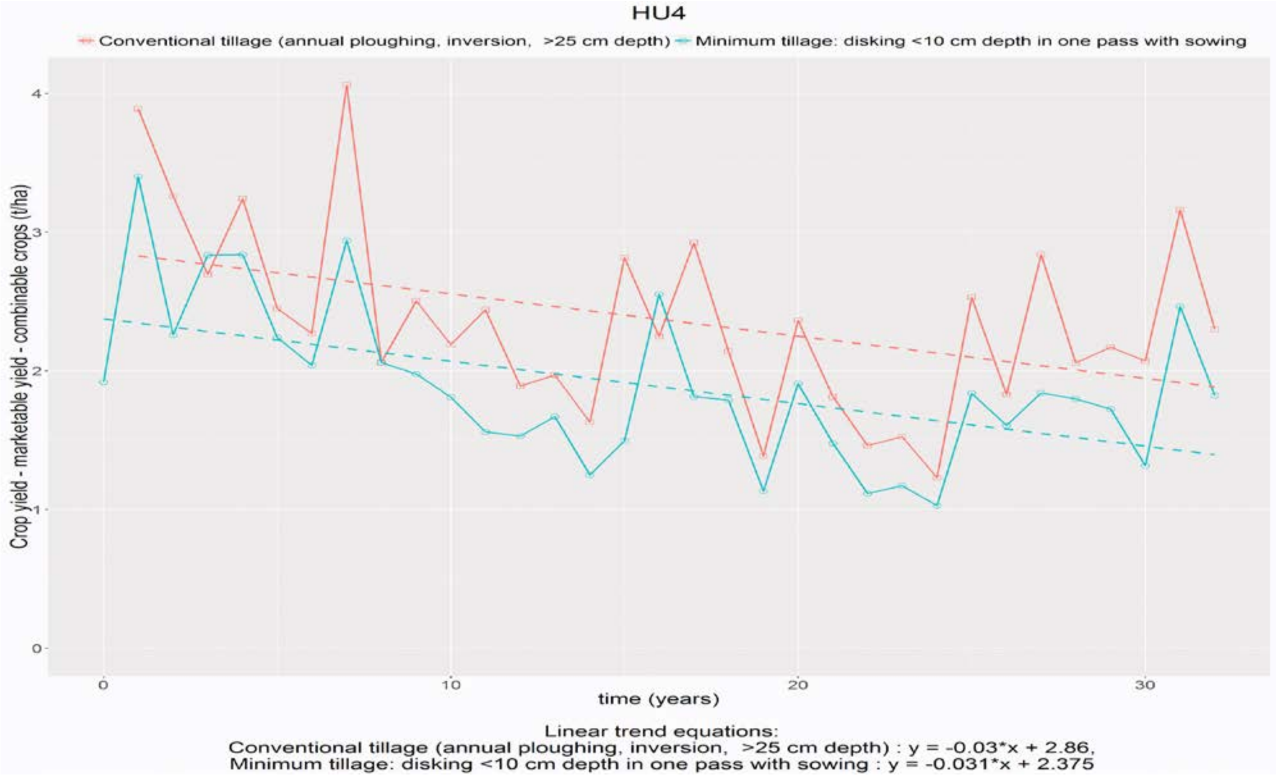


Figure NT-06. Yield trends under different tillage practices from the iSQAPER long-term experiment at Keszthely (HU4), Hungary.

Table NT-02-3. Effects of tillage practices on crop yields as derived from the iSQAPER long-term experiments.

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Braila	Romania	Crop yield - marketable yield - non-combinable crops (t ha^{-1})	2002	0	3.23	2.64	0.82
Braila	Romania	Crop yield - marketable yield - non-combinable crops (t ha^{-1})	2003	1	2.67	2.28	0.85
Braila	Romania	Crop yield - marketable yield - non-combinable crops (t ha^{-1})	2004	2	10.53	10.1	0.96

Overall impact evaluation: the impact of NT versus CT on crop yield is considered to be a small negative impact, or no impact: -, 0.

SOM/SOC

Annual no-tillage, implying yearly practice of no-till system over a long period, is beneficial to maintenance and enhancement of the structure and chemical properties of the soil, most especially the soil organic carbon (SOC) content (Busari *et al*., 2015; Lal *et al*., 1997; Luo *et al*., 2010). Higher mineralization and/or leaching rate subsequent to tillage may cause a reduction in organic C and total N (Busari *et al*., 2015). With annual no-tillage, plant residues left on the soil surface increase the organic matter content in the topsoil until a new equilibrium level is reached. While the adoption of NT usually leads to the accumulation of SOC in the surface soil layers (Palm *et al*., 2014), a number of studies have shown that this effect is sometimes partly or completely offset by greater SOC content near the bottom of the plough layer under full-inversion tillage (Angers *et al*., 2008). According to Baker *et al*. (2007), in the few studies where sampling extended deeper than 30 cm, conservation tillage has shown no consistent accrual of SOC, instead showing a difference in the distribution of SOC, with higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage.

To be meaningful and comparable, possible effects of changes in soil management on bulk density, SOC stocks, and nutrient stocks over time should be presented on an equivalent mass basis (ESM), and not the still commonly used fixed depth (FD) basis (Batlle-Bayer *et al*., 2010; Ellert *et al*., 2002; Wendt *et al*., 2013; Wuest, 2009; Yang *et al*., 2013). Overall, this complicates comparison of results from different researchers as the data provided in the original papers often do not allow for the necessary recalculation, for example the depth of sampling may have been too shallow. Evaluation of the relative carbon balance for no-till and ploughing depends upon complex inter-relationships between soil and climate factors, as well as management, which are

as yet poorly understood (Lal *et al*., 1997; Soane *et al*., 2012), and may further be affected by sampling errors and analysis methodology (Luo *et al*., 2010).
Management induced changes in the respective C pool sizes of fractions, *e.g*. from labile to recalcitrant, will also affect the overall quality of the soil organic matter present (Kogel-Knabner *et al*., 2005; Leifeld *et al*., 2005). Overall, the labile pools will be most important for biological activity and agricultural production, while the more stable fractions are most important for long-term carbon sequestration.

Morris *et al.* (2010), in a study for the UK, reported that the adoption of NT usually leads to the accumulation of SOC in the surface soil layers, but a number of studies have shown that this effect is sometimes partly or completely offset by greater SOC content near the bottom of the plough layer under full-inversion tillage (Angers *et al*., 2008; Baker *et al*., 2007; Umiker *et al.*, 2009). On average, there was 4.9 Mg ha^{-1} more SOC under NT than FIT (P = 0.03). Overall, this difference in favour of NT increased significantly but weakly with the duration of the experiment (R^2 = 0.15, P = 0.05). The relative accumulation of SOC at depth under FIT could not be related to soil or climatic variables in the study (Morris *et al*., 2010). According to Umiker *et al*. (2009), direct seeding management can increase near-surface SOC and TN (total N) concentrations compared to CT practices, but SOC concentrations deeper in the soil appeared to remain the same or possibly decrease. Higher SOC and TN near the soil surface, as found in direct seeding (DS) fields, appear to promote greater earthworm densities, which may improve long-term soil productivity (Umiker *et al.*, 2009). The organic matter accumulating at depth under full-inversion tillage appeared to be present in relatively stable form (Morris *et al*., 2010), but this hypothesis and the mechanisms involved require further investigation (Filley *et al.*, 2006; Gulde *et al*., 2008; Kogel-Knabner *et al*., 2005; Leifeld *et al.*, 2005; Li *et al*., 2009). Although there are other good reasons to use conservation tillage, as overall it will increase soil quality, the evidence that it promotes net C sequestration is not compelling according to various authors (Baker *et al*., 2007; Powlson *et al*., 2012; Powlson *et al*., 2014; Yang *et al*., 2013).

Many soil C studies have indicated that the impacts of NT on soil C sequestration are compounded by many environmental and management factors, as well as by sampling errors and analysis methodology, thus site specific. As such, such results should not be generalised (Luo *et al*., 2010; Yang *et al*., 2013). For example, using meta-analysis, Luo *et al*. (2010) assessed the response of SOC to conversion of management practice from CT to NT based on global data from 69 paired-experiments, where soil sampling extended deeper than 40 cm. They found that cultivation of natural soils for more than 5 years, on average, resulted in soil C loss of more than 20 t ha^{-1}, with no significant difference between CT and NT. Conversion from CT to NT changed distribution of C in the soil profile significantly, but did not increase the total SOC except in double cropping systems. After adopting NT, soil C increased by 3.15 ± 2.42 t ha^{-1} (mean ± 95% confidence interval) in the surface 10 cm of soil, but declined by 3.30 ± 1.61 t ha^{-1} in the 20–40 cm soil layer. Overall, adopting NT did not enhance soil total C stock down to 40 cm. Increased number of crop species in rotation resulted in less C accumulation in the surface soil and greater C loss in deeper layer. Increased crop frequency seemed to have the opposite effect and significantly increased soil C by 11% in the 0–60 cm soil. Neither mean annual temperature and mean annual rainfall nor nitrogen fertilization and duration of adopting NT affected the response of soil C stock to the adoption of NT in the meta-analysis by Luo *et al*. (2010). According to

Palm *et al*'s (2014), who reviewed 100 'NT-CT comparisons', soil C stock in NT was lower in 7 cases, higher in 54 cases and equal in 39 cases compared with CT in the 0- to 30-cm soil depth after 5 years or more of NT implementation.

In the iSQAPER LTEs (Table NT03-1, NT-03-2), on average, SOC content was greater under NT than CT, which is in agreement with other findings.

Table NT-03-1. Effects of tillage practices on soil organic matter carbon content as derived from the iSQAPER long-term experiments (expressed in % mass).

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Teularet	Spain	SOC content	2004	0	1.47	1.26	0.86
Teularet	Spain	SOC content	2005	1	1.23	1.7	1.38
Teularet	Spain	SOC content	2006	2	1.35	1.49	1.1
Teularet	Spain	SOC content	2007	3	1.32	1.85	1.4
Teularet	Spain	SOC content	2008	4	1.3	1.86	1.43
Teularet	Spain	SOC content	2009	5	1.46	2.39	1.64
Teularet	Spain	SOC content	2010	6	1.31	1.74	1.33
Teularet	Spain	SOCcontent	2011	7	1.32	2.47	1.87
Teularet	Spain	SOC content	2012	8	1.48	2.71	1.83
Teularet	Spain	SOC content	2013	9	1.35	2.3	1.7
Teularet	Spain	SOC content	2015	11	1.47	2.43	1.65

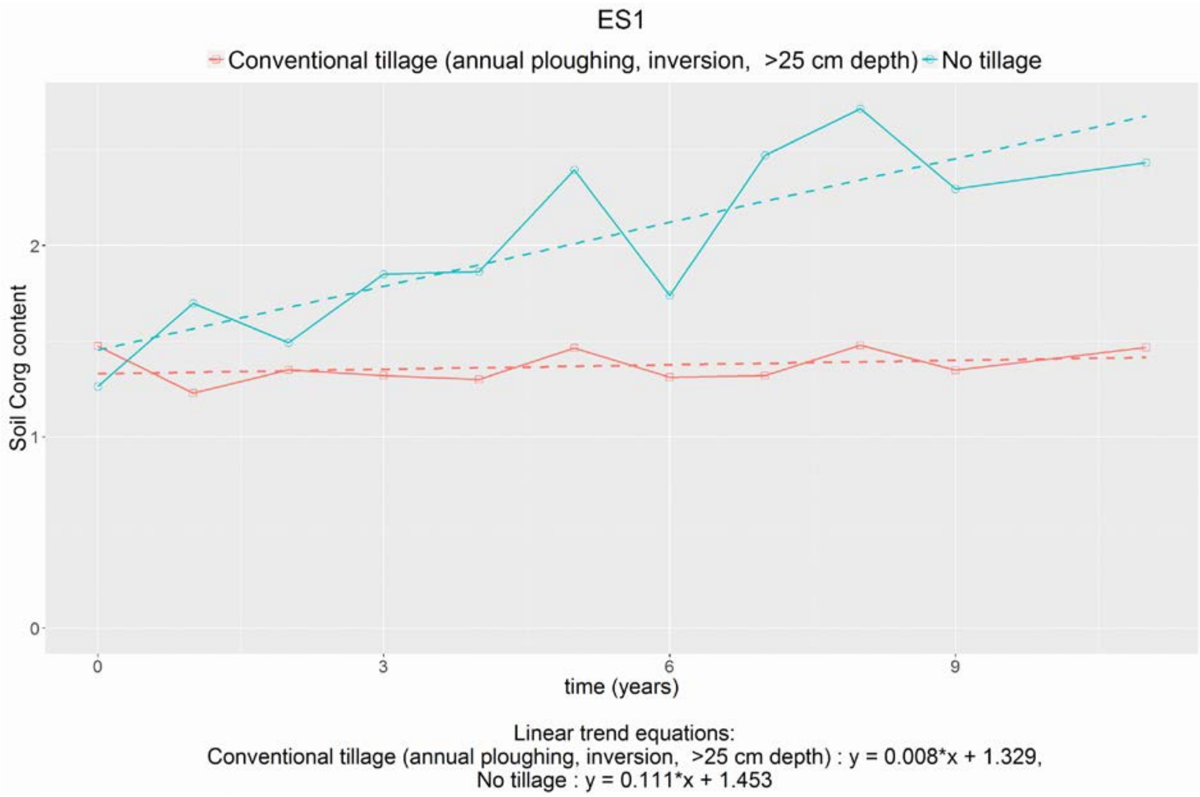


Figure NT-07. Trends of SOC content under no-till and conventional tillage from the iSQAPER LTE site ES1 (Teularet, Spain).

Table NT-03-2. Effects of tillage practices on SOC content as derived from the iSQAPER long-term experiments (expressed in % mass).

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Braila	Romania	SOC content (%)	2002	0	1.56	1.61	1.03
Braila	Romania	SOC content (%)	2003	1	1.71	1.72	1.01
Braila	Romania	SOC content (%)	2004	2	1.63	1.67	1.02

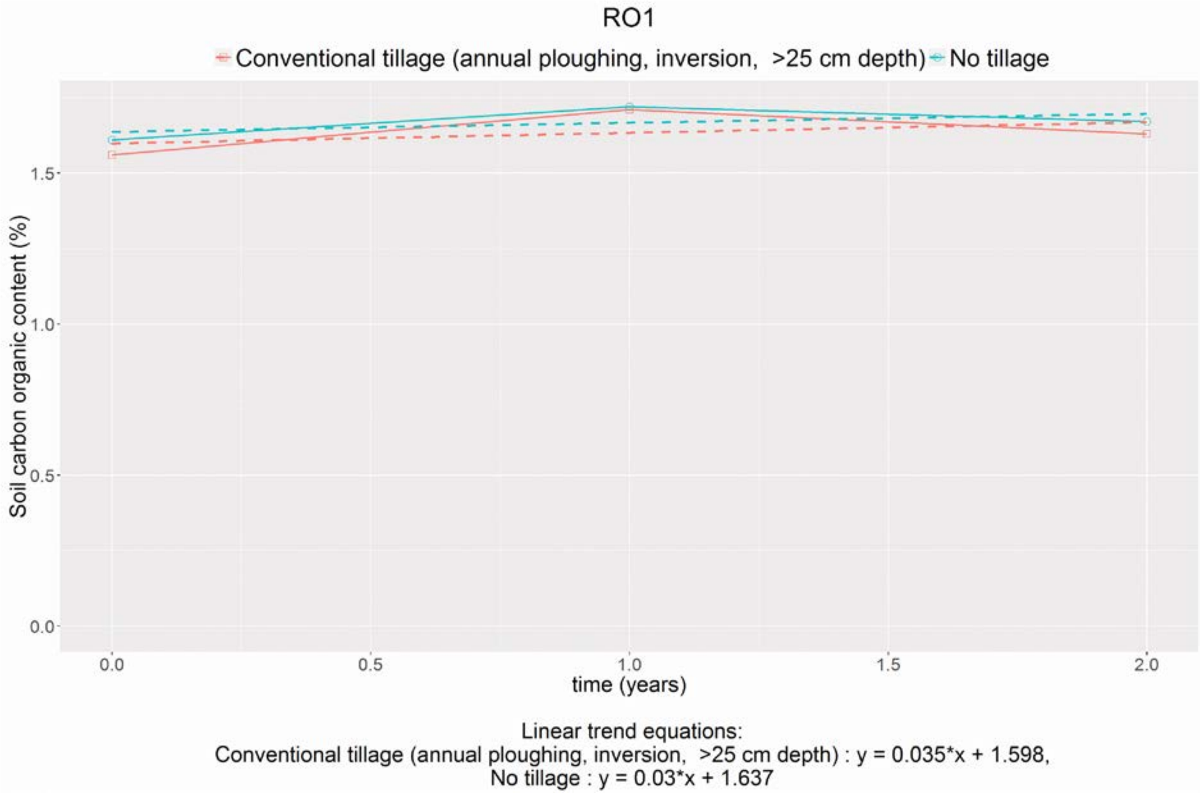


Figure NT-08. Trends of soil organic C content under no-till and conventional tillage from the iSQAPER LTE site RO1 (Braila, Romania).

Establishing a set of strategically located experimental sites that compare NT with CT practices under a range of soil-climate types would facilitate establishing a predictive understanding of the relative controls of different factors (soil, climate, and management) on soil quality and ecosystem services, and ultimately in assessing the feasibility of NT or CT practices in different agro ecological zones and socioeconomic settings (Palm *et al.*, 2014).

Overall impact evaluation: the effect of NT versus CT on SOC content in the topsoil is positive to very positive: +, ++.

pH

Soil chemical properties that are often affected by tillage practices are pH, CEC, exchangeable cations and soil total nitrogen (Busari *et al.*, 2015). Overall, based on the studies consulted for the present review (Cookson *et al.*, 2008; Lal, 1997; Rahman *et al.*, 2008; Rasmussen, 1999), and analysis of iSQAPER LTE data (Tables NT-04-1, NT-04-2), it appears that tillage *per se* does not directly affect the soil's pH, rather effects of tillage on pH will depend on the prevailing climatic conditions, parent material, soil type, and management factors such as the application of chemical fertilizers or lime. For example, wet compacted soils favour denitrification, a bacterial process by which nitrate in the soil is converted to gaseous nitrogen compounds and hence lost to the crop. Such soils may show a reduction in pH, creating an acid condition and making other nutrients less available.

Table NT-04-1. Effects of tillage practices on soil pH as derived from the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Teularet	Spain	soil pH (-)	2004	0	8.4	8	0.95
Teularet	Spain	soil pH (-)	2005	1	8.73	8.7	1
Teularet	Spain	soil pH (-)	2006	2	8.23	8.26	1
Teularet	Spain	soil pH (-)	2007	3	8.33	8.36	1
Teularet	Spain	soil pH (-)	2008	4	8.83	8.8	1
Teularet	Spain	soil pH (-)	2009	5	8.33	8.5	1.02
Teularet	Spain	soil pH (-)	2010	6	8.29	8.21	0.99
Teularet	Spain	soil pH (-)	2011	7	8.39	8.41	1
Teularet	Spain	soil pH (-)	2012	8	8.43	8.36	0.99
Teularet	Spain	soil pH (-)	2013	9	8.23	8.26	1
Teularet	Spain	soil pH (-)	2015	11	8.33	8.3	1

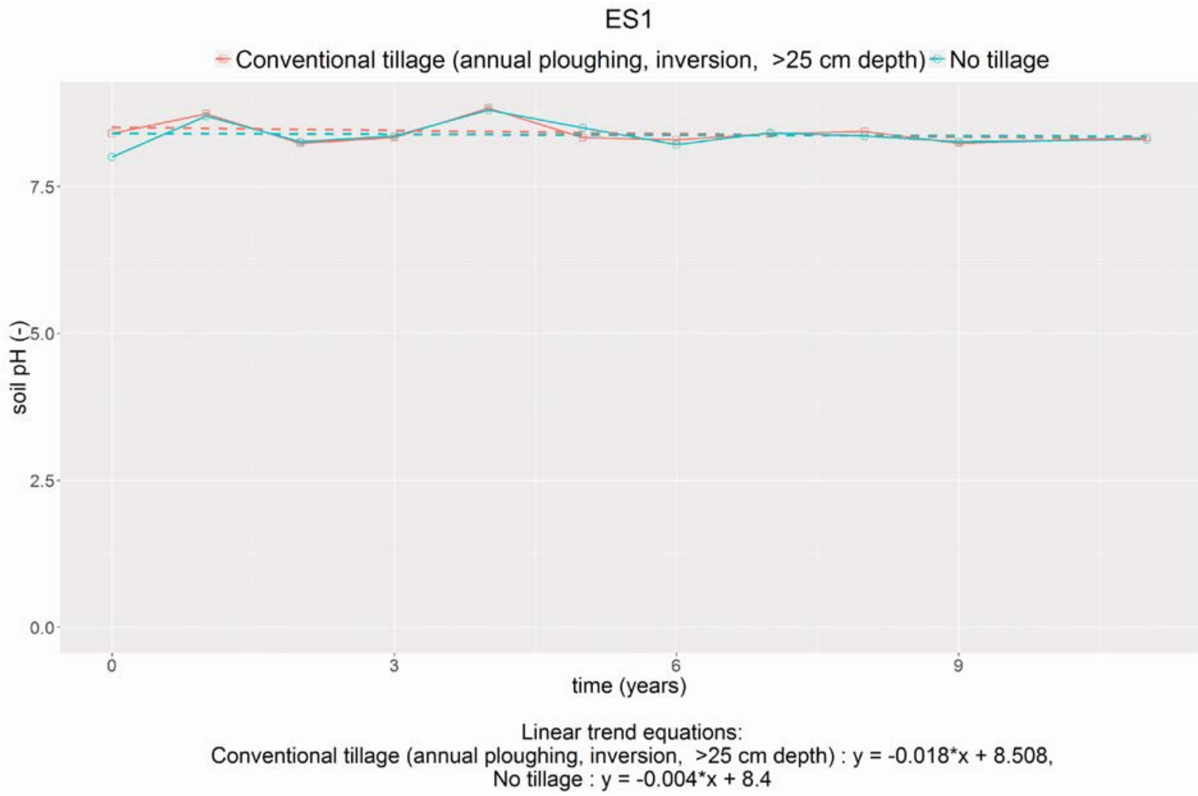


Figure NT-09. Soil pH trends under no-till and conventional tillage from the iSQAPER LTE site ES1 (Teularet, Spain).

Table NT-04-2. Effects of tillage practices on soil pH as derived from the iSQAPER LTEs.

Trial	Country	Response	Year	Time	Inversion tillage, shallow	Non-inversion,	Ratio

name					(<25 cm depth)	<10 cm depth	
Frick	Switzerland	soil pH (-)	2002	0	7.59	7.64	1.01
Frick	Switzerland	soil pH (-)	2005	3	7.37	7.31	0.99
Frick	Switzerland	soil pH (-)	2008	6	7.51	7.44	0.99
Frick	Switzerland	soil pH (-)	2012	10	7.06	7.04	1
Frick	Switzerland	soil pH (-)	2015	13	7.14	7.28	1.02

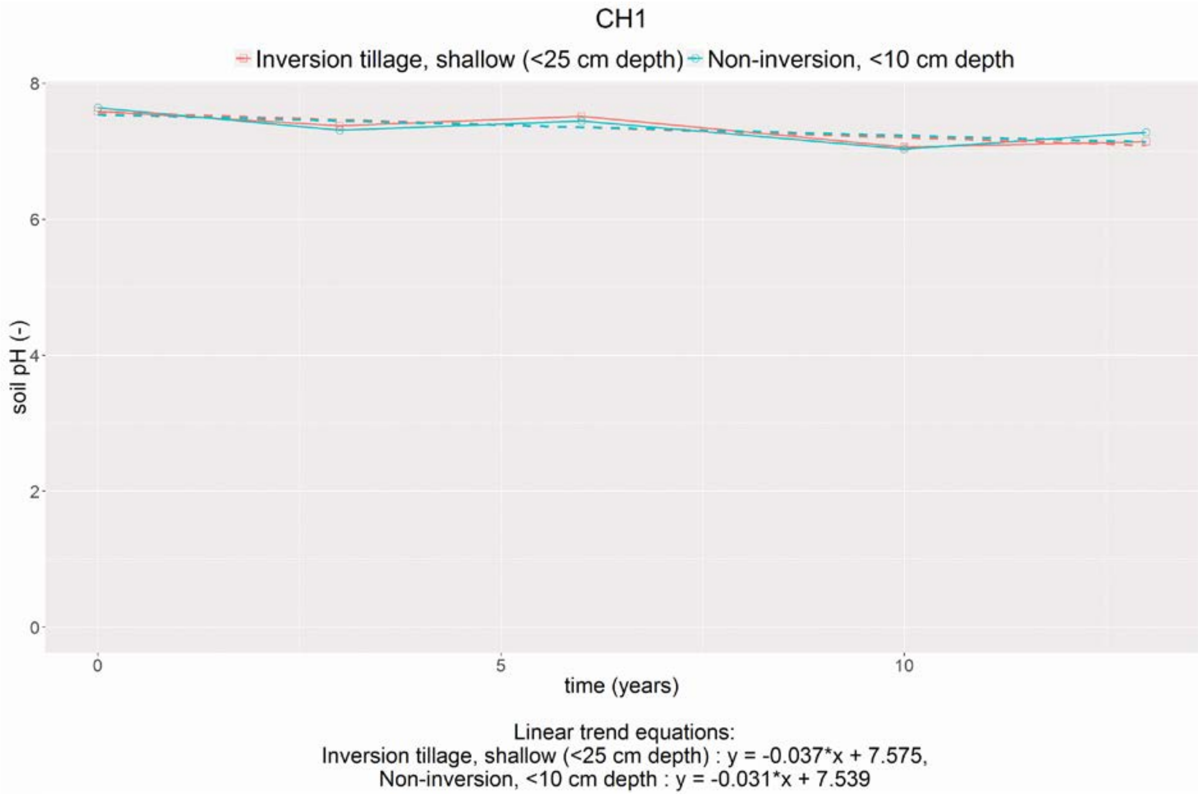


Figure NT-10. Soil pH trends under no-till and conventional tillage from the iSQAPER LTE site CH1 (Frick tillage trial, Switzerland).

Overall impact evaluation: impact of NT versus CT on soil pH is: 0 (many confounding factors, see text)

Aggregate stability/Soil structure

A change in management practices will alter the biological, chemical and physical properties of soil, hence in changes in functional quality of soil (*e.g.* Aziz *et al.*, 2013; Derpsch *et al.*, 2014; Ding *et al.*, 2011; Islam *et al.*, 2000; Madejón *et al.*, 2009; Wolfarth *et al.*, 2011), and thereby provisioning of ecosystem services (Palm *et al.*, 2014). However, results of tillage treatments on soil structure and aggregate stability, resp. porosity and bulk density, with depth have not always been consistent across locations, soils, and experimental designs (Logsdon *et al.*, 2004; Palm *et al.*, 2014; Strudley *et al.*, 2008).

No-till can lead to improvements in soil quality in the upper soil layer by improving soil structure and enhancing soil biological activity, nutrient cycling, reducing bulk density (Hamza *et al.*, 2005), improving soil water holding capacity, water infiltration and water use efficiency (*e.g*. Islam *et al*., 2000; Pittelkow *et al*., 2015). Aggregate stability increased significantly by 7% under NT, while it decreased by 2% under CT in a 5 year factorial experiment (Aziz *et al*., 2013). Similarly, in the iSQAPER long term experiments (Table NT04), overall aggregate stability increased importantly under NT versus CT.

Table NT-05-1. Effects of tillage practices on aggregate stability as derived from the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Teularet	Spain	Aggregate stability	2004	0	61.24	61.52	1
Teularet	Spain	Aggregate stability	2005	1	112	173	1.54
Teularet	Spain	Aggregate stability	2006	2	50.7	68.39	1.35
Teularet	Spain	Aggregate stability	2007	3	59.17	70.6	1.19
Teularet	Spain	Aggregate stability	2008	4	36.54	65.99	1.81
Teularet	Spain	Aggregate stability	2009	5	44.1	82.87	1.88
Teularet	Spain	Aggregate stability	2010	6	45.26	82.31	1.82
Teularet	Spain	Aggregate stability	2011	7	52.17	82.69	1.59
Teularet	Spain	Aggregate stability	2012	8	45.82	79.57	1.74
Teularet	Spain	Aggregate stability	2013	9	44.28	70.96	1.6
Teularet	Spain	Aggregate stability	2015	11	46.03	76.1	1.65

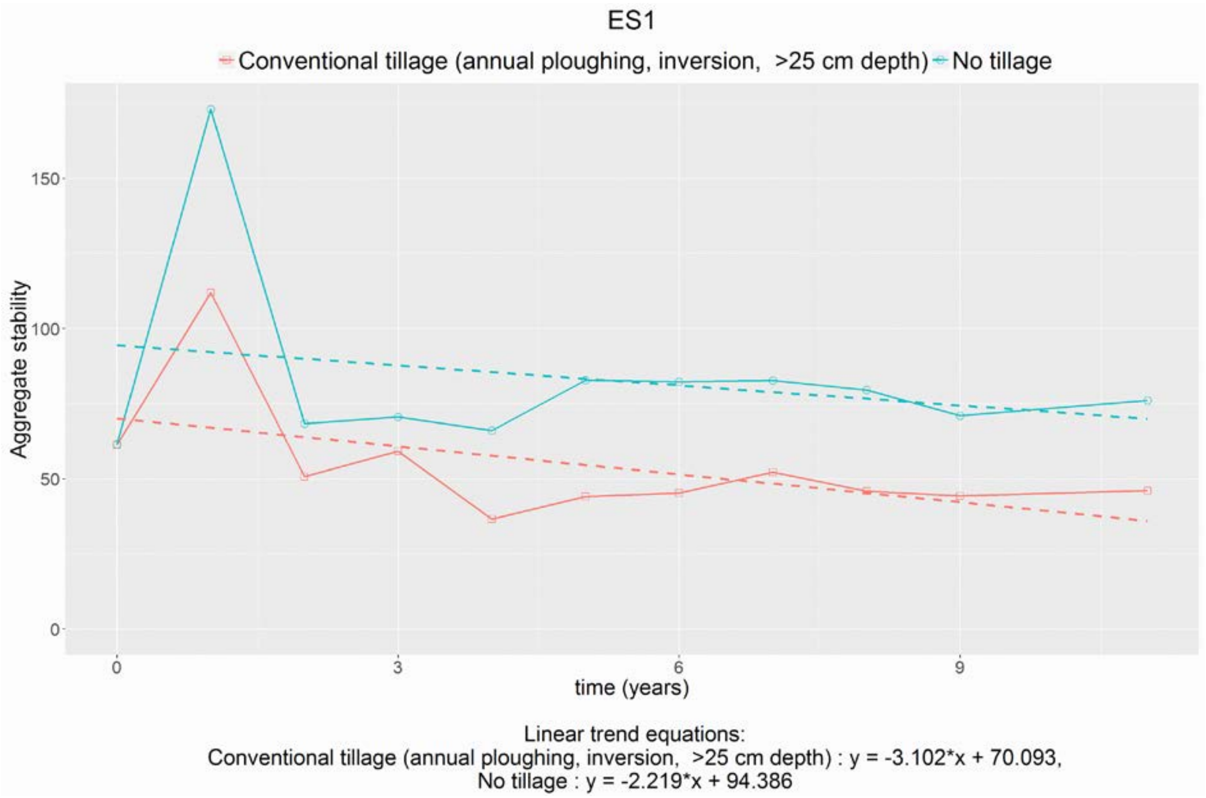


Figure NT-11. Soil aggregate stability trends under no-till and conventional tillage from the iSQAPER LTE site ES1 (Teularet, Spain).

Table NT-05-2. Effects of tillage practices on aggregate stability as derived from the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Conventional tillage (annual ploughing, inversion, >25 cm depth)	No tillage	Ratio
Braila	Romania	Macro-aggregate stability (%)	2002	0	4	3	0.75
Braila	Romania	Macro-aggregate stability (%)	2003	1	3	4	1.33
Braila	Romania	Macro-aggregate stability (%)	2004	2	3	4	1.33

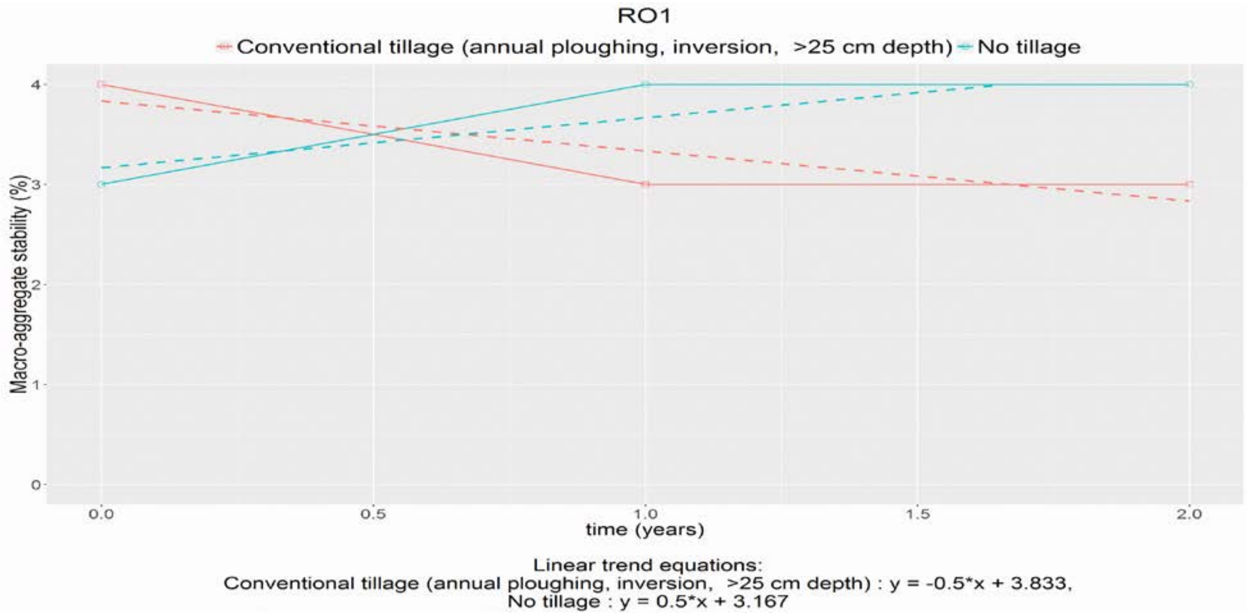


Figure NT-12. Soil aggregate stability trends under no-till and conventional tillage from the iSQAPER LTE site RO1 (Braila, Romania).

No-till in Northeast China has been shown to stimulate the accumulation of C within micro-aggregates, which then are transformed gradually into macro-aggregates, which is beneficial for long-term C sequestration in soil (Huang *et al*., 2010). Similarly, in Spain, soil quality improved under no-till with increase in aggregate stability and residue cover over time (Madejón *et al*., 2009). Alternatively, ploughing enhances disintegration of aggregates and structure of soil by inverting and mixing, resulting in a rapid breakdown of protected particulate organic matter (POM) in both inter-and intra-aggregate due to exposure of soil microbes (Huang *et al*., 2010; Morris *et al*., 2010; Six *et al*., 2000a). Tillage can also increases the rate of decomposition of macro-aggregates by exposing soils to freeze–thaw and wet–dry cycles (Huang *et al*., 2010; Six *et al*., 2000b). Conversely, ploughing with heavy farm machinery can lead to soil compaction (increased bulk density and lower porosity) and ponding, and is often identified as an important problem by producers (Logsdon *et al*., 2004). In compacted wet soils, water fills the limited pore spaces left at the expense of air. As soil water-filled pore space exceeds 80%, soil respiration declines to a minimum level and denitrification occurs resulting in loss of nitrogen as gas, emission of potent greenhouse gases, yield reduction, and/or increased N fertilizer expense (Linn *et al*., 1984). Zhang *et al*. (2009) studied the long-term effects of sub-soiling tillage (ST), NT, and CT on soil properties and crop yields over an 8-year period (2000–2007) in the Beijing area, China. They observed that at 0–0.30 m depth, water stability of macro-aggregates (>0.25 mm) was much greater for subsoiling till (ST, 22.1%) and NT (12.0%) than for CT in Daxing. At the Chanping site, the improvements were 18.9% and 9.5%, respectively. ST and NT significantly ($P < 0.05$) improved aeration porosity by 14.5% and 10.6%, respectively, at Daxing and by 17.0% and 8.6% at Changping compared with CT treatment. Soil bulk density after 8 years was 0.8–1.5% lower in ST and NT treatments than in CT at both sites. Soil organic matter and available N and P followed the same order ST ≈ NT > CT at both sites; consequently, crop yields in ST and NT plots were higher than in CT plots due to improved soil physical and chemical properties (Zhang *et al*., 2009).

Tabaglio *et al.* (2009) observed a net decrease in soil compaction in the top layers after adoption of no-tillage; this improvement occurred after only 4 years after adoption of NT for a soil high in silt (60%). As an example, Figure NT04 shows the observed reduction in values of resistance to penetration between 2005 and 2007 from the NT and CT systems on a silt loam Haplic Luvisol in Northern Italy.

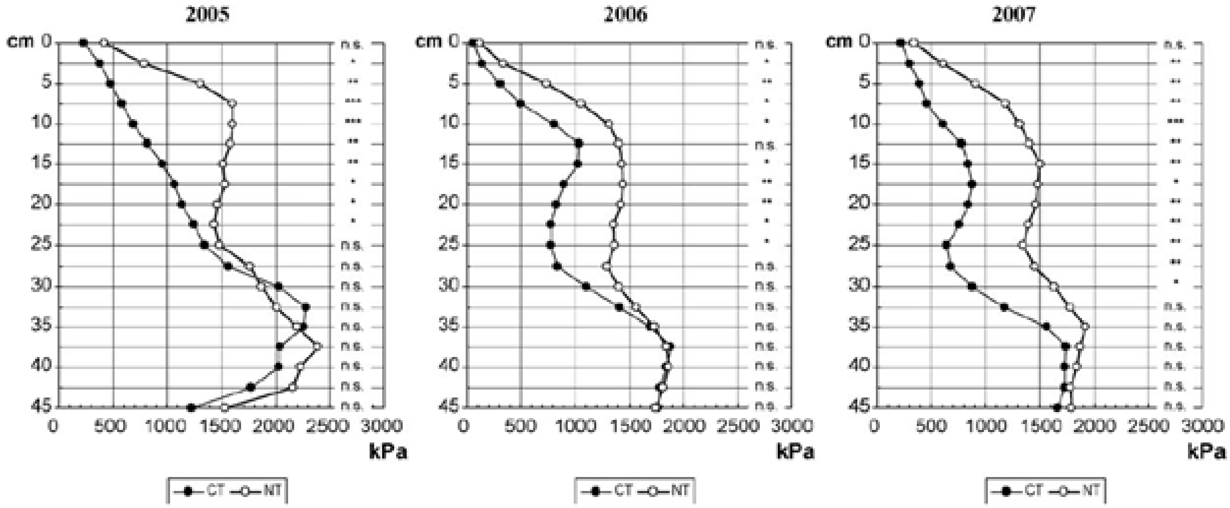


Figure.NT-13. Soil compaction at harvest in 2005, 2006 and 2007 for CT and NT plots. (n.s., not significant; *, significant at P ≤ 0.05; **, significant at P ≤ 0.01; ***, significant at P ≤ 0.001. CT: conventional tillage; NT: no-tillage.) From: Tabaglio *et al* (2009).)

Overall impact evaluation: the impact of NT versus CT on aggregate stability is: positive to very positive effects, +, ++.

Water holding capacity

Some useful measures for soil physical quality include bulk density, porosity, plant-available water capacity, and relative field capacity. Available water capacity, an important determinant of crop production, is affected by soil texture, content of organic matter, porosity, presence and abundance of rock fragments, soil depth and restrictive layers.

Based on a long-term experiment in Ontario (Table NT-06), Drury *et al* (2004) concluded that the effects of tillage system on near-surface soil physical quality seem to be minor relative to other factors such as soil texture and cropping in general. The trend, if any according to Strudley *et al.* (2008), is for NT to increase macro pore connectivity while generating inconsistent responses in total porosity and soil bulk density compared with conventional tillage practices. This corresponds to a general increase in ponded or near-zero tension infiltration rates and saturated hydraulic conductivities. Similarly, controlled equipment traffic may have significant effects on soil compaction and related hydraulic properties on some soils, but on others, landscape and temporal variability overwhelm wheel-track effects (Drury *et al*. 2004).

For a study area Spain, Soane *et al.* (2012) reported that NT increased plant available water content (held between 33 and 1500 kPa) vis a vis CT. Plant available water at 0–5, 5–15 and 15–30 cm was 11.7, 18.1 and 26.6 m^3 100 m^3 for NT, while it was 7.9, 14.8 and 20.9 m^3 100 m^3 for CT (chisel-ploughed to 15 cm depth), on average 4% higher.

Spatial and temporal variability often overshadow specific management effects, and several authors have recognized this in their analyses and interpretations. Differences in temporal variability depend on spatial locations between rows, within fields at different landscape positions, and between sites with different climates and dominant soil types. Most tillage practices have pronounced effects on soil hydraulic properties immediately following tillage application, but these effects can diminish rapidly. Long-term effects (> 10 y) can appear less pronounced and are sometimes impossible to distinguish from natural and unaccounted management-induced variability. New standards for experimental classification are essential for isolating and subsequently generalizing space–time responses. Accordingly, enhanced methods of field measurement and data collection combined with explicit spatio-temporal modelling and parameter estimation should provide quantitative predictions of soil hydraulic behaviour due to tillage and related agricultural management. According to Palm *et al* (2014), soil moisture retention can be higher with conservation agriculture, resulting in higher and more stable yields during dry seasons, however the amounts of residues and soil organic matter levels required to attain higher soil moisture content is not known.

Table NT-06. Impacts of long-term cropping using no-tillage and mouldboard plough tillage on soil physical quality parameters (Drury *et al*., 2004).

Land management	Bulk density (t m^{-3})	Air capacity (%)	Plant-Available Water Capacity (%)	Relative Field Capacity (%)
Virgin soil	0.88	21	23	65
No-till	1.33	9	15	78
Conventional till	1.37	7	19	89
“Optimal” values	0.9-1.2	>15	>20-30	66
Virgin soil	1.05	18	22	66
No-till	1.34	10	23	79
Conventional till	1.55	12	20	76
“Optimal” values	0.9-1.2	>15	>20-30	66
Fox sand				
Virgin soil	1.10	37	15	33
No-till	1.53	26	10	33
Conventional till	1.52	27	10	32
“Optimal” values	0.9-1.6	>15	>20-30	66

Overall impact evaluation: the impact of NT versus CT on water holding capacity is: no or slightly positive effect, 0, +.

Earthworms

Soil biota play a major role in important soil processes, such as releasing nutrients via mineralisation of organic matter and creating and maintaining a good soil structure (CATCH-C, 2015; Buckerfield *et al.*, 1997; Mele *et al*., 1999), and strongly influence soil organic carbon cycling (Don *et al.*, 2008). Biological soil properties can quickly change in response to changes in soil and crop management practices, such as tillage (Fig. NT-14), hence they are considered good indicators for changes in soil quality and functioning (Aziz *et al*., 2013; Bertrand *et al*., 2015; Buckerfield *et al.*, 1997; Mele *et al.*, 1999). Amongst the biological indicators considered, earthworm abundance and microbial biomass carbon (MBC) content are most frequently monitored in long-term experiments (Bertrand *et al*., 2015; CATCH-C, 2015; Chan, 2001). Here, we will focus on the impacts of earthworms on soil quality and function as essentially determined by changes in cultivation depth and intensity.

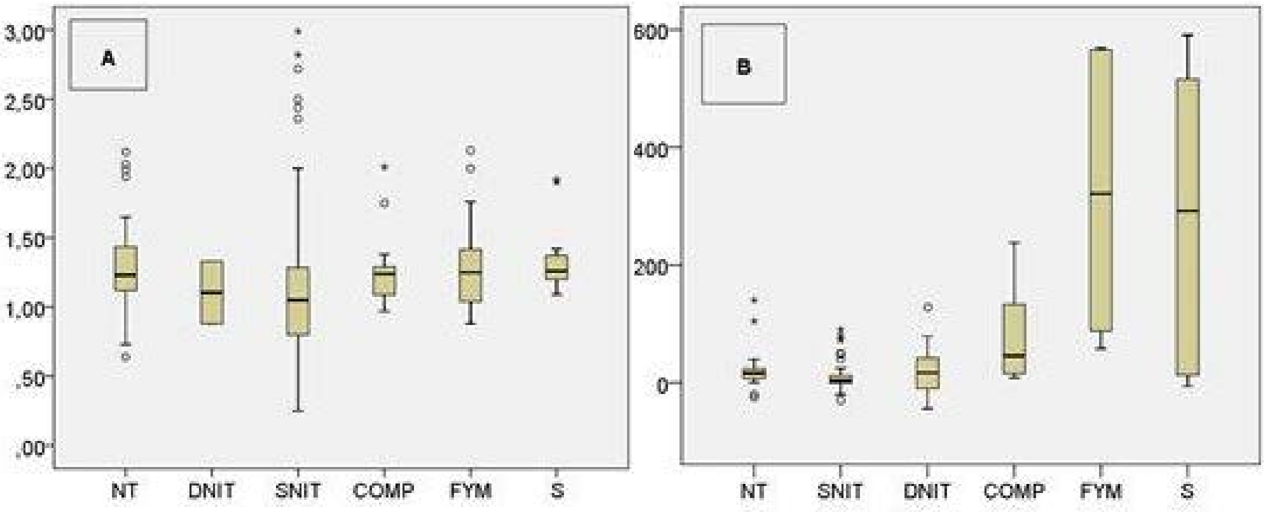


Figure NT-14. Relative (A) or absolute (B) increase/decrease of microbial biomass carbon (MBC) content (A) and earthworm number (B) when adopting potential best management practices (NT: no tillage; SNIT: shallow non-inversion tillage; DNIT: deep NIT; COMP: compost; FYM: farmyard manure; S: animal slurry) compared to a reference practice (*i.e.* ploughing and mineral fertilisation) (MBC: reference practice equals 1; earthworm number: reference practice equals 0). (Source: CATCH-C, 2015).

Earthworms are grouped into three distinct ecological groups according to their feeding and burrowing habits (Chan, 2001; Jordan *et al.*, 1997; USDA, 2001). Litter dwelling or Epigeic earthworms live and feed in surface litter; they move horizontally through leaf litter or compost with little ingestion of or burrowing into the soil. Shallow dwelling or Endogeic earthworms are active in mineral topsoil layers and associated organic matter; they create a three-dimensional maze of burrows while consuming large quantities of soil. Alternatively, deep burrowing or Anecic earthworms live in permanent, nearly vertical burrows that may extend into the subsoil; they feed on surface residues and drag them into their burrows. Overall, organic amendments will enhance earthworm abundance.

Once established, earthworms contribute to soil function in various ways (Bertrand *et al.*, 2015; Buckerfield *et al*., 1997; Kladivko *et al*., 1997; Mele *et al*., 1999; USDA, 2001; Van Groeningen *et al*., 2014) (Figure NT-15):

1) They generally improve soil structural stability and soil porosity by burrowing and aggregating soil, thus improving water infiltration (by forming channels) and reducing runoff.
2) They alter SOM and nutrient cycling by producing casts rich in N, P, K, and other nutrients. Specifically, earthworms stabilize SOM fractions within their casts, and they increase the mineralization of organic matter in the short term by altering physical protection within aggregates and enhancing microbial activity.
3) Earthworm abundance and species diversity increases under direct drilling, however the beneficial effect(s) of reduced tillage depend(s) upon the species present and tillage intensity.
4) The positive correlation between earthworm abundance and crop production has been observed. Earthworms induce the production of hormone-like substances that improve plant growth and health; Epigeic earthworms that feed at soil surface are the most exposed to pesticides and other agrochemicals.

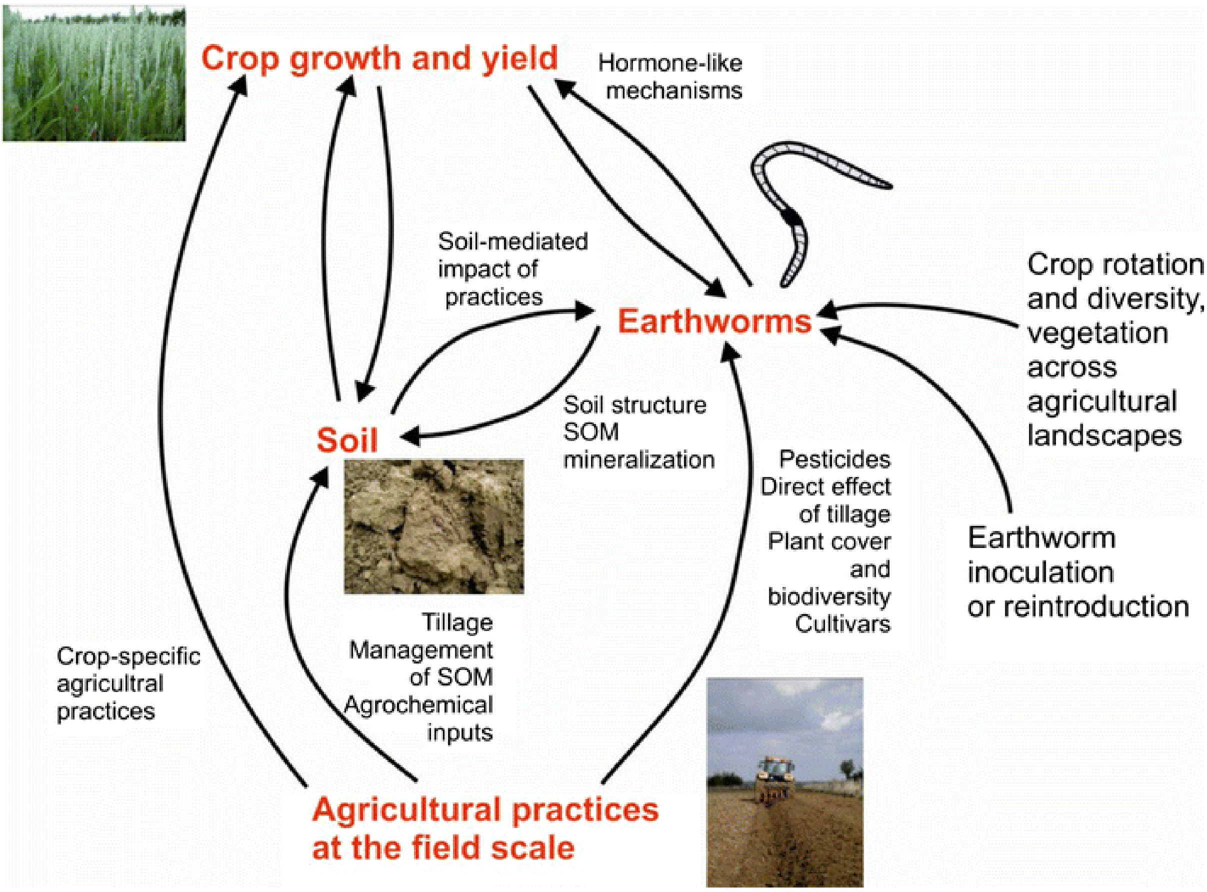


Figure NT-15. Earthworms provide similar effects as tillage practices, on crop nutrition, health and yield. (Source: Bertrand *et al*. 2015)

Of the 14 paired sites considered by Kladivko *et al.* (1997), eight sites had higher earthworm populations in no-till than conventional, four sites had roughly equal populations in both systems, and two sites had slightly lower populations in no-till than conventional till. Overall, earthworm

populations increase under reduced tillage (Catch-C, 2015; Chan, 2001; Jordan *et al.*, 1997; Rasmussen, 1999), unless organo-phosphatic insecticides, acaricides and miticides are applied as this negatively affects litter decomposition (De Silva *et al*., 2010; Domínguez *et al*., 2016). Tillage type/intensity can change the abundance (by 2–9 times) as well as the composition (diversity) of earthworm populations (Chan, 2001). For example, in a replicated research station plot experiment, the density of earthworms was significantly greater under NT (150 individuals m^{-2}) than under CT (38 individuals m^{-2}) (Johnson-Maynard *et al*., 2007). For Ontario, Drury *et al* (2004) reported that the long-term no-till site (established in 1983) had a mean population of 89 worms m^{-2} (range of 43 to 170). Mean population numbers for ridge tillage (50 worms m^{-2}) was lower than NT but higher than CT (14 worms m^{-2}). In a comparison of NT and CT in a paired watershed, the NT site was observed to have over 114% more earthworms (163 earthworms m^{-2}) than the nearby NT site (76 earthworms m^{-2}). Similarly earthworm biomass (weight) was greater in no-tillage vs conventional tillage sites (Drury *et al*., 2004). Carbon accumulation in earthworm burrows can be fast with C sequestration rates of about 22 g C m^{-2} yr^{-1} in the burrow linings, however C accumulated in the burrows may be mineralised fast with turnover times of only 3–5 years (Don *et al*., 2008).

Earthworm species differentially affect incorporation of fresh organic matter into stable micro aggregates within macro aggregates, and that interactive effects of earthworm species might have important consequences for the incorporation and protection of C, especially when residues are placed on the soil surface (Bossuyt *et al*., 2006).
Chisel tillage, for example, may kill worms in the surface or cause the worms to move deeper in the soil profile (Jordan *et al*., 1997); mechanical tillage is one of the main management practices that negatively affects earthworm abundance (Chan, 2001; Kladivko, 2001). Alternatively, in no-tillage plots, a greater source of food is available for the earthworms and any burrows present are minimally disturbed. The abundance of the deep burrowing species (Anecic) tends to decline under intensive tillage, particularly under deep ploughing; surface feeding (Endogeic) species can actually increase in number especially when there is increased food supply (Chan, 2001). Chisel tillage, for example, may kill worms in the surface or cause the worms to move deeper in the soil profile (Jordan *et al*., 1997). Similarly, Kemper *et al*. (1987) reported that less intense tillage increased the activities of surface-feeding earthworms. Higher SOC and total Nitrogen (food supply) in the soil surface, as found in direct seeding fields, appear to promote greater earthworm densities, which may improve long-term soil productivity (Umiker *et al*., 2009). Similarly, Aziz *et al* (2013) observed that conservation management most consistently and markedly influenced soil quality indicator properties by increasing total and active microbial biomass carbon, increasing the ratio of active microbial biomass carbon to total organic carbon, increasing aggregation, and decreasing the rate of basal respiration per unit of microbial biomass carbon. Finally, and importantly, it should be noted that many biological indicators are subject to seasonal changes as illustrated in Figure NT-16, as well as long-term management induced effects. Thus the timing and frequency of sampling may result in partially different responses and, as a result, different interpretations (Tabaglio *et al*., 2009; Umiker *et al*., 2009). Crop rotation and landscape position will alter the effects of specific tillage practices on earthworm populations and soil microclimatic conditions. Earthworms are known to have patchy spatial distributions, which

make it difficult to assess changes in population size (Whalen, 2004).

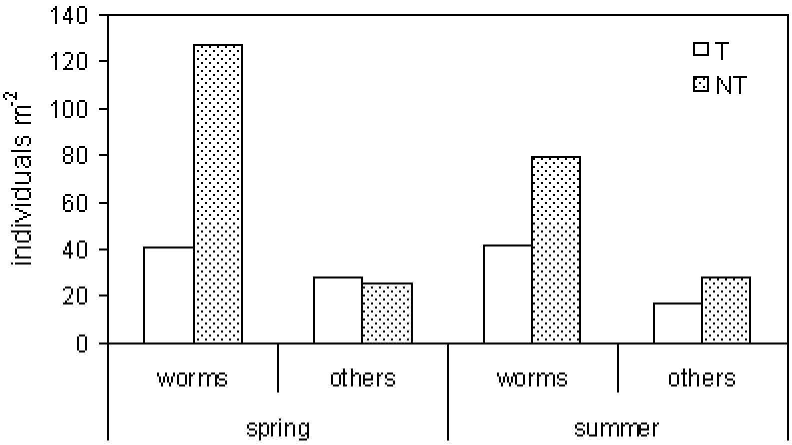


Figure NT-16. Average number of earthworms and other macrofauna for NT and CT in a Csb Köppen climate (Guy, 2001).

Overall impact evaluation: the impact of NT versus CT on earthworms is: positive to very positive, +, ++.

3.1.3 Crop rotation

Crop rotation or cropping sequence refers to a planned sequence of crops grown in a regularly recurring succession on the same area, in contrast to continuous monoculture or growing a variable sequence of crops (SSSA, 1997). It is a long-term plan for soil and farm management rather than just changing crops from year to year based on current economic situations (Martin *et al.*, 1976). There are many benefits of crop rotation for soil properties and plant growth: 1) manage weed, insect, and disease pests; 2) reduce soil erosion by wind and water; 3) maintain or increase soil organic matter; 4) provide biologically fixed N when legumes are used in rotation; and 5) manage excess nutrients and so on. These factors all serve to increase crop yields.
Crop rotation affects soil quality and crop yield in many ways, *e.g.*, changes of SOC content, soil structure and aggregation, pH, water hold capacity, nutrients cycling, and incidence of pests. The effect of crop rotation on soil quality and yield depends on diversity of crop species grown in the rotation and the length of the rotation. Crop or cropping system selection has a major impact on carbon inputs to the soil (Ingram and Fernandes, 2001). In combination with minimum or no-till management, crop rotations can reduce soil erosion, enhance SOM, and sequester SOC (Lal, 2001).

Because there are so **many possible rotations** with **many different crops** and **cropping practices**, it is difficult to summarize all possible ways soil quality is affected.

Yield

Intensive monoculture decreases crop yield with attendant reduction in biomass returned to the soil (Elliot *et al.*, 1978). Diversified crop rotations resulted in similar or higher grain yields than mono-cropping system (Davis *et al.*, 2012). Yield of maize-wheat rotation under zero tillage with residue retention was 18% higher than that of the rotation under tillage and residue retention (4.25 out of 5.025 t ha^{-1}) (Fischer *et al*, 2002a, b). Maize, in a 2-year rotation with soybean,

yielded 5 to 20% more than continuous maize (Bullock, 1992). Cotton-corn rotation increased SOC content by 28% at 0-5cm, 18% at 5-15cm or an average of 518 kg C ha^{-1} y^{-1} compared to continued cotton under the same conventional tillage (Wright *et al*., 2008).
The EU-funded Catch-C project reviewed impacts of crop rotation on various soil quality indicators based on data from 29 long-term experiments and literatures; on average, the crop rotations increased yield by 5% (Spiegel *et al*., 2014). Different crop rotations influenced yield potential to a larger extent than pesticide use intensity or tillage (Deike *et al*., 2008).

Within the iSQAPER LTEs, rotations were variable in length ranging from 3 to 35 years and in crops involved. Main crops were maize, potato, forage crops or other small grains cereals, while secondary rotated crops were grain legumes (*e.g*. pea) or forage legumes. Overall monocrops reduced yield and rotation slightly increase yield (Table CR-01 and Figure CR-01).
Table CR-01. Yields in monocrops and crop rotation systems in the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	1964-1984 potato, 1985- maize	Arable rotation with annual forage crops	Ratio
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1964	0	11.37	30.11	2.65
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1974	10	26.52	50.32	1.9
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1984	20	27.49	46.17	1.68
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	1994	30	11.74	16.68	1.42
Organic/inorganic fertilization in different rotations	Hungary	Crop yield - marketable yield - combinable crops (t ha^{-1})	2004	40	11.17	61.3	5.49

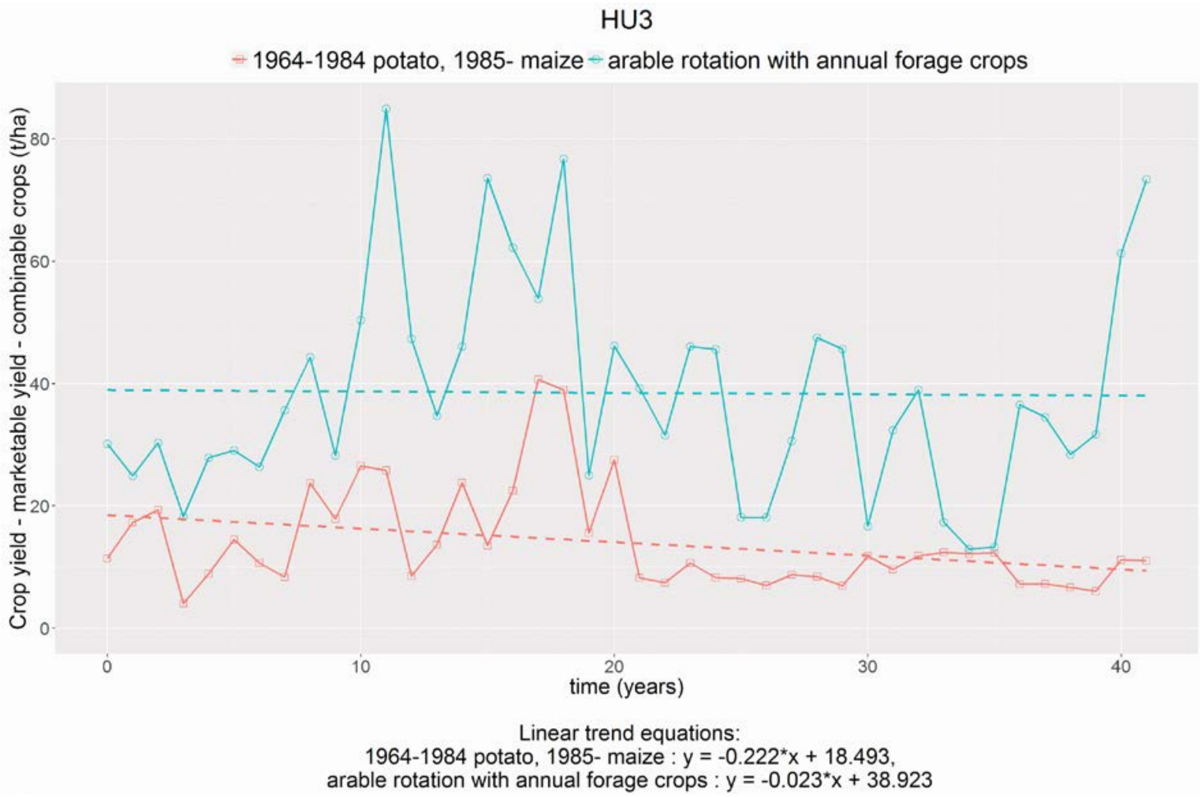


Figure CR-01. Yield trends under crop rotation and monoculture from the iSQAPER LTE site HU3 (Organic/inorganic fertiliser in rotation; Keszthely, Hungary).

Overall impact evaluation: crop rotation has a very positive effect on yield levels, + +.

SOM/SOC

Crop rotation can affect SOC both positively and negatively depending on crop grown, return of residues to soils and duration of rotation. Long periods of crop rotation improve SOC better than do short rotations in two ways: either reducing SOC loss or increase in SOC (Bullock, 1992). West and Post (2002) analysed a global database containing 67 long-term experiments and found that crop rotation could increase SOC by 200 ±120 kg ha^{-1} y^{-1}. However, a change from continuous corn (*Zea mays* L.) to corn-soybean *max* L.) may not result in a significant accumulation of SOC. The increase in SOC was relatively low since the data were recalculated from no-till treatments. West and Post (2002) concluded upon adoption of more complex crop rotations SOC levels may reach a new equilibrium in approximately 40–60 years. Jarecki and Lal (2003) reviewed various long-term trials on impacts of crop rotations on SOC (Table CR-02), and indicated that crop rotation enhanced SOC concentration.

Table CR-02. Increase of SOC concentration under different crop rotations*.

Location	Crop or Land Use	Increase in SOC Sequestration (kg ha^{-1} y^{-1})	Depth (cm)	Duration (Years)	Reference[1]
Canada	Corn-oat-alfalfa-alfalfa rotation compared				
(1) Ontario	to continuos corn on clay loam:				Gregorich et al. (2001)
	Unfertilized	703	70	35	
	Fertilized	403	70	35	
(2) Miscellaneous regions	Cereal-fallow versus continuous cropping:				Dumanski et al. (1998)
	Cereals in semiarid	200			
	Cereals in subhumid	170			
	Cereals in boreal	520	30	50	
	Hay in semiarid	510			
	Hay in subhumid	760			
	Hay in boreal	480			
(3) Miscellaneous regions	Conversion wheat-wheat-fallow to continuous wheat	164	20	20	Desjardins et al. (2001)
Spain	Rotation versus wheat monoculture:				Lopez-Fando and Pardo (2001)
	Barley vetch	91	30	11	
	Barley sunflower	82			
Syria	Various rotation versus wheat-fallow:				Jenkinson et al. (1999)
(International Center	Wheat-wheat	160			
for Agricultural	Wheat-vetch	220			
Research in Dry Areas)	Wheat-lentil	170	20	10	
	Wheat-chickpea	160			
	Wheat-medic (*Medicago spp.*)	380			
USA	Rotations on loam:				Halvorson et al. (2002)
(1) North Dakota	Spring wheat-winter wheat-sunflower versus Spring wheat-fallow with no-till	642			
	Spring wheat-winter wheat-sunflower versus Spring wheat-fallow with minimum till	283	30.4	12	
	Spring wheat-winter wheat-sunflower versus Spring wheat-fallow with conventional till	−125			
(2) Ohio	Rotations on clay loam:				Dick et al. (1998)
	Corn-oats-meadow versus continuous corn	66	30	30	
	Corn-soybean versus continuous corn	−433	30	30	
(3) Texas	Increasing crop intensity from wheat to Wheat/soybean with no-till management	550	20	9	Franzluebbers et al. (1994)
World database	Enhancing rotation:				West and Post (2002)
67 long-term agricultural experiments	Monoculture to continuous cropping, crop fallow to continuous cropping, increasing number of crops in rotation with exception of continuous corn to corn-soybean rotation	200 ± 120	Various depth	Various time	

*Adopted from Jarecki and Lal (2003).

Buyanovsky and Wagner (1998) reported from a long-term experiment in Missouri that monoculture of wheat with N fertilization accumulated 50 g C m^{2} y^{-1} compared with 150 g C m^{-2} y^{-1} by corn–wheat clover rotation with manuring and N fertilization (Table CR-03).

Table CR-03. Changes in SOC content (0-20cm) under 25-year continuous and crop rotation*

Crop, treatment	Carbon, Mg ha^{-1}		
	1963	1988	Change
Continuous wheat			
manure	32.6	42.7	+10.1
miner. fert.	27.2	36.0	+8.8
none	25.4	24.4	−1.0
Continuous corn			
manure	32.3	37.7	+5.4
miner. fert., no till	26.7	37.9	+11.1
miner. fert., convent. till	24.9	32.5	+7.6
none	21.9	18.2	−3.7
Corn/Wheat/Clover			
miner. fert.	27.8	35.9	+8.1
manure + N	30.6	47.0	+16.4

*Adapted from Buyanovsky and Wagner (1998).

Spiegel *et al*. (2014) reviewed impacts of crop rotation on SOC based on the data from the 29 long-term experiments and literatures within the EU-funded Catch-C project and found that overall crop rotation neutrally impacts on SOC content.

The iSQAPER LTEs data indicate that crop rotation increased SOC content (Tables CR-04-1, CR-04-2, Figures CR-02 and CR-03)

Table CR-04-1. SOC changes under crop rotation from the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Intensive arable (no ley crops, %)	Arable with ley periods	Ratio
Teularet	Spain	SOC content	2004	0	1.47	1.23	0.84
Teularet	Spain	SOC content	2005	1	1.23	1.26	1.02
Teularet	Spain	SOC content	2006	2	1.35	1.29	0.96
Teularet	Spain	SOC content	2007	3	1.32	1.12	0.85
Teularet	Spain	SOC content	2008	4	1.3	1.06	0.82
Teularet	Spain	SOC content	2009	5	1.46	1.37	0.94
Teularet	Spain	SOC content	2010	6	1.31	1.34	1.02
Teularet	Spain	SOC content	2011	7	1.32	1.28	0.97
Teularet	Spain	SOC content	2012	8	1.48	1.44	0.97
Teularet	Spain	SOC content	2013	9	1.35	1.19	0.88
Teularet	Spain	SOC content	2015	11	1.47	1.27	0.86

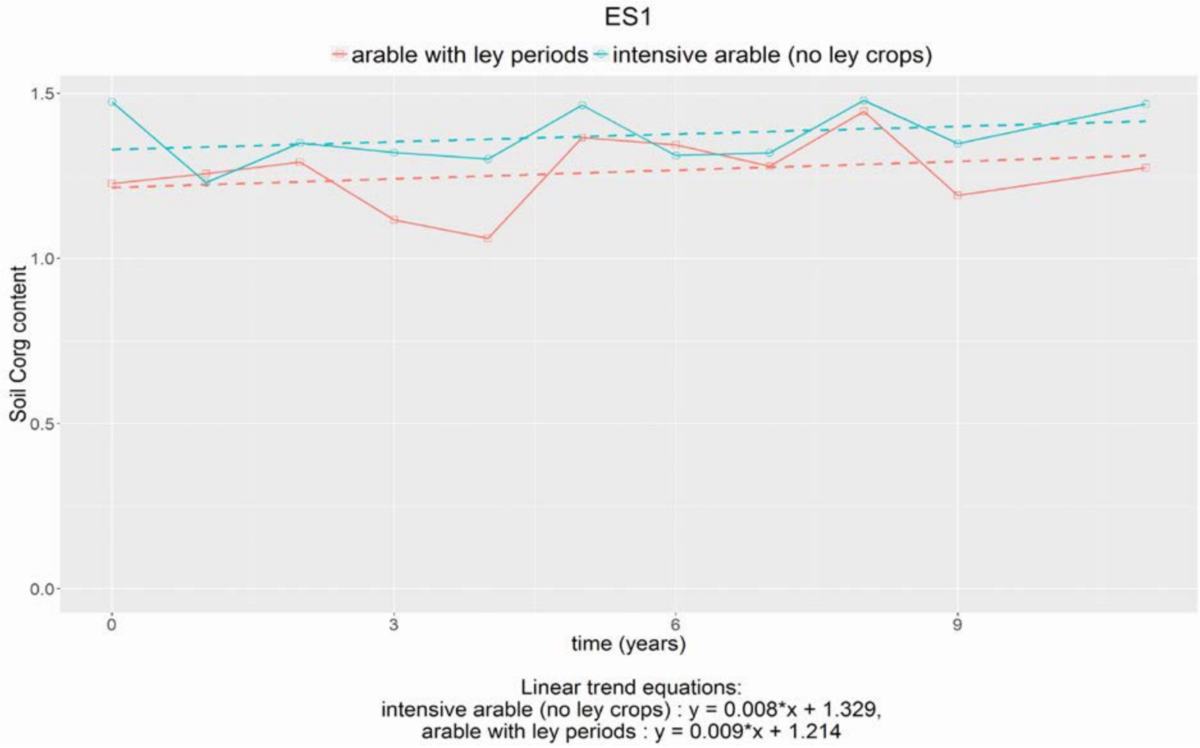


Figure CR-02. SOC trends under crop rotation and monoculture from the iSQAPER LTE site ES1 (Teularet, Spain).

Table CR-04-2. SOC changes under crop rotation from the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Intensive arable (no ley crops)	Arable with ley periods	Ratio
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2004	0	1.04	1.22	1.17
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2007	3	0.39	1.06	2.72
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2009	5	0.83	--	--
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2010	6	0.99	1.48	1.49
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2013	9	1.03	1.32	1.28
ESAC: conventional vs biological maize	Portugal	Topsoil carbon content (%)	2014	10	1.12	1.34	1.2

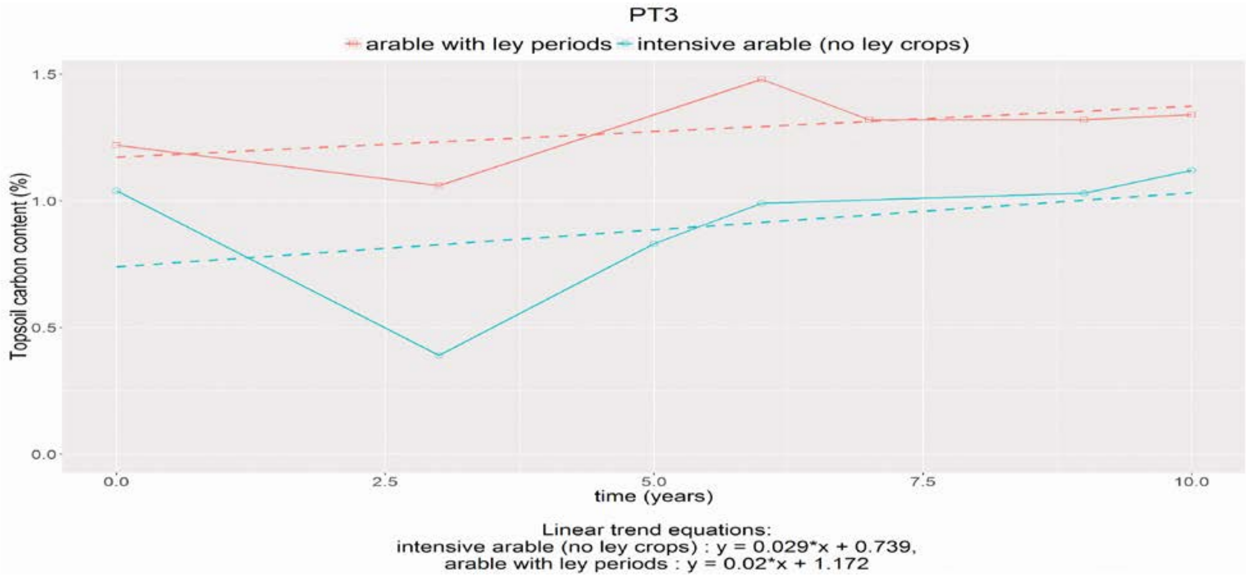


Figure CR-03. SOC trends under crop rotation and monoculture from the iSQAPER LTE site PT3 (ESAC: conventional vs biological maize, Portugal).

Effects of crop rotation on SOC depend also on quantity of crop residues returned to the soil. Introducing alfalfa in rotation with wheat grown on a sandy soil decreased salinity and increased SOC content three fold as compared with continuous wheat (Shahin *et al*., 1998). SOC content was high in wheat-grassland and wheat-alfalfa (*Medicago sativa*) rotations, especially with a conservation tillage system (Miglierina *et al*., 1993, 1996). Galantini and Rosell (1997) found that rotations of mixed pasture and annual crops maintained 17.3 Mg ha^{-1} of SOC compared with 11.2 Mg ha^{-1} in continuous cultivation with a wheat-sunflower (*Helianthus annulus*) rotation in semi-arid regions of Argentina. Lopez-Fando and Pardo (2001) compared SOC concentration in barley (*Hordeum vulgare L.*)–vetch (*Vicia sativa L.*), barley–sunflower, and barley monoculture systems in semiarid regions of Spain, and observed the lowest SOC concentration in barley monoculture. Similar results were reported by Havlin *et al*. (1990) and Robinson *et al*. (1996). Crop rotation with no tillage significantly improved soil accumulated organic carbon of a Rhodic Ferralsol at the surface layer (0–5 cm), which were destroyed by conventional tillage in Brazil (Madari *et al*., 2005). The intensification of cropping system from spring wheat monoculture to annual cropping rotation spring wheat–winter wheat–sunflower (*Hellianthus annus L.*) and introducing no-till management had a positive impact on reducing SOC loss from croplands in the northern Great Plains (Halvorson *et al*., 2002).

Rotation of crops with legume is the most favourable (Bullock, 1992). However Campbell *et al.* (1991) reported that fertilization or the inclusion of legume green manure or legume hay crops did not increase the SOC based on a 31-year rotation experiment on an Orthic Black Chernozem in Canada, this could be due to very high antecedent SOC concentration.
Crop rotation is more effective in retention of C and N in soil than monoculture (Biederbeck *et al.*, 1984). Collins *et al*. (1992) observed that the highest retention of SOC was obtained in grass pasture system, and wheat-fallow system reduced SOC significantly in 58-year long-term crop rotation experiments. Drury *et al*. (1998) compared mono-culturing corn with mono-culturing Kentucky bluegrass (*Poa pratensis L.*) and 4-year corn-oat (*Avena sativa L.*)–alfalfa-alfalfa (*Medicago sativa L.*) rotation and found that the SOC level was in the order bluegrass > 4-year rotation > mono-culturing corn.

The SOC concentration could be increased when crop rotation increases agronomic production (Campbell *et al.*, 1996). In contrast, Havlin *et al.* (1990) observed SOC dynamics in long-term experiments: mono-culturing sorghum (*Sorghum bicolor L.*), mono-culturing soybean (*Glycine max L.*), continuous corn, and sorghum-soybean, corn-soybean combined with tillage and N fertilization and found that the high residue-producing mono-culturing sorghum in the first and mono-culturing corn in the second rotation combined with reduced tillage and surface residue maintenance resulted in more SOC sequestration than grain-legume rotations. Similar results were reported by Omay *et al.* (1997) indicating more SOC under mono-culturing corn than under corn-soybean rotation.

Overall impact evaluation: Crop rotation increases SOC levels, +.

pH

The iSQAPER LTEs data analysis indicates that there is little influence of crop rotation on soil pH (Table CR-05-1, Table CR-05-2). Similar results were found by Spiegel *et al.* (2014) based on the data from 29 long-term experiments and literature collated within the EU-funded Catch-C project.

Table CR-05-1. Soil pH in the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Intensive arable (no ley crops)	Arable with ley periods	Ratio
Teularet	Spain	soil pH (-)	2004	0	8.4	8.2	0.98
Teularet	Spain	soil pH (-)	2005	1	8.73	8.47	0.97
Teularet	Spain	soil pH (-)	2006	2	8.23	8.47	1.03
Teularet	Spain	soil pH (-)	2007	3	8.33	8.37	1
Teularet	Spain	soil pH (-)	2008	4	8.83	8.97	1.02
Teularet	Spain	soil pH (-)	2009	5	8.33	8.67	1.04
Teularet	Spain	soil pH (-)	2010	6	8.29	8.31	1
Teularet	Spain	soil pH (-)	2011	7	8.39	8.39	1
Teularet	Spain	soil pH (-)	2012	8	8.43	8.47	1
Teularet	Spain	soil pH (-)	2013	9	8.23	8.27	1
Teularet	Spain	soil pH (-)	2015	11	8.33	8.37	1

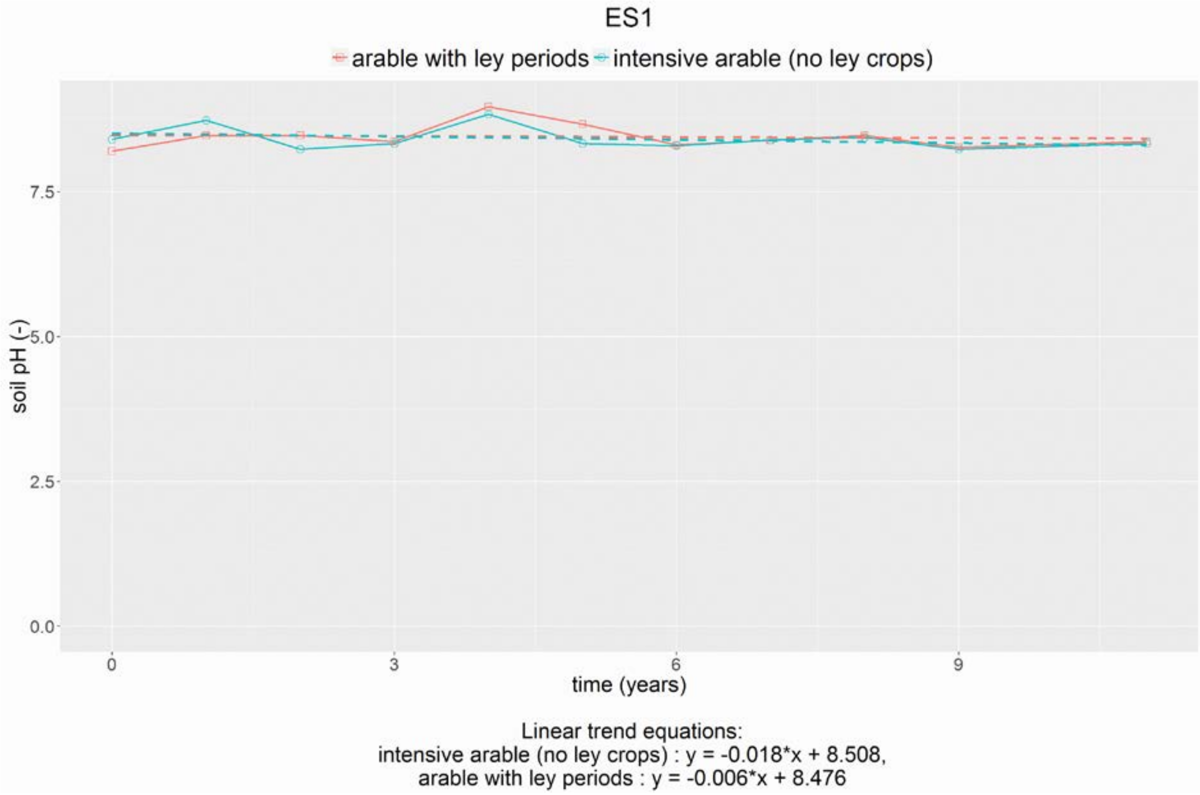


Figure CR-04. Soil pH trends under crop rotation and monoculture from the iSQAPER LTE site ES1 (Spain).

Table CR-05-2. Soil pH in the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Intensive arable (no ley crops)	Arable with ley periods	Ratio
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2004	0	6.67	5.47	0.82
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2007	3	7.62	5.96	0.78
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2009	5	6.47	--	--
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2010	6	7.14	6.83	0.96
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2013	9	6.2	5.63	0.91
ESAC: conventional vs biological maize	Portugal	soil pH (-)	2014	10	6.55	7.06	1.08

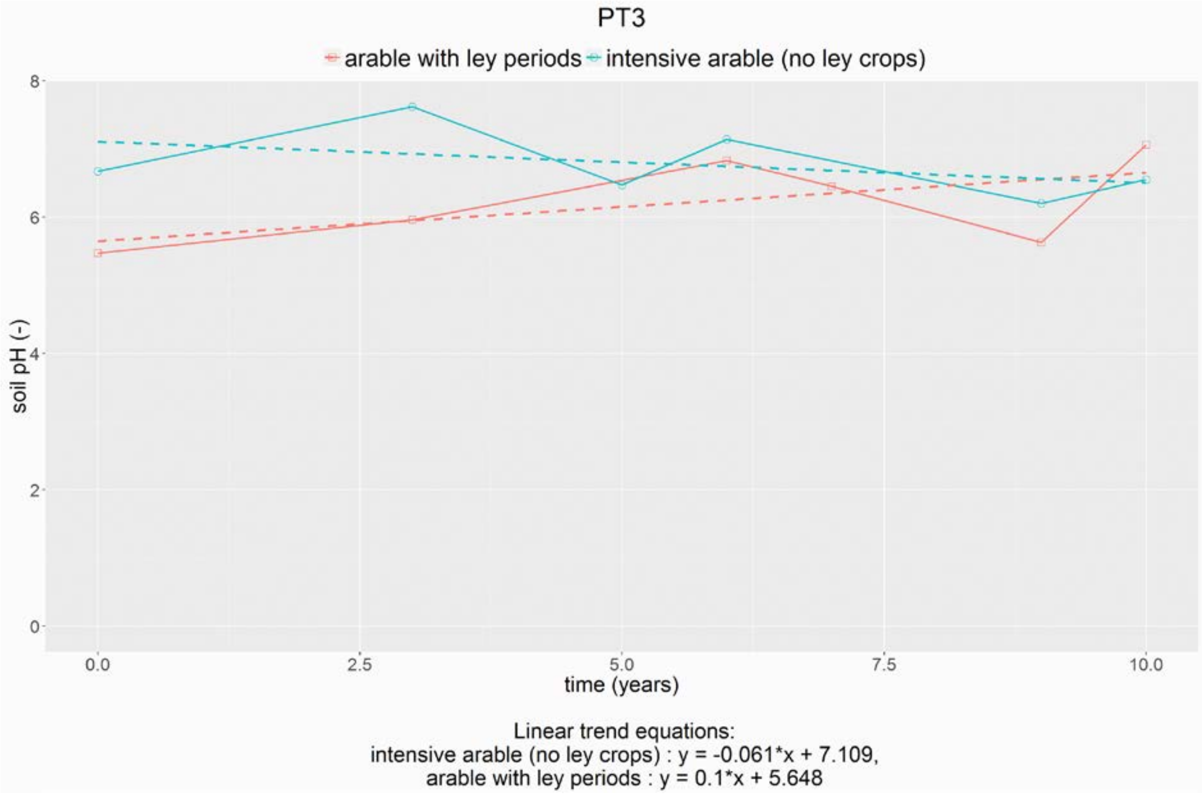


Figure CR-05. Soil pH trends under crop rotation and monoculture from the iSQAPER LTE site PT3 (Portugal).

Overall impact evaluation: Crop rotation has no significant influence on soil pH, 0.

Aggregate stability/Soil structure

A good reference to look into how crop rotation impacts on soil physical properties in general and soil aggregation in particular, is Bullock (1992). He notes that although it may be convenient to suggest that crop rotation improves soil aggregate formation and stabilization, it is in fact not that simple. In rotations that produce less overall organic matter than well-fertilised monocultures, the reduction in residues may actually lead to a decline in soil organic matter, and subsequently in soil aggregation. Where rotations are involving sod, pasture and hay, they are improving soil aggregate stability better than do short rotations because the species involved are different, the time periods they exist in the field are different, and tillage is absent for long periods.
There are exceptions to this general trend, *e.g*. where soils naturally have a strong structure: Castro Filho *et al.* (2002) observed no effect of crop rotations on aggregate stability indices in a Latosol (Rhodic Ferralsol) from southern Brazil. In Argentina, soil aggregation did not change under rotation of wheat/soybean-maize and soybean-maize , whilst soybean monoculture or soybean-sunflower rotation reduced aggregate stability in long-term crop rotation trials (Arrigo *et al.*, 1993).

Guzman *et al*.(2015) investigated within the EU-funded Catch-C project 22 records in the long-term experiments on crop rotation in European countries and found that, compared to monoculture, crop rotation has overall a negative effect on aggregate stability, *i.e*., response ratio

(rotation/mono-cropping = 0.77). The authors explained this by the compaction produced by the machinery, and the timing of agricultural operations under different soil moisture conditions from autumn to spring.

From the iSQAPER LTE data we had 1 data set available for analysis from the Teularet site in Spain (Figure & Table CR-06). The data show quite some variability, with the soils under crop rotation being slightly better aggregated overall. However, aggregate stability appears to be slowly decreasing under both, monoculture and crop rotation.

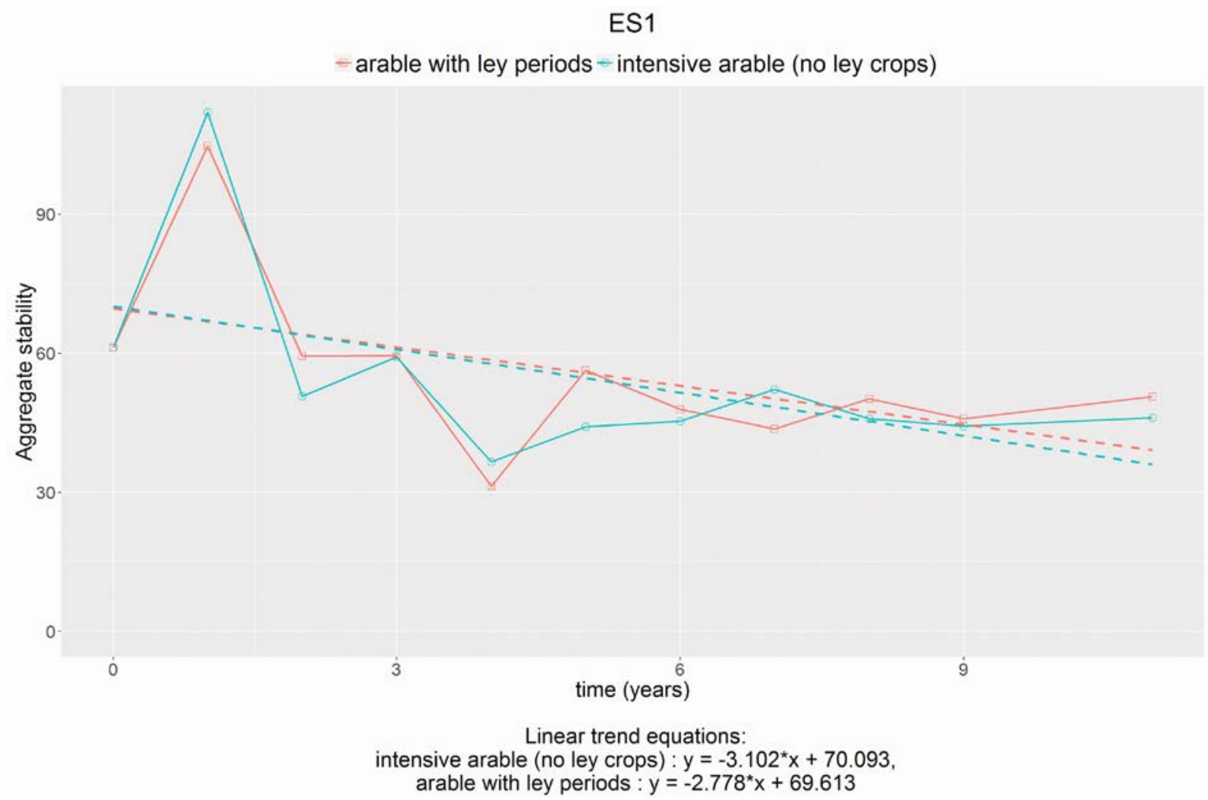


Figure CR-06. Soil aggregate stability trends under crop rotation and monoculture from the iSQAPER LTE site ES1 (Estonia).

Table CR-06. Soil aggregate stability in the iSQAPER LTEs.

Trial name	Country	Response	Year	Time	Intensive arable (no ley crops)	Arable with ley periods	Ratio
Teularet	Spain	Aggregate stability	2004	0	61.24	61.2	1
Teularet	Spain	Aggregate stability	2005	1	112	104.67	0.93
Teularet	Spain	Aggregate stability	2006	2	50.7	59.34	1.17
Teularet	Spain	Aggregate stability	2007	3	59.17	59.4	1
Teularet	Spain	Aggregate	2008	4	36.54	31.25	0.86

		stability					
Teularet	Spain	Aggregate stability	2009	5	44.1	56.27	1.28
Teularet	Spain	Aggregate stability	2010	6	45.26	47.86	1.06
Teularet	Spain	Aggregate stability	2011	7	52.17	43.66	0.84
Teularet	Spain	Aggregate stability	2012	8	45.82	50.12	1.09
Teularet	Spain	Aggregate stability	2013	9	44.28	45.81	1.03
Teularet	Spain	Aggregate stability	2015	11	46.03	50.59	1.1

Overall impact evaluation: crop rotation slightly increases soil aggregate stability, 0, +.

Water holding capacity

Bullock (1992) states that increased soil aggregation results in *de*creased available water. This is because a larger fraction of the water is held at potentials less than -15 bars and because of an increase in macropore volume and a decrease in the micropore volume. These changes reduce the water content of the soil volume at field capacity and consequently decrease the total amount of water available to plants. With no or just a slight increase in soil aggregate stability from crop rotation noted above, it is not expected that soil water holding capacity is substantially affected either.

We have not been able to find recent literature evidence on this topic. And there are no iSQAPER LTE data to allow for further analysis.

Overall impact evaluation: No statement can be made..

Earthworms

It is well established that soils under grassland tend to contain more earthworms than arable land (Edwards & Bohlen 1996). Leys as intercrop are therefore expected to have a positive effect on earthworm populations. The same - to a lesser extent - is for legumes: Schmidt *et al.* (2001) have shown that legumes as intercrop for cereal monocropping can support much larger earthworm populations as compared to those of conventional monocrops.

The effects are quite different where rotation is without ley and between non-legume crops only. Jordan *et al.* (2004) found that continuous corn growth had greater earthworms in number (151) than corn rotations with wheat (95). Edwards & Bohlen (1996) also mention that rotation with

root crops in particular discourages the buildup of earthworm populations, as most of the crop is removed during harvest.

Data from LTEs on this topic are rare. Evidence from 1 LTE of the EU-funded Catch-C project confirmed that both earthworm number and biomass were significantly higher in the permanent grassland as compared to the permanent arable land (D'Hose *et al*. 2014b). No data were available from within the iSQAPER long-term experiments.

Overall impact evaluation: Depending on the type of intercrop, rotation can have positive or negative impact on soil earthworm abundance, +, -.

3.1.4 Irrigation

Irrigation is the application of water to ensure that sufficient soil moisture is available for good plant growth throughout the growing season. It is most frequently applied in arid and semi-arid regions, with poor water quantity and quality. In these regions, the limited rainfall is not sufficient to leach out salts from the root zone, so that salt from the irrigation accumulates in the soil and affects the soil properties (Huang *et al.*, 2011).
Within the iSQAPER project area, irrigation is most widely practiced in the Mediterranean region (Table IR-01). China has a cultivated land of $1.35*10^8$ ha; with an effective irrigation area of $6.3*10^7$ ha at the end of 2014 (China Land and Resources Communique for 2015, Ministry of land and Resources of P. R. of China, 2016).

Table IR-01. Irrigable and irrigated areas in the EU and China project area and of iSQAPER. UAA = Utilised Agricultural Area; (¹) Agricultural area calculated without common land (Eurostat 2016, adapted).

	Agricultural area	Total irrigable area		Area irrigated at least once a year	
	(ha)	(ha)	(% of UAA)	(ha)	(% of UAA)
Belgium	1,307,900	19,180	1.5	5,740	0.4
Estonia	957,510	430	0.0	310	0.0
Greece (¹)	3,381,510	1,516,930	44.9	1,164,620	34.4
Spain (¹)	21,694,850	6,751,710	31.1	2,898,970	13.4
France (¹)	27,064,300	2,811,440	10.4	1,423,640	5.3
Italy (¹)	11,813,630	4,004,450	33.9	2,866,330	24.3
Hungary (¹)	4,589,290	258,960	5.6	141,190	3.1
Netherlands	1,847,570	499,400	27.0	101,770	5.5
Poland	14,409,870	75,810	0.5	45,550	0.3
Portugal (¹)	3,539,350	551,760	15.6	477,160	13.5
Romania (¹)	11,509,310	230,390	2.0	152,840	1.3
Slovenia(¹)	462,750	4,270	0.9	2,540	0.5
United Kingdom (¹)	15,900,920	115,380	0.7	49,130	0.3
China	135,057,300			62,466,000	46.3

Outside the Mediterranean region, irrigation is mostly practiced as "supplemental" or "summer" irrigation, augmenting the rainfall prior to and during the growing season to reduce water stress from insufficient soil moisture. Irrigation can vary in type, rate and duration, with furrow/flood and sprinkler irrigation being the main types.

No comprehensive reviews on the effect of irrigation on soil properties were found. However, there are numerous reports from local studies which can help to shed light on how irrigation affects soil physical, chemical and biological parameters, and how this knowledge could be used to optimise irrigation schedules.

Yield

Irrigation management is mainly targeted at plant growth, and assessed by yield as primary indicator. Where yields are water-limited, a positive effect can be observed until a certain optimum irrigation rate or amount are achieved (Figure IR-01). If irrigation is further increased, waterlogging will cause yields to decrease.

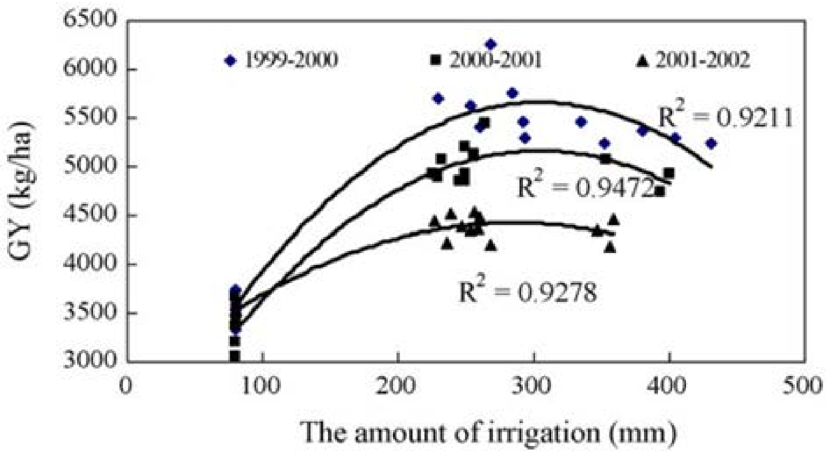


Figure IR-01. Relationships between grain yield (GY) of winter wheat and irrigation from 1999-2002 (Sun *et al*., 2006).

Given the many types and rates of irrigation practiced in different climates and on different soil types for a wide range of agricultural crops, no specific increase in yield can be reported.
Out of the 30 long-term experiments covered by iSQAPER, only 8 are reporting irrigation management. Two of these (PT4, PT5) show contrasting irrigation between treatments, but do not report any yield data.

Overall impact evaluation: positive to very positive, + +.

SOM/SOC

Due to increased yields under irrigation, subsequent organic matter additions (harvest residues) are higher. It has therefore been claimed that under certain conditions irrigation can help to increase SOC stocks or at least decrease the rate of SOC loss. Carbon sequestration rates as high as 50 to 150 kg ha^{-1} y^{-1} have been estimated (Lal *et al*., 1998).
However, effects of irrigation on the C balance are not clear at field-scale. Gillabel *et al*. (2007) found significantly higher top soil total organic carbon (TOC) stocks of 940 g m^{-2} in the irrigated centre vs. 746 g m^{-2} at the dry corners of a centre-pivot irrigation system. Manojlović *et al*. (2008) reported no significant changes in the SOC content of a calcareous Chernozem in Serbia subjected to more than 40 years of irrigation. Dersch and Böhm (2001) concluded that 21 years of

supplementary irrigation in Austria decreased SOC between 3.7 and 12.6 g C m^{-2} y^{-1} (37–126 kg C ha^{-1} y^{-1}). A similar observation was made in New Zealand, where 60 years of flood irrigation on pasture land had 17% lower topsoil SOC as compared to non-irrigated land (Kelliher *et al*., 2012; Fraser *et al*., 2012).

A decrease in SOC under irrigation was attributed to higher microbial activities and consequently higher mineralization rates, *i.e*. a faster C cycling. This effect appears to be particularly pronounced in drier climates, where irrigation could thus contribute to significant C losses over time. These results show that the C sequestration potential of irrigation cannot be evaluated in terms of a C input effect alone, but that changes in soil C dynamics caused by irrigation have to be included as well (Gillabel *et al.*, 2007).

Since CO_2 emissions can be higher than the equivalent increase in SOC, regardless of tillage type, irrigation is not considered a valid soil C sequestration option in Europe (Manojlović *et al.*, 2008).

The iSQAPER LTEs data indicate that SOC decreased after irrigation at the Portugal site (Table IR-02, and Figure IR-02).

Table IR-02. SOC change from the iSQAPER LTEs.

Trial name	Country	Response	Rainfed	Irrigated	Ratio
ESAC vineyards *since 2003*	Portugal	Topsoil carbon content (%)	Treatment 2: 1.41 (2005) 1.39 (2014)	Treatment 1: 1.38 (2004) 1.15 (2014)	0.98 0.83
ESAC conv. vs biological grazing *since 2003*	Portugal	Topsoil carbon content (%)	Treatment 1 (conv. & primarily rainfed) 1.54 (2004) 0.57 (2014)	Treatment 2 (org. & primarily irrigated): 2.14 (2004) 0.79 (2014)	1.39 1.39

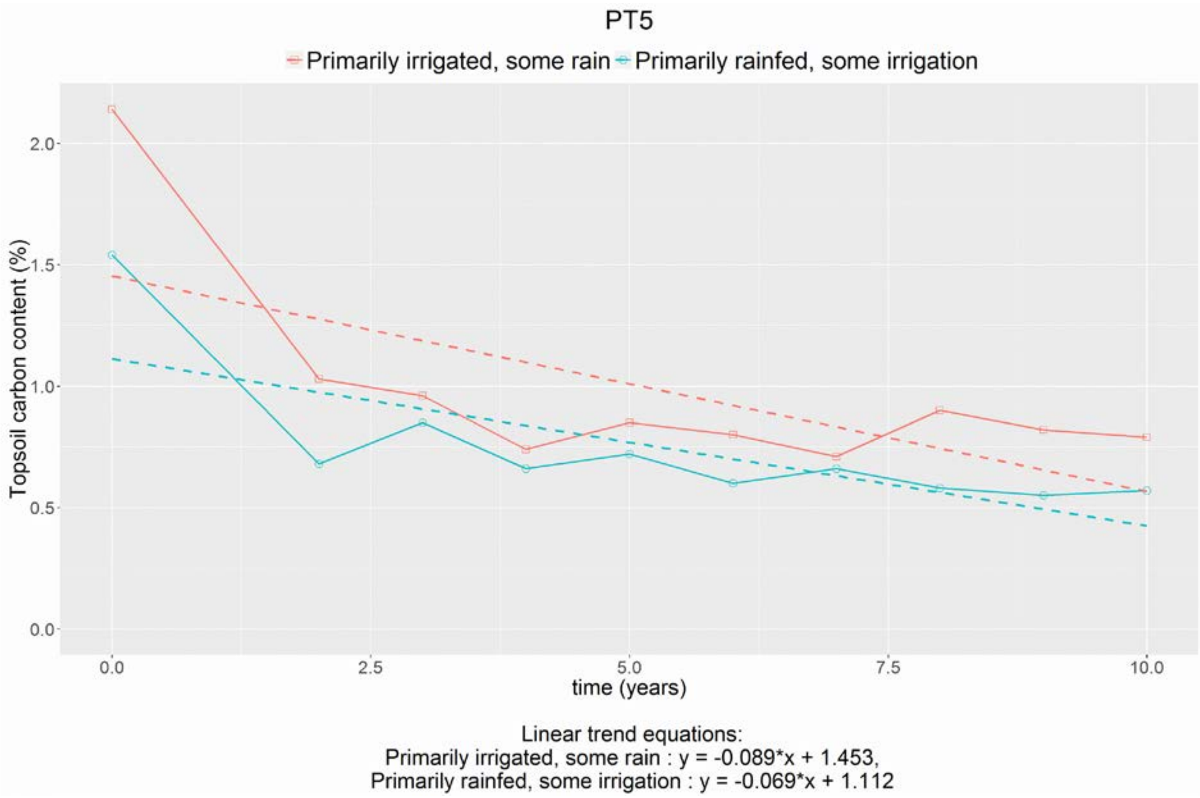


Figure IR-02. SOC trends under irrigation from the iSQAPER LTE site PT5 (ESAC: conventional vs biological grazing, Portugal).

Overall impact evaluation: positive, +.

pH

In arid regions, irrigation water is often highly sodic. This can induce a high levels of exchangeable sodium at the soil surfaces with a concomitant dispersal of clay particles and soil structure degradation (Amézketa, 1999).

Where good quality irrigation water is available, it can be used to decrease pH and salt contents of saline soils. Mohammad and Mazahreh (2003) showed how both, potable as well as treated wastewater treatments were able to significantly lower soil pH during 2 consecutive growing seasons. The authors also stated that the observed pH changes may not persist for long due to the high buffering capacity of the highly calcareous alkaline soil. Nevertheless, the crops would have benefited from even a temporary decrease in soil pH because of enhanced solubility and availability of P, Fe, Mn, Zn, and Cu.

Lobry de Bruyn and Kingston (1997) reported “no detrimental influence” of irrigation during a 2-year irrigation of Tasmanian dairy farm soils (pH_{Ca} 5.2), with topsoil pH values remaining the same.

The iSQAPER LTEs data show almost no change or in soil pH under irrigation in the Portuguese site (Table IR-03 and Figure IR-03).

Table IR-03. Soil pH change from the iSQAPER LTEs in Portugal.

Trial name	Country	Response	Rainfed	Irrigated	Ratio
ESAC vineyards *since 2003*	Portugal	Soil pH	Treatment 2: 6.8 (2005) 6.8 (2014)	Treatment 1: 6.33 (2004) 6.65 (2014)	0.93 0.98
ESAC conv. vs biolog. grazing *since 2003*	Portugal	Soil pH	Treatment 1 (conv. & primarily rainfed) 6.74 (2004) 6.63 (2014)	Treatment 2 (org. & primarily irrigated): 7.38 (2004) 7.10 (2014)	1.09 1.07

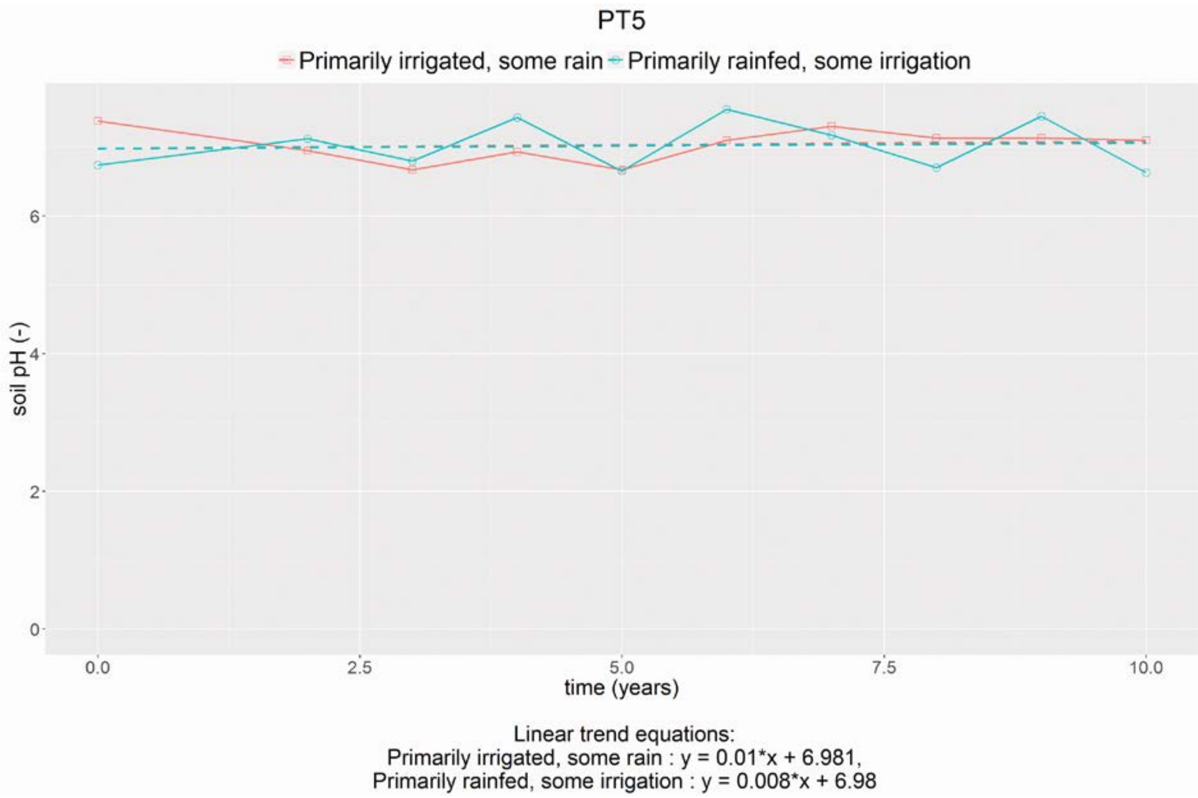


Figure IR-03. Soil pH trends from the iSQAPER LTE site PT5 (ESAC: conventional vs biological grazing, Portugal).

Overall impact evaluation: not possible, as strongly dependent on soil type and quality of irrigation water.

Aggregate stability/Soil structure

The type, rate and duration of irrigation, as well as the quality of irrigation water can strongly affect soil structural stability (Amézketa, 1999). Most publications on the topic report a negative impact of irrigation with saline water on physical properties such as bulk density, porosity, and hydraulic conductivity (Moreno *et al.*, 1986; Al-Nabulsi, 2001). Tedeschi and Dell'Aquila (2005) showed that aggregate stability in water decreased linearly with amounts of NaCl in irrigation water applied. Under NaCl loads of 20 t ha^{-1} y^{-1} the stability index had decreased from 40% to 10%. Huang *et al*. (2011) reported that structural stability decreased with increasing salt content of the irrigation water; soils receiving 0.8 g l^{-1} irrigation water had more than twice the amount of

aggregates (4.75-2 mm) as compared to soils receiving 5 g l^{-1}. Once the soil structure is weakened, it becomes more prone to disruption of aggregates by irrigation water (Gillabel *et al*., 2007).

Irrigation reduces the occurrence of dry–wet cycles in soil, but effects thereof on overall aggregate stability are largely unclear (Denef *et al.*, 2001).
On the positive side, proper irrigation increases yields and increased SOM input with residues can lead to increased aggregate formation (De Gryze *et al*., 2005; Kong *et al*., 2005), which in turn enhances C sequestration by physical protection of SOM inside aggregates.
In a field experiment in Nebraska, Gillabel *et al*. (2007) found that macro-aggregate stability was highest under native vegetation (control, grassland) as compared to irrigated and non-irrigated soils at the same area. They postulated that other factors than climate and inherent soil properties were responsible for the low macro-aggregate levels under irrigation.
What happens to soil structural stability under irrigation appears to be hard to predict and depends on both irrigation water quality as well as local soil properties. No additional insight on this topic could be extracted from the data collected as part of the iSQAPER project.

Overall impact evaluation: positive, +. Strongly dependent on soil type and quality of irrigation water.

Water holding capacity
Analogous to the sparse literature on structural changes in soil, no clear trends for changes in water-holding capacity under irrigation could be found. Most evidence relates to the application of sewage effluent which has been shown to improve both soil structure and water-holding capacity over time (Abd Elnaim *et al*., 1987).

For soils irrigated with saline water in northwest China, Huang *et al.* (2011) found that water-holding capacity was 32% higher in the 5 g l^{-1} irrigation water as compared to the 0.8 g l^{-1} irrigation water. This finding appeared to have been caused by the fraction of pore space at smaller pore diameters decreasing, and the contribution of larger pores increasing. They explained at such results are relevant for irrigation management, as *e.g*. due to the higher storage capacity it would be possible to stretch irrigation intervals.

For green roof system substrates, Cho *et al*. (2010) have shown that water holding capacity was in the order of drip irrigation > wick irrigation (self-watering using a wick and a reservoir) > reservoir-drainage method. Only the wick irrigation method constantly maintained the water content in the substrate during the growing period.

Overall impact evaluation: not possible, as strongly dependent on soil type and quality of irrigation water.

Earthworms

Soil moisture is probably the most important regulating factor for earthworm reproduction and activity. Earthworms can deal with a lack of water and have adapted to surviving drought: some species retreat into deeper soil layers and become less active during dry periods, others move to an area where there is more moisture while others die after producing cocoons that hatch when conditions become more favourable. A few studies (Watt and Burgham, 1992; Baker *et al.*, 1993) have shown that if pores <3 mm diameter are drained for extended periods, earthworm activity ceases. An experiment with soil pF measurements on Krasnozem suggests that soil moisture content below 22% is critical for earthworm activity (pF = 2.7; Lobry de Bruyn and Kingston, 1997).

But how do earthworms deal with a surplus of water? There unfortunately is an astonishing lack of information on how irrigation influences their community. It is generally known that - like other soil invertebrates - earthworms have limited defences against moisture stress. In a long-term irrigation experiment under pasture in New Zealand, Fraser *et al.* (2012) found significantly higher earthworm abundance under irrigation in summer time; abundance on the plots irrigated at 20% gravimetric soil moisture was nearly four times higher than under dryland control plots. During winter, no significant differences were observed. The authors elucidated that the higher abundance of earthworms in the summer months under irrigation may partly explain the lower soil carbon observed under irrigation, *i.e.* due to enhanced rates of soil organic matter turnover. They concluded that irrigation schedules have to be considered not only to optimise plant growth, but also to optimise the invertebrate community and its activity. Higher earthworm numbers under irrigation were also confirmed by Manono and Moller (2015).

Overall impact evaluation: positive, +.

3.1.5 Organic farming

Conventional agriculture has improved crop yields, but often at large costs to the environment. The main idea behind organic farming systems is to have agricultural production systems which are economically *and* ecologically sound at the same time. This approach acknowledges that besides the production of food, agricultural soils also play a role *e.g*. in water quality, climate regulation and biodiversity conservation. Organic agriculture is considered a pathway to minimise trade-offs between various soil functions, and means to guarantee a more sustainable farming.

But does organic farming really lead to higher levels of soil fertility, as evidenced in the soil quality indicators selected for this study? One important thing to keep in mind is that rather than being a single practice, organic farming is a bundle of soil, water, nutrient and pest management measures. Consequently, the setup of experiments with conventionally and organically managed plots has to be closely analysed before conclusion are drawn. For example, organic management tends to include ley (or fallow) periods, making a direct comparison of crop rotation or yield figures difficult.

Since the onset of organic farming in the early 20th century, uncountable evidence for its positive effects on soil quality has been accumulating. Good overviews have been provided by Stolze *et al*. (2000), Gomiero *et al*. (2011) and Tuomisto *et al*. (2012). Organic farming/agriculture or

ecological agriculture in China was reviewed within the EU-China Trade Program (Scoones and Elsaesser, 2008), Zhang *et al*. (2007) and Song *et al*. (2012).

Yield

A comprehensive analysis on how organic farming performs in terms of yields has recently been provided by Ponisio *et al*. (2014). Based on data from 115 studies with more than 1000 observations they found that organic yields are 19.2% (± 3.7%) lower than conventional yields. Tuomisto *et al*. (2012) analysed 71 studies on European farming systems and found that average organic yields over all crops in the data were 75% of conventional yields. Most other evidence we collected confirms this organic “yield gap”, although local results can vary a lot. Seufert *et al* (2012) did a comprehensive meta-analysis to examine the relative yield performance of organic and conventional farming systems globally, they found that overall, organic yields are typically lower than conventional yields: 5% lower organic yields in rain-fed legumes and perennials on weak acidic to weak-alkaline soils; 13% lower yields in the best organic practices and 34% lower yields when the conventional and organic systems are most comparable). In the Swiss DOK long-term experiment, yields in the organic treatments were 80% of those of the conventionally managed systems over the same period (1978-2005) and averaged over all crops (Gunst *et al.,* 2007). For an arable system in Nebraska/USA, Wortman *et al.* (2012) found organic yields at 72% or conventional ones, and the same value was found for a organic/conventional comparison of 26 agricultural fields in Central Catalonia/Spain (Romanyà *et al*., 2012). Some studies report no significant differences in yield levels, *e.g.* Eyhorn *et al*. (2007) for cotton-based farming systems in India. And for a study on a broad-bean/water-melon rotation in Spain substantially higher yields were reported under organic management (Melero *et al.*, 2006).

Although the organic yield gap is widely reported, it is also recognised that proper land management can help to decrease it. Ponisio *et al.* (2014) reported that two agricultural diversification practices, multi-cropping and crop rotations, substantially reduce the yield gap (to 9 ± 4% and 8 ± 5%, respectively) when the methods were applied in only organic systems. Also, studies have shown that organically managed crop systems have lower long-term yield variability and higher cropping system stability (Smolik *et al*., 1995; Lotter *et al*., 2003).

The iSQAPER LTEs data show that yields decreased in both organic and conventional farming system in the Swiss LTEs. Interestingly in the sites in China yield increased under organic farming and decreased under conventional farming (Table OF-01 and Figure OF-01).

Table OF-01. Yield changes from the iSQAPER long-term experiment under organic and conventional farming.

Trial name	Country	Response	Conventional	Organic	Ratio
Aesch *since 2010*	Switzerland	Dry yield, aboveground (t ha^{-1})	Treatment 10: 18.5 (2010) 15.0 (2015)	Treatment 8: 19.0 (2010) 14.7 (2015)	 1.03 0.98
DOK (Therwil) *since 1978*	Switzerland	Dry yield, aboveground (t ha^{-1})	Treatment 2: 19.21 (2006) 11.70 (2012)	Treatment 4: 20.03 (2006) 12.08 (2012)	 1.04 1.03
BASIS *2008-2015*	Netherlands	Marketable yield (t ha^{-1})	Treatment 1: 9.11 (2009) 58.91 (2014)	Treatment 6: 5.07 (2009) 40.10 (2014)	 0.56 0.68
Org-Conv system experiment *since 2008*	Estonia	Dry yield (t ha^{-1}) - winter wheat - barley - potato - pea	Treatment N3: 4.01 (2008) 2.32 (2008) 18.35 (2008) 2.00 (2008)	Treatment M2: 1.30 (2008) 1.26 (2008) 21.68 (2008) 2.40 (2008)	 0.32 0.54 1.18 1.20
Soil forming (moraine) *since 1964*	Estonia	Dry yield (t ha^{-1})	Treatment 8: 2.37 (1965-69) 3.72 (1986-93)	Treatment 11: 4.49 (1965-69) 3.70 (1986-93)	 1.89 0.99
Suining *since 1981*	China	 Rice yield (t ha^{-1}) Wheat yield (t ha^{-1})	Treatment NPK (4): 6.478 (1982) 6.244 (1993) 7.181 (2003) 6.206 (2015) 4.866 (1983) 3.990 (1993) 3.431 (2003) 2.981 (2015)	Treatment M (5): 3.497 (1982) 4.125 (1993) 5.456 (2003) 2.906 (2015) 3.600 (1983) 2.287 (1993) 2.100 (2003) 1.500 (2015)	 0.54 0.66 0.76 0.47 0.74 0.57 0.61 0.50

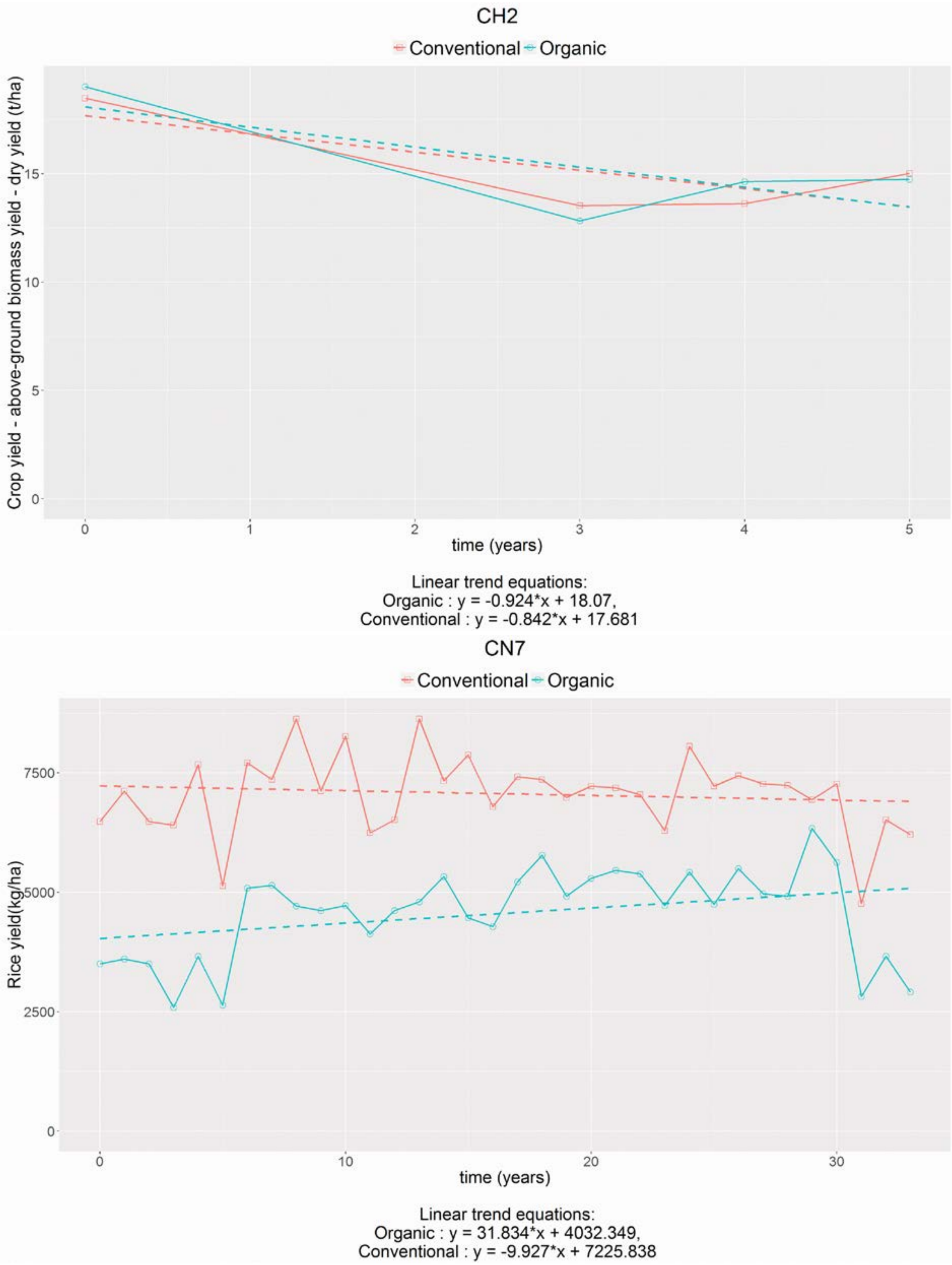


Figure OF-01. Yield trends from the iSQAPER LTE sites in Switzerland (CH2, tillage trial Aesch, top) and in China (CN7, Suining, bottom).

Overall impact evaluation: negative, -.

SOM/SOC

In a meta-analysis covering 74 studies with pairwise organic vs. non-organic farming system comparisons, Gattinger *et al*. (2012) found 0.18 ± 0.06% points (1.8 g kg^{-1}) for SOC concentrations, 3.50 ± 1.08 Mg C ha^{-1} for stocks, and 0.45 ± 0.21 Mg C ha^{-1} y^{-1} for sequestration rates compared with non-organic management. The difference was slightly more pronounced when the authors restricted the analysis to zero net input organic systems and retaining only the datasets with highest data quality. More substantial differences were reported by Mondelaers *et al*. (2009) who in another meta-analysis reported a SOM content on organically managed fields which exceeds conventional ones by 6.4% points.
These findings are in line with expectations after which SOM levels under organic management should be higher as a consequence of higher inputs of organic matter in the form of animal and green manures, the efficient cycling of crop residues, and the use of leys. However, this is counterbalanced by the fact that a) conventional crops tend to yield higher and so crop residue inputs will be higher, and b) organic soils require more mechanical ploughing for pest management.

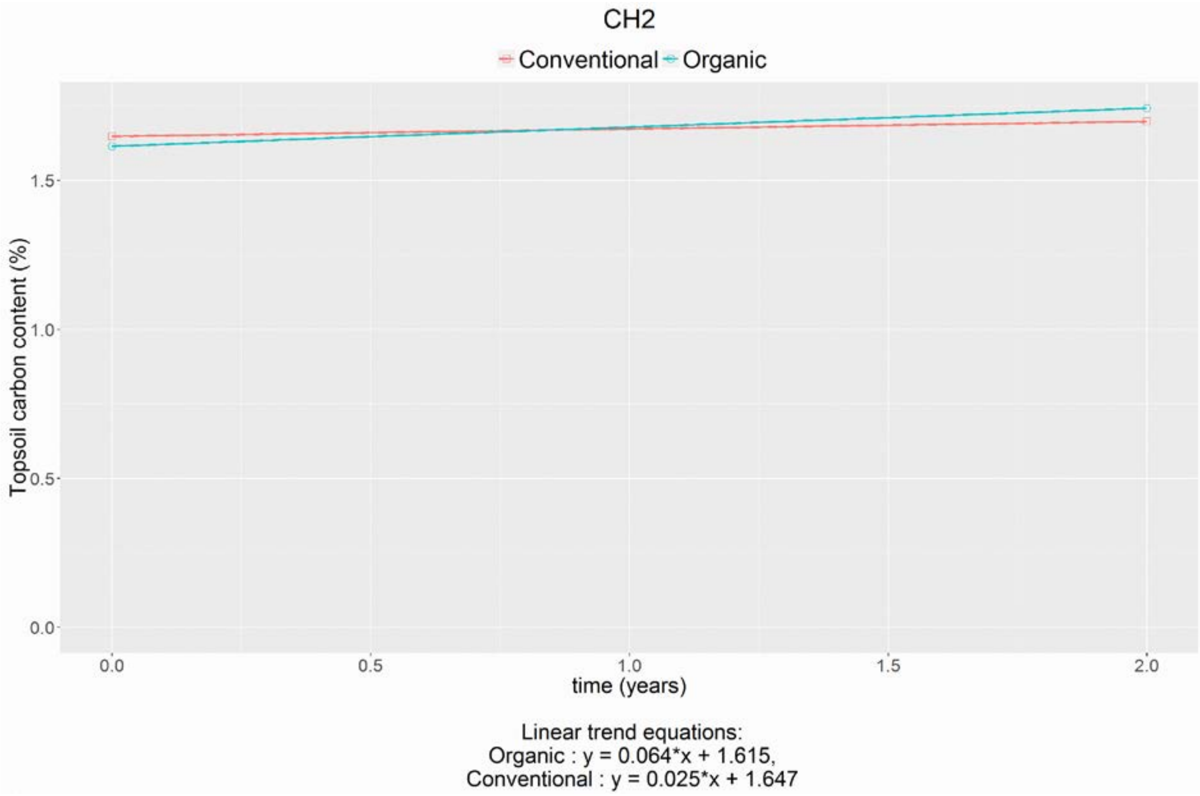
Of the 15 on-field studies analysed on the topic, 7 report elevated SOC contents on the organic plots in the order of 6-22% as compared to conventional management (Condron *et al*., 2000; Gosling and Shepherd, 2005; Schjønning *et al.*, 2002; Heinze *et al*., 2010; Reganold *et al*., 2010; Romanyà *et al*., 2012; Domagala-Swiatkiewicz and Gastol, 2013). Five report no significant differences between organic and conventional treatments (Schjønning *et al*., 2002; Marinari *et al*., 2006; van Diepeningen *et al*., 2006; Eyhorn *et al*., 2007; Fliessbach *et al*. 2007). And 3 of them report SOC increases of more than 100% (Gerhardt, 1997; Melero *et al*., 2006; Wang *et al*., 2011). The findings of Gerhardt (1997) - who detected a >200% increase over a period of 40 years - illustrate how important time is as a factor in the evaluation. Gomiero *et al*. (2011) mention that in the longest trial so far (Rothamsted Experimental Station/UK, running for > 150 years) SOM levels have increased by about 120% over 150 years in the organic manured plots, and only by about 20% in the plots employing NPK fertilizer.

The iSQAPER LTEs data show that SOC increased or remained stable under both organic or conventional farming (Table OF-02 and Figures OF-02, OF-03 and OF-04).

Table OF-02. Trend evaluation from iSQAPER long-term experiment data.

Trial name	Country	Response	Conventional	Organic	Ratio
Aesch *since 2010*	Switzerland	Topsoil C content (%)	Treatment 10: 1.65 (2010) 1.70 (2015)	Treatment 8: 1.62 (2010) 1.74 (2015)	 0.98 1.02
DOK (Therwil) *since 1978*	Switzerland	Topsoil C content (%)	Treatment 2: 1.17 (2006) 1.18 (2010)	Treatment 4: 1.23 (2006) 1.21 (2010)	 1.05 1.03
BASIS *2008-2015*	Netherlands	Soil organic matter content (%)	Treatment 1: 3.00 (2013)	Treatment 5: 3.05 (2013)	 1.02
Org-Conv system	Estonia	Topsoil C content	Treatment N3:	Treatment M2:	

experiment *since 2008*		(%) under winter wheat	1.47 (2008) 1.68 (2014)	1.22 (2008) 1.66 (2014)	0.83 0.99
Soil forming (moraine) *since 1964*	Estonia	Soil organic matter content (%) Soil organic matter content (t ha^{-1})	Treatment 8: 0.74 (1969) 0.37 (1976) 34.2 (1993)	Treatment 11: 0.96 (1969) 0.42 (1976) 47.2 (1993)	 1.30 1.14 1.38
ESAC: conventional vs biological maize *2003-2014*	Portugal	Topsoil C content (%)	Treatment 1: 1.04 (2004) 1.12 (2014)	Treatment 2: 1.22 (2004) 1.34 (2014)	 1.17 1.20
ESAC: conventional vs biological grazing *2003-2014*	Portugal	Topsoil C content (%)	Treatment 1: 1.54 (2004) 0.57 (2014)	Treatment 2: 2.14 (2004) 0.79 (2014)	 1.39 1.39
Suining *since 1981*	China	Soil C content (%)	Treatment NPK (4): 0.92 (1981) 1.0 (1986) 1.2 (2005) 1.0 (2014)	Treatment M (5): 0.92 (1981) 1.0 (1986) 1.2 (2005) 1.0 (2014)	 1.00 1.00 1.00 1.00



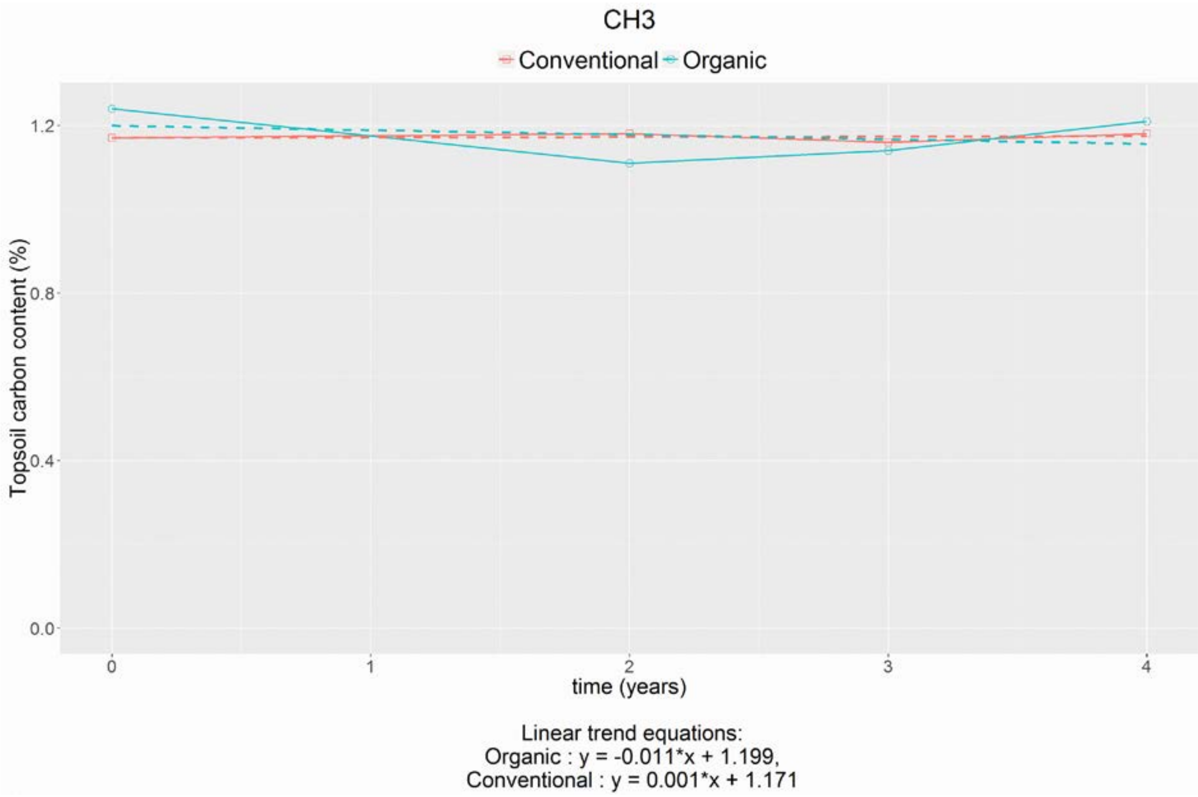


Figure OF-02. SOC trends from the Swiss iSQAPER LTE sites CH2 (tillage trial Aesch, top), and CH3 (DOK trial, bottom).

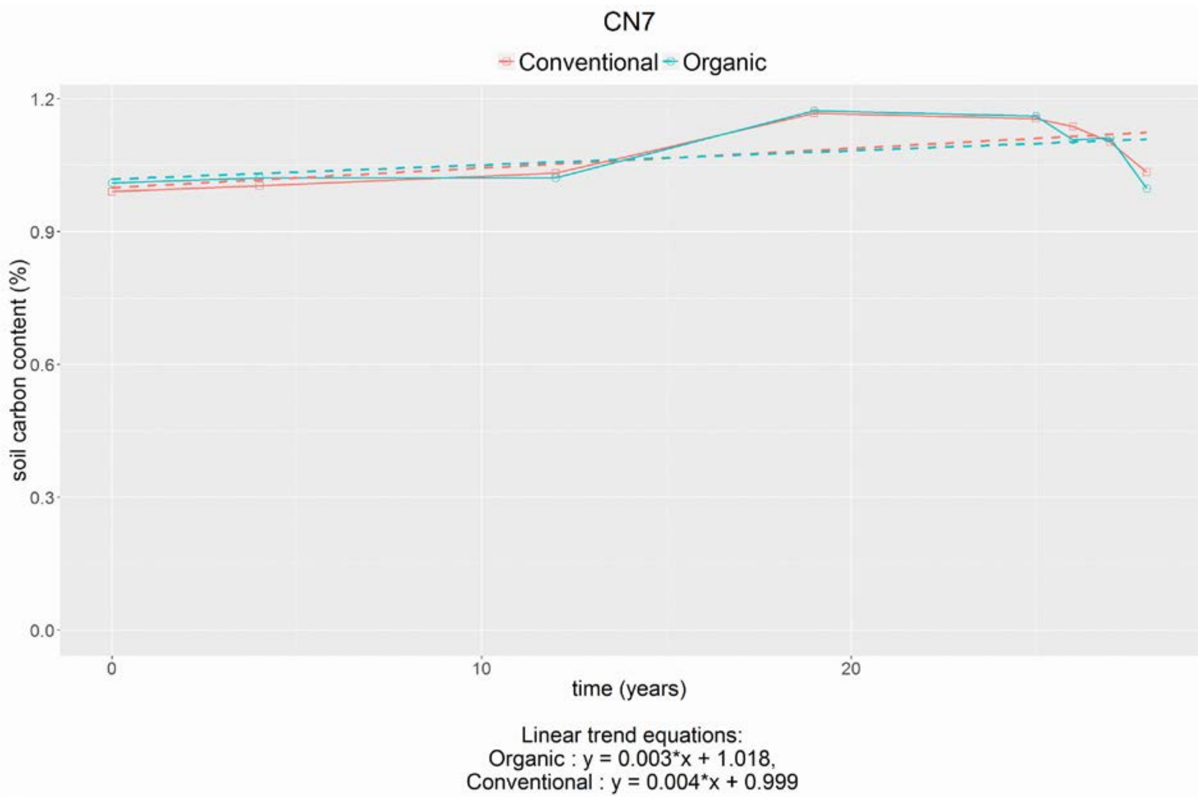


Figure OF-03. SOC trends from the iSQAPER LTE site CN7 (Suining, China).

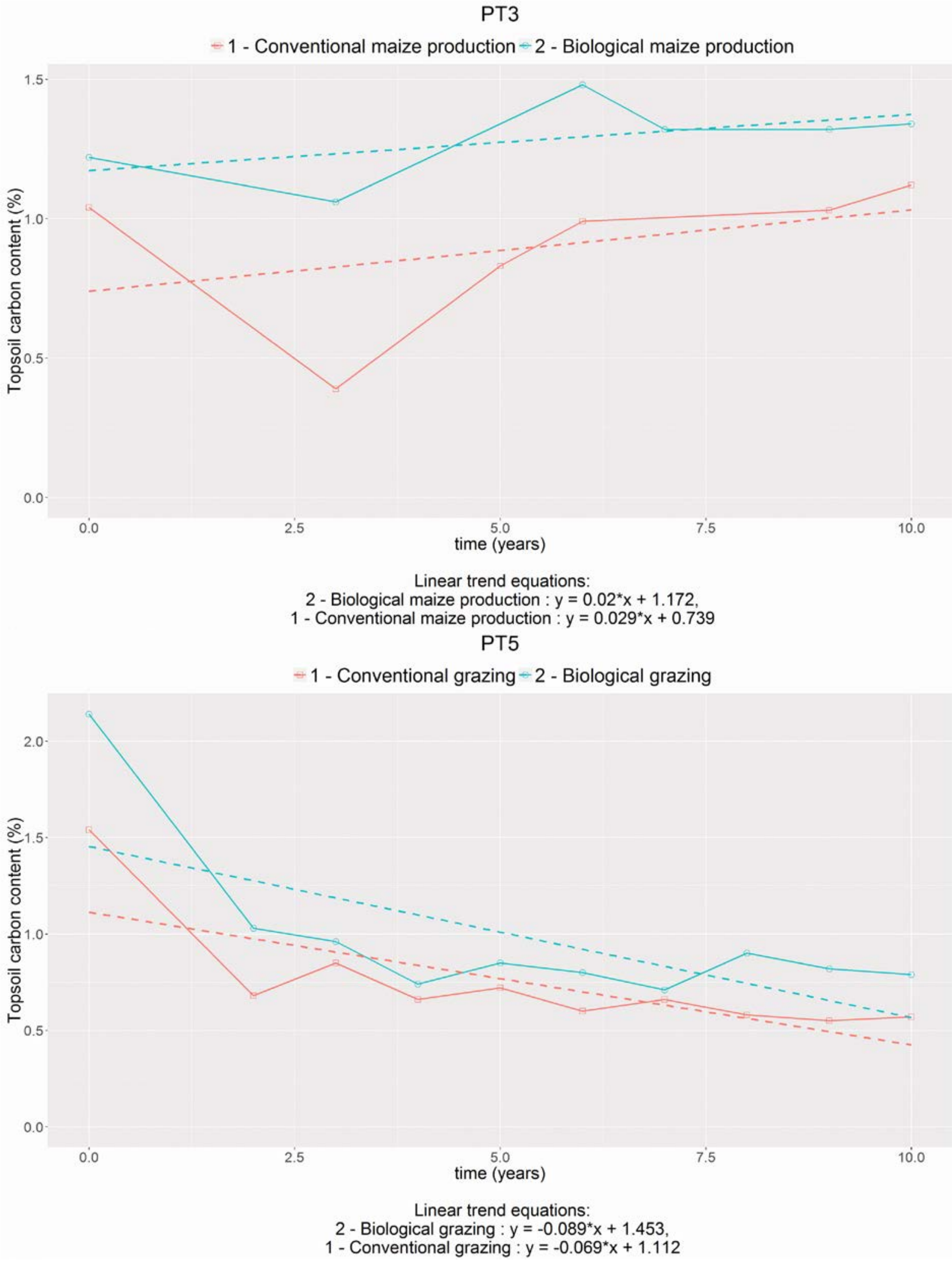


Figure OF-04. SOC trends from the Portuguese iSQAPER LTE sites PT3 (ESAC: conventional vs biological maize, top) and PT5 (ESAC: conventional vs biological grazing, bottom).

Overall impact evaluation: positive, +.

pH

To our knowledge, no meta-analysis has been done on how organic and conventional systems compare when it comes to soil pH. Recently, Romanian scientists have been in a heavy debate on potential evidence for acidification under organic farming practices in their country (Toncea *et al*., 2015; Ştefănescu *et al*., 2015). Generally, soil pH will depend on both the soil type and its buffering capacity, and the type of organic fertilizer or soil amendment applied. It is therefore of paramount importance to specifically look at the local soil and management conditions. Using (a decrease in) soil pH as a general indicator for organic farming systems as suggested by Toncea *et al.* (2015) does therefore not make sense.

The 9 local studies we have analysed on this subject (Condron *et al.*, 2000; Gosling and Shepherd, 2005; Marinari *et al*., 2006; Melero *et al*., 2006; Eyhorn *et al*., 2007; Heinze *et al*., 2010; Reganold *et al*., 2010; Ge *et al*., 2011; Domagala-Swiatkiewicz and Gastol, 2013) confirm how remarkably small soil pH differences are between organic and conventional systems (on similar soils). In six out of nine cases, pH is slightly but not significantly lower in organic systems, with all observed differences being < 0.4 units. In the Swiss DOK experiment, soil pH was even slightly higher in the organic systems (Mäder *et al*., 2002).
The iSQAPER LTEs indicate a stable or slightly increase in soil pH under both organic and conventional farming (Table OF-03 and Figures OF-05).

Table OF-03. Trend evaluation from iSQAPER long-term experiment data.

Trial name	Country	Response	Conventional	Organic	Ratio
DOK (Therwil) *since 1978*	Switzerland	Soil pH	Treatment 2: 6.6 (2006) 6.5 (2012)	Treatment 4: 6.4 (2006) 6.3 (2012)	 0.97 0.97
BASIS *2008-2015*	Netherlands	Soil pH	Treatment 1: 7.53 (2013)	Treatment 6: 7.45 (2013)	 0.99
Org-Conv system experiment *since 2008*	Estonia	Soil pH under winter wheat	Treatment N3: 5.77 (2008) 5.58 (2014)	Treatment M2: 5.95 (2008) 6.10 (2014)	 1.03 1.09
ESAC: conventional vs biological maize *2003-2014*	Portugal	Soil pH	Treatment 1: 6.67 (2004) 6.55 (2014)	Treatment 2: 5.47 (2004) 7.06 (2014)	 0.82 1.08
ESAC: conventional vs biological grazing *2003-2014*	Portugal	Soil pH	Treatment 1: 6.74 (2004) 6.63 (2014)	Treatment 2: 7.38 (2004) 7.10 (2014)	 1.09 1.07
Suining *since 1981*	China	Soil pH	Treatment NPK (4): 8.6 (1981) 8.5 (1998) 8.3 (2014)	Treatment M (5): 8.6 (1981) 8.4 (1998) 8.4 (2014)	 1.00 0.99 1.01

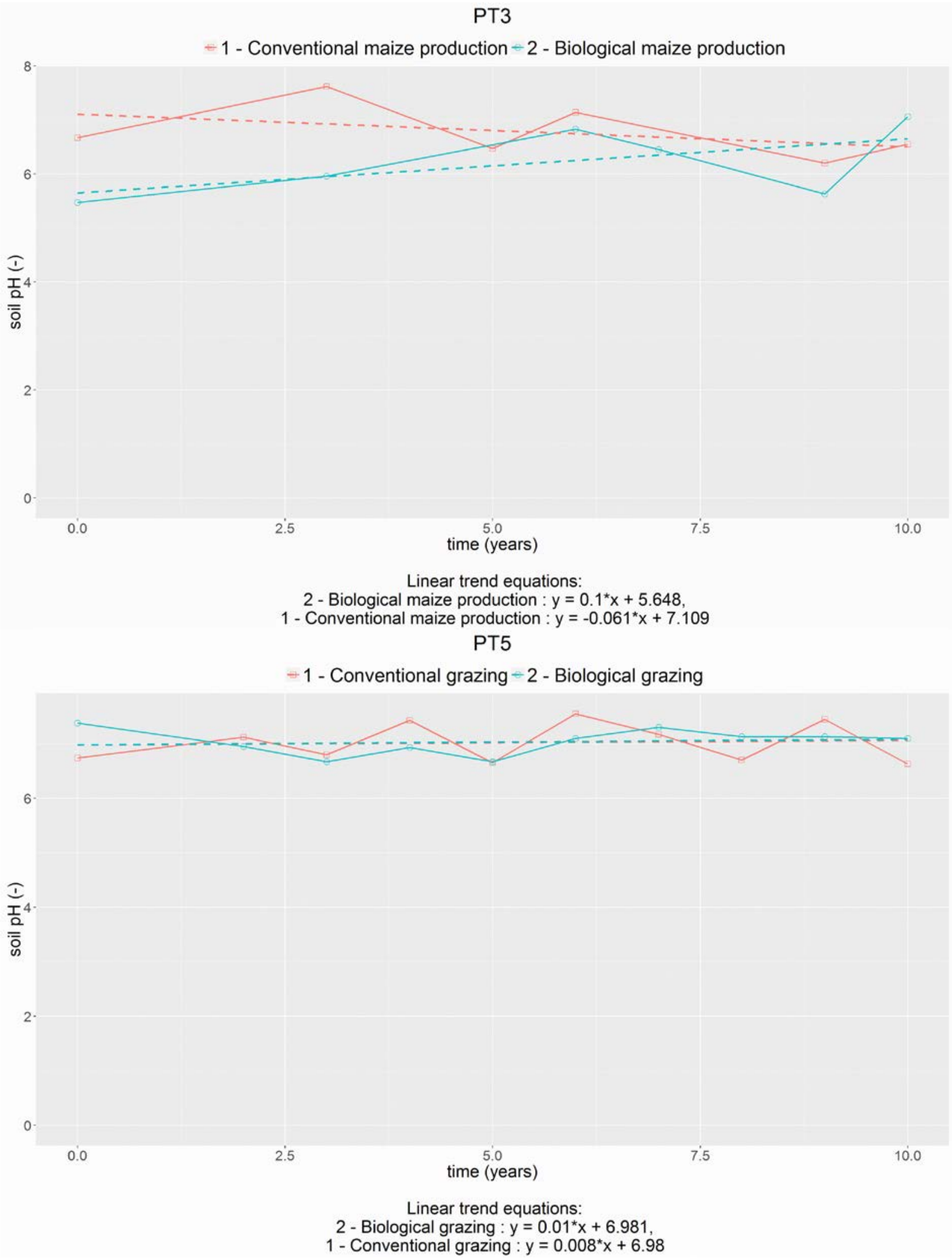


Figure OF-05. Soil pH trends from the Portuguese iSQAPER LTE sites at PT3 (ESAC: conventional vs biological maize, top) and PT5 (ESAC: conventional vs biological grazing, bottom).

Overall impact evaluation: no significant change, 0.

Aggregate stability/Soil structure

Aggregate stability at a given soil depth is dependent on the crop species, soil texture, and tillage (Jordahl and Karlen, 1993). Also, there is a proven relationship between organic matter content and aggregate stability (*e.g.* Loveland and Webb, 2003). Higher organic input under organic farming systems leads to a more vibrant soil life which in turn creates a more stable soil structure. However, as shown for soil organic matter above, significant changes can take decades to establish (Stolze *et al*., 2000; Stockdale *et al*., 2001).

In their review on comparison of alternative farming systems, Jordahl and Karlen (1993) found wet aggregate stability for a range of crops to be significantly higher in organic vs. conventional systems. The largest difference detected was under corn (78.3% vs. 48.6% water-stable aggregates). Significant increases under organic management have also been reported by Mäder *et al*. (2002), with 10 to 60% higher stability in the organic plots. Williams and Petticrew (2009) have been comparing soils from farms in Devon/England which have been organic or conventional for > 10 years. They found a tendency to higher aggregate stability in the organic systems. Similar evidence was reported by Gerhardt (1997), Siegrist *et al*. (1998), and Schjønning *et al*. (2002). No evidence could be found for deteriorating soil structure under organic management.

No evidence was found from the iSQAPER LTEs data.

Overall impact evaluation: positive, +.

Water holding capacity

There is evidence that in the long term aggregate stability is increasing under organic management, while porosity also increases (see above). Such changes in soil structure largely result from changes in the management of crop residues and organic matter inputs and may also lead to increased aeration and water holding capacity of soils under organic management (Stockdale *et al*., 2001).

In their comprehensive review, Gomiero *et al*. (2011) state that organically managed soils have a much higher water holding capacity than conventionally managed soils. Besides enhancing soil water content, organic farming seems to improve water use efficiency. Especially under drought conditions this can lead to organic crops out-yielding conventional crops by 70–90% (Gomiero *et al*., 2011; Lotter *et al*., 2003). For the DOK experiment in Switzerland, the water holding capacity was reported being 20 to 40% higher in organically managed soils than in conventional ones (Mäder *et al*., 2002).

No evidence was found from iSQAPER long-term experiment data on this matter.

Overall impact evaluation: positive, +.

Earthworms

A major objective of organic farming is to encourage soil biological activity. Ample research has been done comparing earthworm biomass, abundance and population characteristics under organic vs. conventional farming. The major reviews on the topic (Stolze *et al*., 2000; Hansen *et*

al., 2001; Bengtsson *et al*., 2005; Hole *et al*., 2005; Gomiero *et al*., 2011; Tuomisto *et al*., 2012) agree that biodiversity in general and earthworms in particular greatly benefit from organic inputs. Prohibition of pesticide use may also be a factor benefiting anecic and juvenile earthworms close to the soil surface (Pfiffner and Mäder, 1997). The inclusion of grass leys, preferably of several years, into farming systems appears to be of particular importance (Stolze *et al*., 2000).

In the English ‘Haughley experiment’ running since 1939, earthworm numbers under an organic ley-arable section supporting stock were one third higher as compared to a stockless intensive arable section dependent on agrochemical inputs. In a Swiss long-term experiment, mean abundance of earthworm species in the organic system (O, receiving rotted manure) was up to two times higher that of the conventional one (C, receiving stacked FYM and mineral fertiliser) (Pfiffner and Mäder, 1997). Even higher Lumbricide population density increases of up to nearly 300% have been observed in Denmark after making the transition to organic systems (Hansen *et al*., 2001).

In contrast, a couple of studies has found no significant differences between the two systems (*e.g.* Foissner, 1992; Nuutinen and Haukka, 1990) or even lower earthworm biomass in soils under organic management (Czarnecki and Paprocki, 1997; Yeates *et al*., 1997). One reason for these differences could be that excessive tillage - as often practised in organic systems for pest management - can have serious negative impacts on earthworm populations (Berry and Karlen, 1993), even in the presence of high levels of organic matter input.

The iSQAPER LTEs show a higher earthworm abundance under organic farming than that under the conventional farming (Table OF-04).

Table OF-04. Trend evaluation from iSQAPER long-term experiment data.

Trial name	Country	Response	Conventional	Organic	Ratio
Org-Conv system experiment *since 2008*	Estonia	Earthworm biomass (g m^{-2}) under - winter wheat - barley - potato - pea	Treatment N3: 5.58 (2014) 94.4 76.7 49.1 130.8	Treatment M2: 6.10 (2014) 190.6 137.5 103.1 190.6	 1.09 2.02 1.79 2.10 1.46

Overall impact evaluation: very positive, ++.

3.2 Synthesis

Table SY-1 shows descriptive statistics for the selected soil quality indicators under the chosen paired management practices.

Table SY-1. Descriptive statistics for impact of selected management practices on specific soil quality indicators.

Paired Management Practices	Indicators	Mean	Median	Min	Max	SD	skewness	Number of observations
OM addition versus no OM addition	Yield	1.97	1.21	0.16	9.59	1.947	2.079	133
	Water holding capacity	1.32	1.26	1.04	1.88	0.255	0.950	9
	SOM/SOC	1.51	1.29	0.12	9.59	1.254	3.688	163
	pH	1.08	1.05	0.95	1.34	0.090	0.543	70
	Earthworm numbers	2.02	1.78	1.43	3.08	0.696	0.503	5
	Aggregate stability	1.34	1.19	0.80	2.30	0.432	0.908	22
No-till versus tillage	Yield	1.09	0.96	0.34	3.76	0.509	2.603	118
	Water holding capacity	1.10	1.10	1.09	1.11	0.014	0.000	2
	SOM/SOC	2.69	1.49	0.67	13.33	2.691	2.050	100
	pH	1.00	1.00	0.95	1.03	0.017	-0.898	17
	Earthworm numbers	1.55	1.53	0.75	2.29	0.617	-0.020	6
	Aggregate stability	1.44	1.30	0.75	3.86	0.593	2.490	33
Crop rotation versus monoculture	Yield	1.26	1.18	0.91	2.57	0.368	2.408	19
	SOM/SOC	1.25	1.08	0.82	3.00	0.536	2.122	31
	pH	0.98	1.00	0.78	1.08	0.074	-1.417	19
	Earthworm numbers	0.87	0.63	0.20	1.92	0.650	0.590	3
	Aggregate stability	1.15	1.02	0.77	3.10	0.537	2.955	15
Irrigation versus rain-fed agriculture	Yield	1.03	1.03	1.03	1.03	NA	NA	1
	SOM/SOC	1.10	1.13	0.53	1.55	0.319	-0.228	18
	pH	0.99	0.98	0.83	1.09	0.071	-0.389	14
	Earthworm numbers	3.70	3.70	3.70	3.70	NA	NA	1
	Aggregate stability	2.12	1.76	0.96	4.00	1.361	0.453	4
Organic versus conventional agriculture	Yield	1.07	0.76	0.08	11.88	1.435	6.066	77
	SOM/SOC	1.58	1.11	0.13	9.31	1.563	2.959	117
	pH	0.99	0.99	0.78	1.10	0.065	-1.006	40
	Earthworm numbers	1.75	1.93	1.32	2.00	0.374	-0.370	3
	Aggregate stability	1.38	1.39	1.15	1.61	0.190	-0.028	4

Figure SY-0 shows location of the observations in the LR-database where the locations were given (60% of the total observations) and iSQAPER LTE sites and the Köppen climate classification.

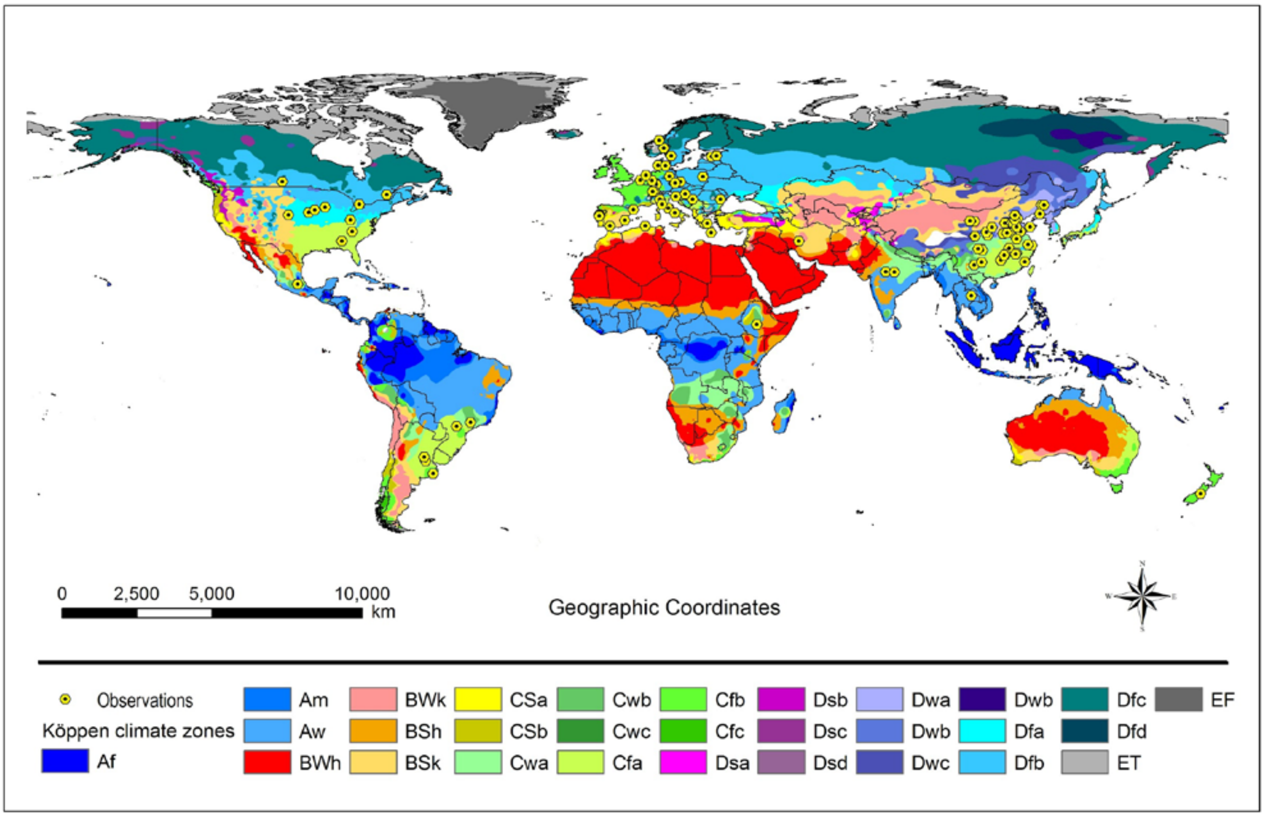


Figure SY-0. Distribution of the observations and iSQAPER LTEs in the Köppen climate zones.

Statistics indicates that 22% of the observations are Dfb, 17.4% Cfa , Dwa 15.4%, Cfb 9.1%, Cwa 8.3%, Csa 6.1%, Dfa 4.5%, Csb 3.8%, BSk 3%, BWk, Cwb and Dfc 2.3%, Aw and Dwb 1.5 and BSh 0.8%.

3.2.1 Cumulative effects of organic matter addition versus non-organic matter addition

Organic matter (OM) input favourably affected all the indicators under consideration as shown in Figure SY-1. The most favourable effects were reported for earthworm numbers, followed by SOM/SOC, soil aggregate stability and yield. OM addition enhances soil water holding capacity. For pH, no general effect of OM addition was observed, effects depended on soil type, for example OM input favourably affected the pH of acid soils.

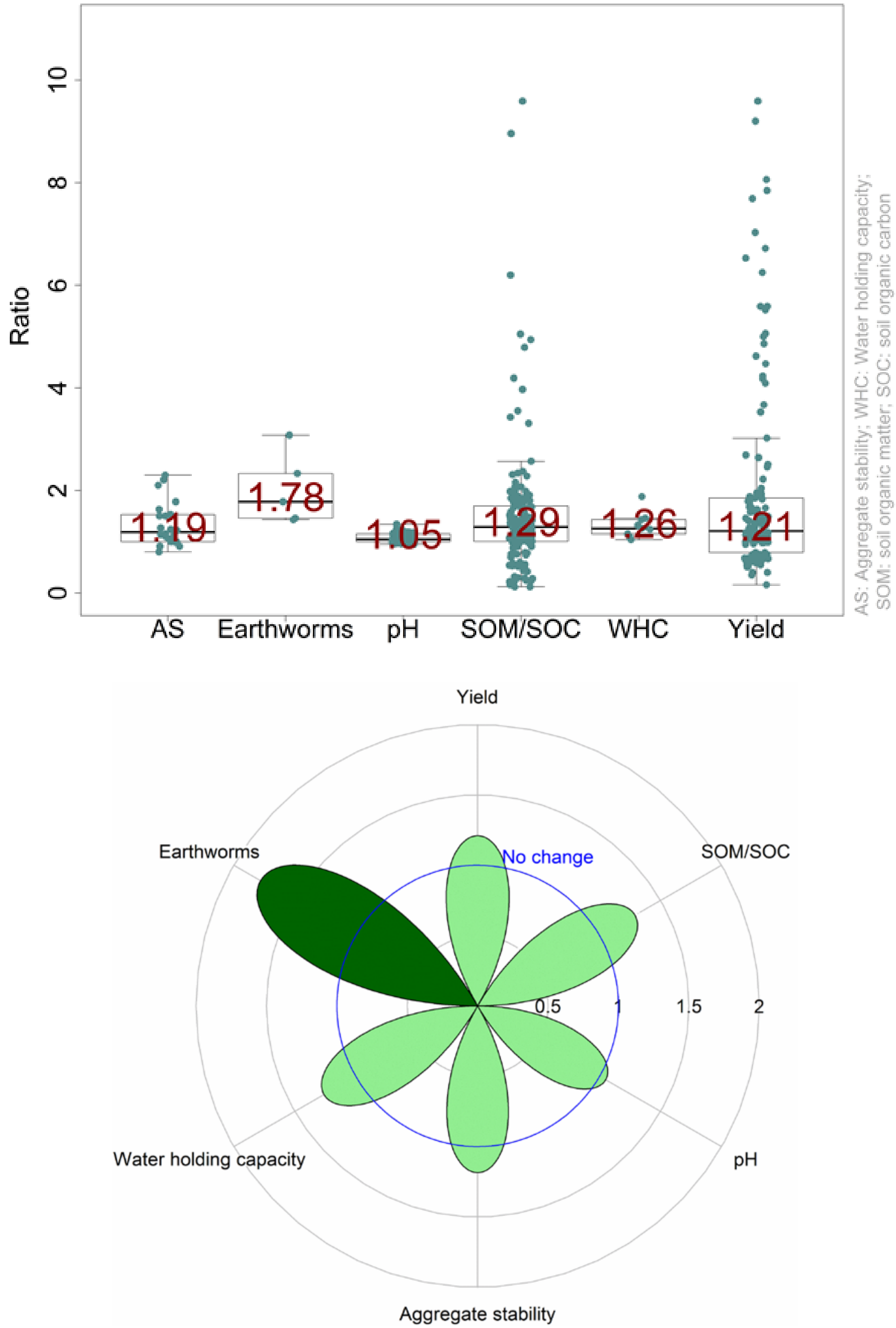
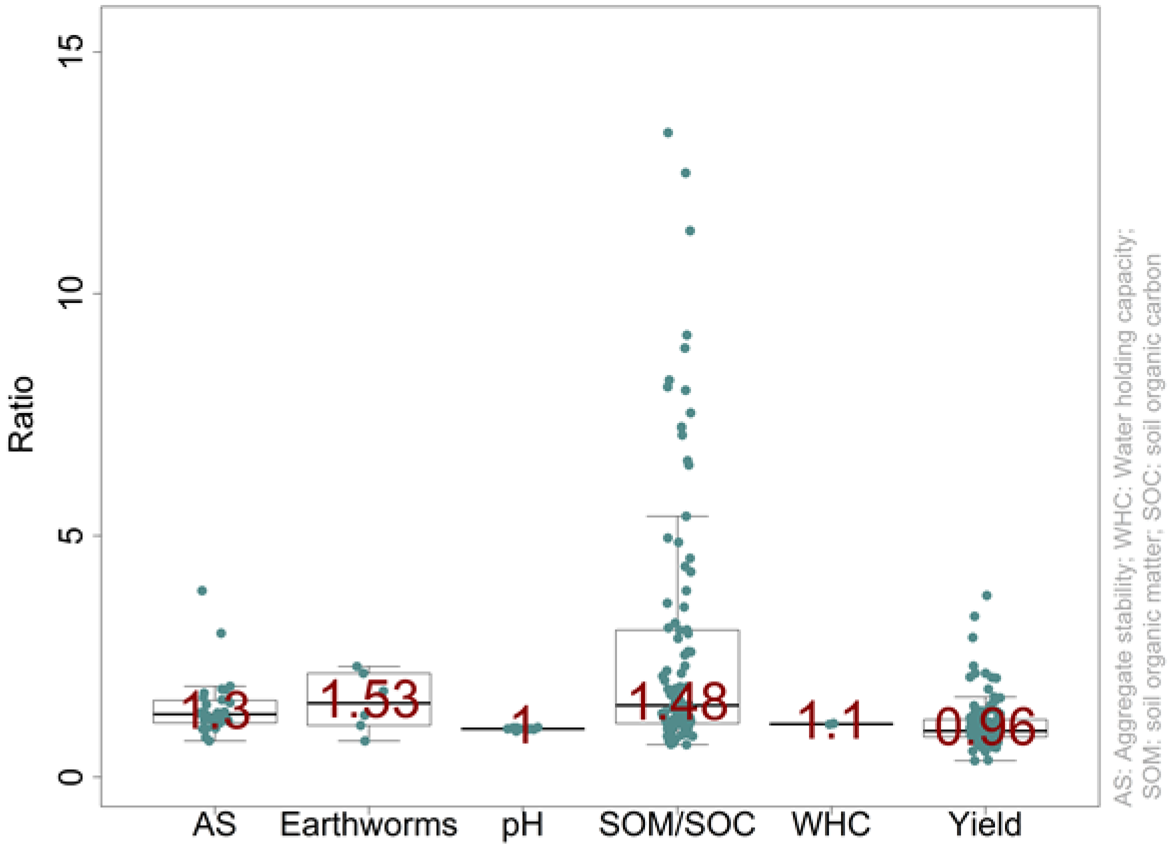


Figure SY-1. Long-term effects of organic matter addition on soil quality indicators compared to no organic matter input: spread (median and lower and upper quartiles) (top) and visualisation (bottom), expressed by a median of ratios.

3.2.2 Cumulative evaluation of no-till versus conventional tillage

Broad effects of tillage practices on the selected land quality indicators, based on the materials reviewed in Section 3.1.2, are shown in Figure SY-2. Overall, no clear trends were observed for soil pH, while NT generally led to increased aggregate stability/porosity and greater soil organic matter content in upper layers. These effects were reflected in a greater water holding capacity; the magnitude of the effects varied *a.o.* with soil texture. No-till practices favourably affected earthworm populations, yet not always in cases where herbicides or pesticides were needed to combat weeds and pests. Overall yield in this review decreased under NT. However, as especially shown by Pittelkow *et al* (2015), there were no clear trends for yields, as such are ultimately determined by many interacting factors. Variations in responses found in different studies reflected different magnitudes of tillage disruption and residue burial, timing of the tillage operations, timing of the measurements, and different soil, crop, and climate combinations (*e.g.* Bertrand *et al*, 2015; Palm *et al*, 2004).



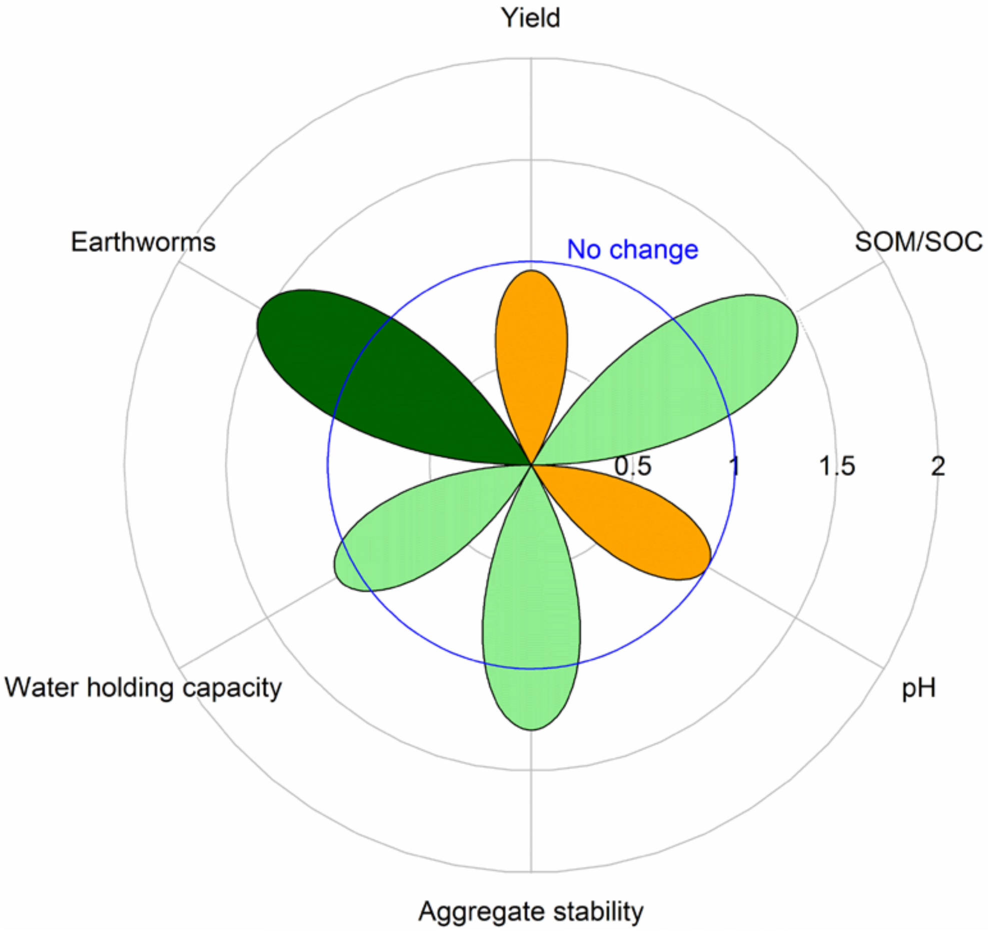


Figure SY-2. Long-term effects of no-till on soil quality indicators compared to conventional tillage: spread(top) and visualisation (bottom), based on a median of ratios.

3.2.3 Cumulative effects of crop rotation versus monoculture

Effects of crop rotation, based on the materials reviewed for this study in Section 3.1.3, are shown in Figure SY-3. Crop rotation had a positive effect on SOM/SOC content and yield; overall, crop rotation had little impact on soil pH, aggregate stability and water holding capacity - depending on the type of intercrop; whereas rotation of arable crops only could have adverse effects, rotation with ley very positively influences population numbers; Mixed, *i.e.,* positive, negative or neutral effects on earthworm numbers were observed; overall result was unfavourable.

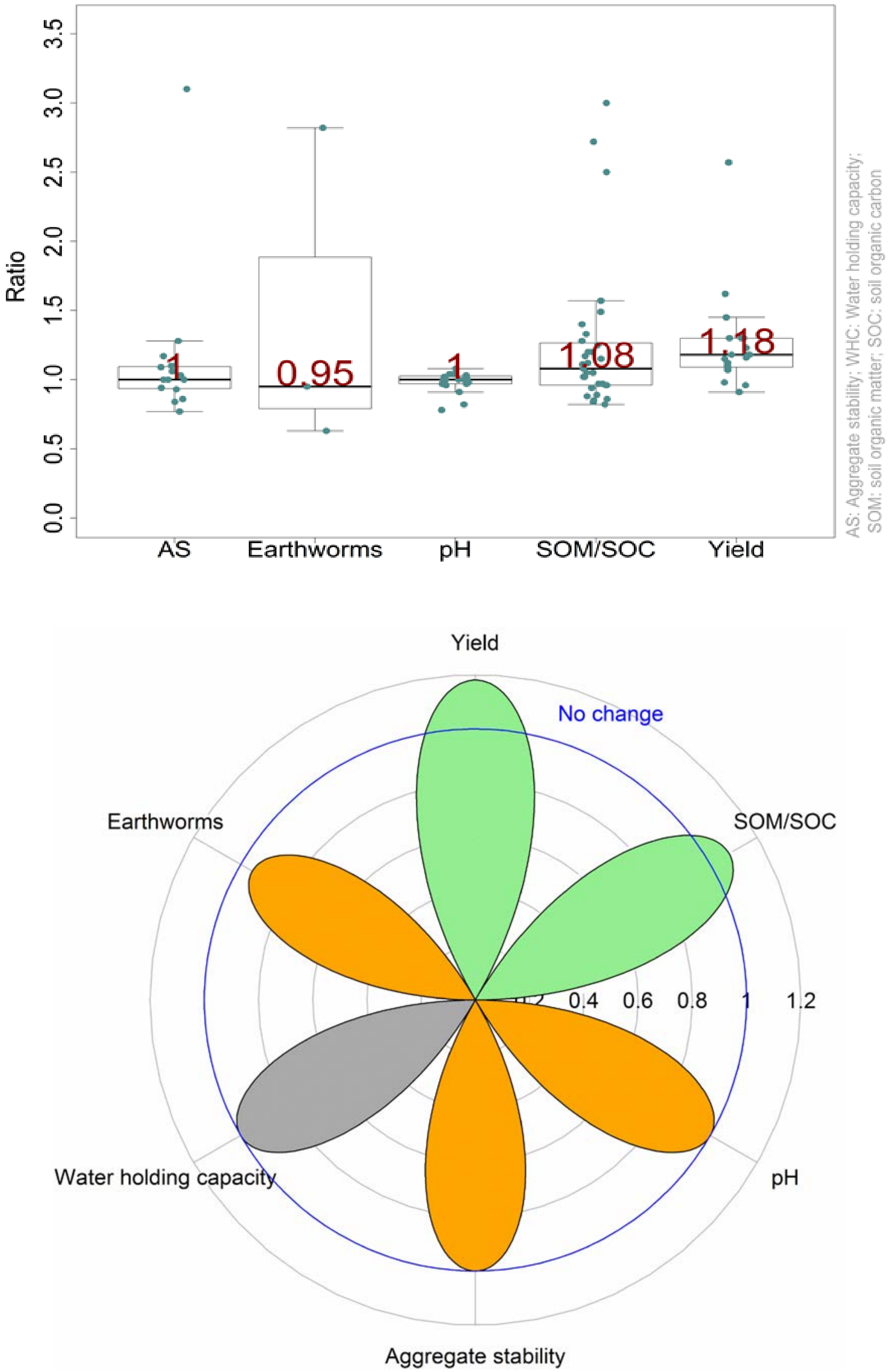
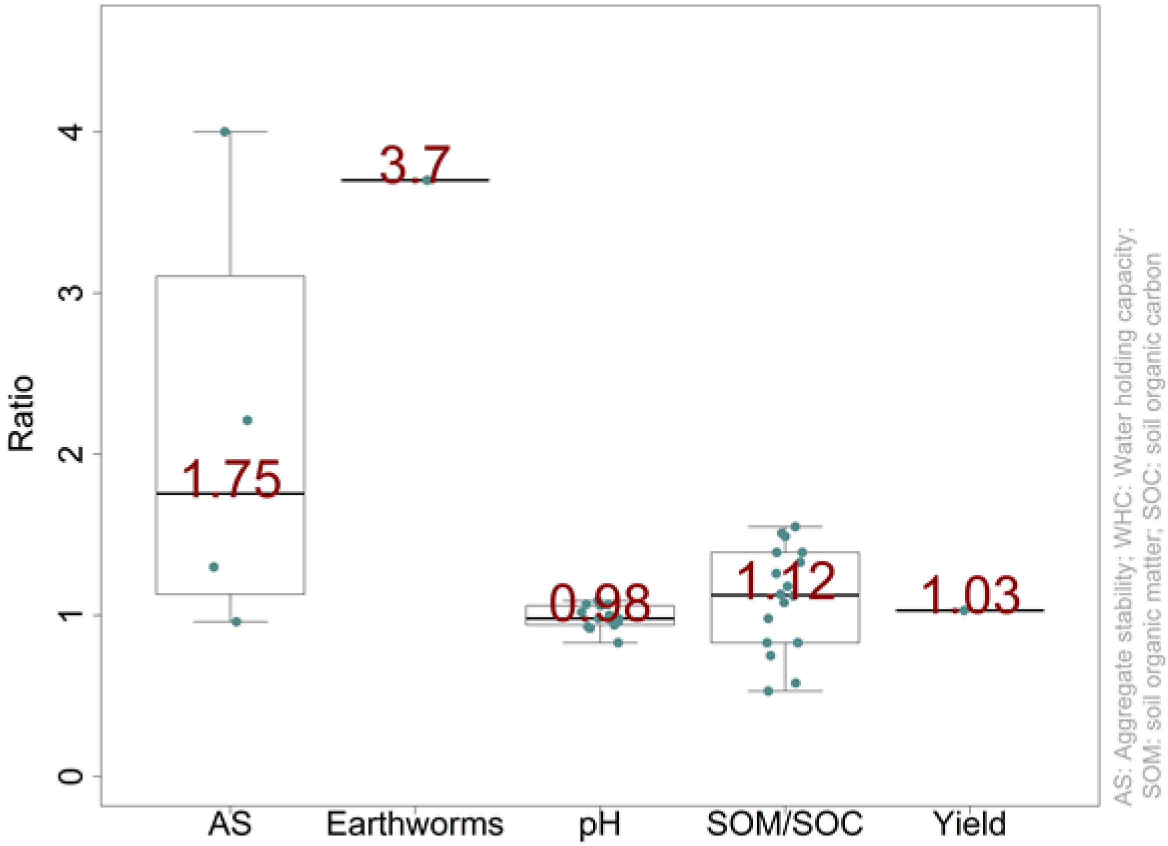


Figure SY-3. Long-term effects of crop rotation on soil quality indicators compared to monoculture: spread (top) and visualisation (bottom), expressed by a median of ratios.

3.2.4 Cumulative evaluation of irrigation vs. rainfed farming

Relatively few studies/publications were available for this assessment. Figure SY-4 shows impacts of irrigation on the selected soil quality indicators: irrigation increases earthworm population, aggregate stability and SOC content; no clear trends were observed for soil pH and water holding capacity. Effects are strongly dependent on soil type, amendments used, and quality of irrigation water.



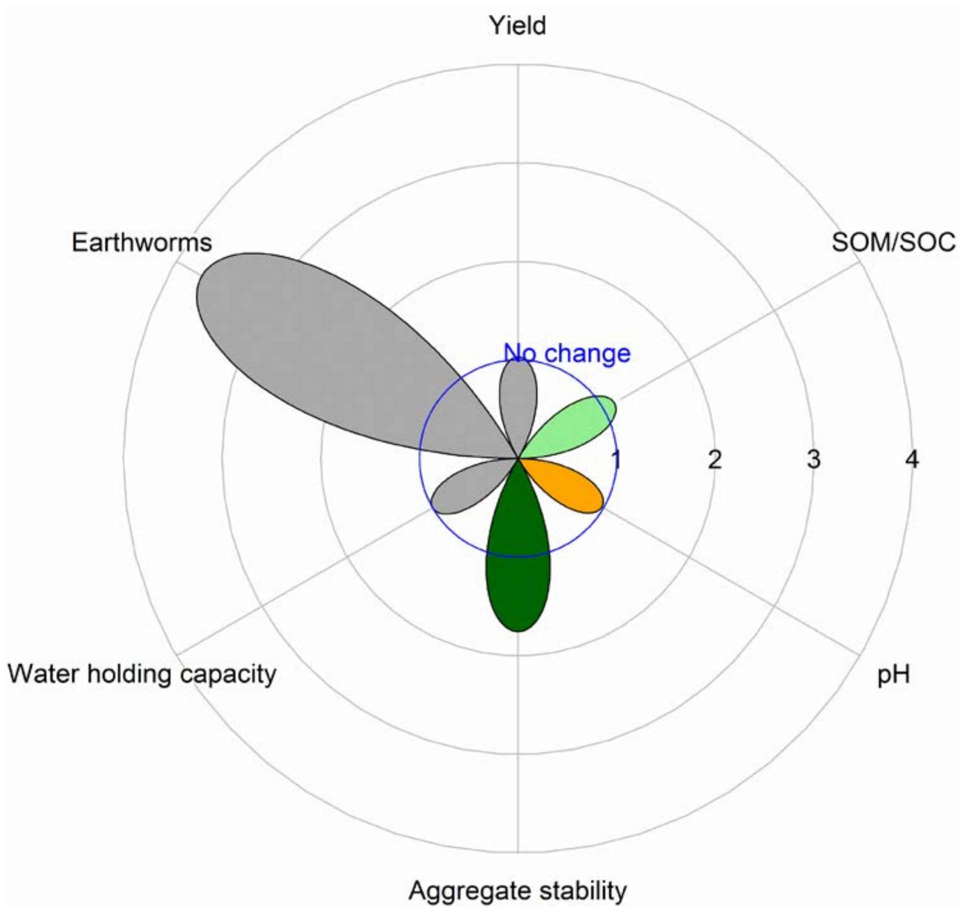


Figure SY-4. Long-term effects of irrigation on soil quality indicators compared to rain-fed agriculture: spread (top) and visualisation (bottom), expressed by a median of ratios.

3.2.5 Cumulative evaluation of organic vs. conventional agriculture

Effects of organic agriculture, as distilled from this review, are shown in Figure SY-5. A clear positive trend was observed for earthworm abundance, further organic agriculture generally resulted in increased aggregate stability, water holding capacity and greater SOC contents. Overall, no clear trend was found for pH, and a decrease in yield was observed in this review.

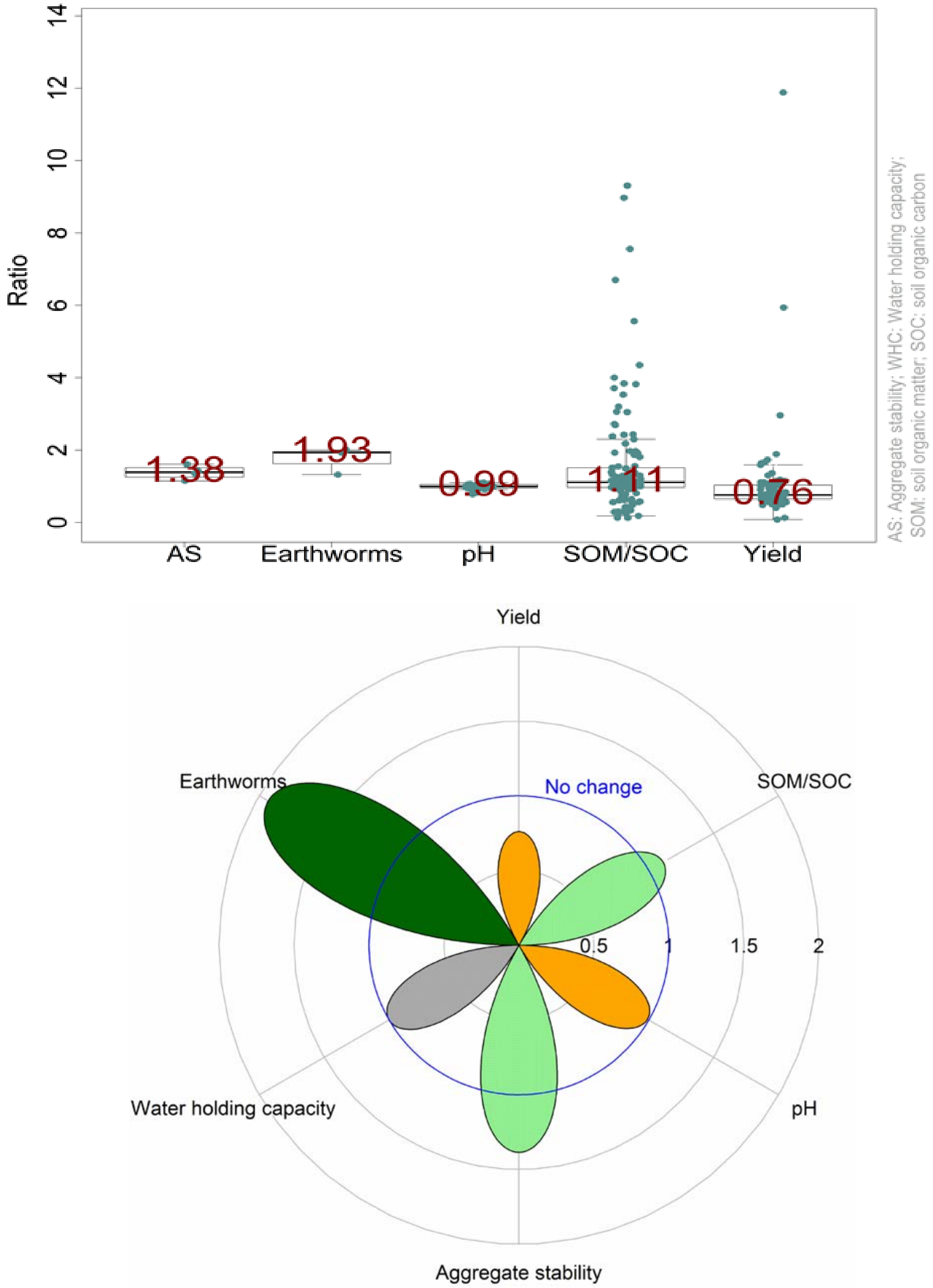


Figure SY-5. Long-term effects of organic agriculture on soil quality indicators compared to conventional agriculture: spread (top) and visualisation (bottom), expressed by a median of ratios.

Overall, earthworm appears to be the most sensitive indicator for all the discussed management practices; however its magnitude of the trends and direction of change vary with climate zone, soil type and crop species; SOC/SOM content responds positively to all the practices after a long-term (on average, 23 years in this study) in comparison with the references. Water holding capacity, aggregate stability and yield are less sensitive to the practices and pH appears to be the most insensitive indicator.

Table SY-2 summarises an overall evaluation of effects of the selected practices on the chosen soil quality indicators based on both statements of the reviewed literatures and data analysed.

Table SY-2. Impacts of agricultural management practices on soil indicators*.

Selected Soil Quality Indicators		**Nutrient management**	**Tillage practices**	**Crop rotation**	**Irrigation**	**Farming system**
		OM addition	No-tillage	Rotation		Organic
Chemical	SOM/SOC	+++	+,++	++	-	+
	pH	+	0	0	?	0
Physical	Aggregate stability	+	+,++	-	?	+
	WHC	+	0,+	+	?	+
Biological	Earthworm	++	+,++	+, -	+	+ +
Others	Yield	++	-,0	++	++	-

* + small positive trend; ++ moderate positive trend; 0 no change or neutral; ? no clear trend; - small negative trend. SOM: soil organic matter; SOC: soil organic carbon; WHC: water holding capacity.

3.3 Soil quality indicators required for analysis of soil functions/soil threats

Soil quality indicators for evaluation of soil functions and threats are required to 1) integrate soil physical, chemical, and biological properties and processes and serve as basic inputs for estimation of soil properties or functions which are more difficult to measure directly; 2) relatively easy to use under field conditions and assessable by both specialists and farmers; 3) sensitive to variations in management and climate on long-term changes in soil quality, but not be so sensitive as to be influenced by short-term weather patterns; 4) be components of existing soil databases where possible; and 5) correlate well with ecosystem processes (Doran and Parkin, 1996). For any parameter to be suitable as an indicator of soil quality some conditions must be met, *i.e.*, spatial heterogeneity must be accounted for (Ettema and Wardle, 2002); it must be

sufficiently stable over time under non-changing conditions, and annual fluctuations must be sufficiently predictable to discriminate the signal of human-induced change from the natural background (van Straalen, 1997); and it must be both specific for environmental factors and sensitive to agricultural management measures to indicate, at an early stage, changes in rhizosphere functioning, soil OM, nutrient cycling and soil structure affecting biological productivity (Brussaard, 2004).

Table SQI-1 and Table SQI-2 presented linkages between the chosen soil quality indicators and soil functions and threats defined within iSQAPER, respectively, based on expert assessment.

Table SQI-1. Expert-based assessment of linkages between selected soil quality indicators (this report) and soil functions (FAO). √: Suitable as direct indicator; (√): Suitable within certain limits, as indirect indicator.

SQ indicators / Soil functions	SOM/SOC	Soil pH	Aggregate stability	WHC	Earthworms	Yield
Provision of food, fibre and fuel	√	√	√	√	√	√
Carbon sequestration	√	√	√	√	√	(√)
Water purification and soil contaminant reduction	√	√	√	√		√
Climate regulation	√	(√)	√	√	√	(√)
Nutrient cycling	√	√	(√)	(√)	√	(√)
Habitat for organisms	√	(√)	√	√	√	
Flood regulation	√		√	√		
Source of pharmaceuticals and genetic resources		(√)			(√)	
Foundation for human infrastructure	(√)		(√)	(√)		
Provision of construction materials			(√)			
Cultural heritage		(√)		(√)		

Table SQI-2. Linkages between selected soil quality indicators and soil threats (expert-based assessment).

SQ indicators / Soil threats	SOM/SOC	Soil pH	Aggregate stability	WHC	Earthworms	Yield
SOM decline	√		√	√	√	√
Acidification	√	√				√
Erosion	√		√	√		√
Nutrient loss	√		√			√
Soil sealing					√	√
Salinisation	√	√	√		√	√
Desertification	√		√			√
Soil biodiversity loss	√		√		√	
Compaction		√	√	√		√
Pollution	√	√			√	√

Table SQI-1 shows that all the soil quality indicators reflect well on the soil functions defined in iSQAPER project. For soil threats, only SOM/SOC and yield are representative well for all the threats except for soil sealing(Table SQI-2). The usefulness of the remaining indicators varies depending on the threats, for example, soil pH can be a suitable indicator for acidification and salinisation. Stolte *et al.* (2016) reviewed indicators for soil threats within the EU-funded RECARE project (see Appendix I: Indicators for soil threats) and implied that there is no universal set of indicators for either all soil threats or an individual threat; soil properties or soil quality indicators are indicators among other indicators biophysical (climate, water, vegetation and so on), economic and social-cultural.

4 Discussion and Recommendations

4.1 Possible limitations

Trends for the indicators and their relative changes under the paired practices were determined based on the collected long-term experiment data, analytical data from the 42 LTEs in China, and reviewed studies. As such it is possible that some important works may not have been considered in this short desk study.

4.2 Suitability of chosen indicators

As indicated, soil quality is best assessed by soil properties that are neither so stable as to be insensitive to management, nor so easily changeable as to give little indication of long-term alterations (Bertrand *et al*., 2015; Islam *et al*., 2000; Pittelkow *et al*., 2015; Scopel *et al*., 2013). The soil quality indicators discussed in this review are sensitive to variations in agricultural management practices reported for long-term changes in soil quality in the iSQAPER partner countries. As such, overall, these indicators are suitable measure for the soil functions and threats described in Table SQI-1 and Table SQI-2. Although no clear trend in soil pH was observed for most practices except for organic matter input, pH is still a useful parameter for evaluation of overall soil quality as it is a measure for changes in soil acidity hence crop growth. Concerning SOM, it may be important to consider long-term changes in pool sizes in relation to the desired ecosystem services (*e.g.* crop production versus carbon sequestration relating to climate change mitigation/adaptation).

4.3 Reliability and simplicity of measurement of the chosen indicators

Ease of measurement is a prerequisite for a soil quality indicator in almost all soil quality concepts and reliability is also an important consideration (Larson & Pierce, 1994; Southorn & Cattle, 2000; Nortcliff, 2002; Idowu *et al*., 2008; Ritz *et al*., 2009; Oberholzer *et al*., 2012; Bone *et al*., 2014; Bünemann *et al*., 2016).

The chosen soil indicators were frequently used in concept and assessment of soil quality (Bünemann *et al*., 2016) and they were measured consistently in the iSQAPER LTEs as well as the LR-database except for earthworm; therefore they are reliable. The indicators were sampled and measured mostly in labs; field measurements were rarely reported in both the LTEs and LR-database. The methods for the indicator measurements varied, *e.g*., for SOC, Walkley-Black (Nelson and Sommers, 1982), Tiurin's method (Ostrowska *et al*., 1991), dry combustion at 600°C with a Leco-RC 412 analyzer and so on were used; A reference measurement (lab) would be needed to compare results obtained from these methods to assess accuruacy of the measurments or reliability. Overall soil biological indicators and their measurement were observed much less than soil chemical and physical properties; these will be enhanced in upcoming EC LUCAS Soil Sur-vey (2018) (Fernández-Ugalde *et al*., 2016).

4.4 Conclusions and recommendations

All the selected management practices affected soil quality indicators reviewed in this report. Overall, there were clear trends and relative changes in the six indicators under the five paired practices. However, the magnitude of the trends and direction of change varied with crop species and climate zone and soil type.

Earthworm appears to be the most sensitive indicator for all the discussed management practices; however its magnitude of the trends and direction of change varied with climate zone, soil type and crop species; SOC/SOM responded positively to all the practices after 23 years (on average

in this study) in comparison with the references. Water holding capacity, aggregate stability and yield were less sensitive to the practices and pH appeared to be the most insensitive indicator.

Five paired practices were analysed for their impacts on soil quality indicator trends and relative changes to the references (control). However, influence of irrigation on soil pH was not clear as it was strongly dependent on soil type and quality of irrigation water.

Some of the practices were investigated as ‘general’ category *e.g.*, organic matter input. However, there were various types of organic matters *e.g*., farmyard manure, green manure, crop residue, slurry. Application of such materials would have different effects on soil quality indicators. Although such aspects were distinguished in the LR-database and text, they could not be included in the synthesis. For this, a full scale metadata analysis would be required, which was beyond the scope of this study.

Although some negative effects of the practices were observed biophysically, *e.g.*, negative trend in yield under organic farming compared to conventional farming, there were also positive aspects under organic farming, *i.e*., higher marketing price and reduced environmental damage. Therefore, to evaluate whether to convert conventional farming to organic farming, socio-economic aspects should be considered as well.

Results obtained in this study could be used as a reference or input in other work packages of the iSQAPER project, especially for WP 4 - the development of a soil quality-based mobile phone application (SQAPP) for in-field soil quality assessment and monitoring, *e.g*. help users to identify promising soil quality indicators and management practices; and WP 5 - will inventory soil quality and select innovative practices with stakeholders.

It should be observed here that farmers often know very well which specific soil parameters are particularly relevant for their situation. Therefore in the future, view of land managers should be taken into account when evaluating various sets of indicators for soil quality. This would require a transdisciplinary and participatory approach.

Acknowledgements

We would like to thank all the iSQAPER project case study partners for providing the long-term experimental data and Olaf Koster for compiling the data into one dataset for analysis in this report. We are also grateful to iSQAPER colleagues, Coen Ritsema, Violette Geissen, Luuk Fleskens, Giulia Bongiorno, Lijbert Brussaard, Wijnand Sukkel and Ron de Goede for sharing in-depth experiences, knowledge and comments which helped to improve this report. We thank Luc Steinbuch for providing an R script for drawing the flower petals.

The iSQAPER project is funded d through the European Union Horizon-2020 Programme, under grant agreement n° 635750.

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Appendix I:

Appendix I: Indicators for soil threats (summarised from the report by Stolte *et al*. 2016).

SQ indicators / Soil threats	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5	Indicator 6	Indicator 7	Indicator 8	Indicator 9	Indicator 10	Indicator 11	Indicator 12	Indicator 13
Erosion by water	Area affected by soil erosion (in km^2), extent of area affected by soil erosion (in %)	Magnitude of soil erosion or sediment delivery (in tons)											
Erosion by wind	Estimated soil loss by wind erosion (t ha^{-1} yr^{-1})	Measured soil loss by wind erosion (t ha^{-1} yr^{-1})											
SOM decline in peat soils	Peat stocks (Mt)	Topsoil organic carbon content (%)	Soil organic carbon stocks (t ha^{-1})										
SOM decline in mineral soils	Topsoil organic C content (g kg^{-1})	Topsoil organic carbon stocks (t/ha)	C : N ratio	Deep (1-m depth) soil organic carbon stocks (t/ha)	Clay/SOC								

Soil compaction	Soil density	The air-filled pore space when drained to a matric potential in the range 30-60 hPa												
Soil sealing	Sealing Rate - the proportion of a sealed area in a total area or the increase of a sealed area in a specific period.													
Soil contamination	Heavy metal contents in soils	Critical load exceedance by heavy metals	Area under organic farming	Gross nutrient balance	Concentration of persistent organic pollutants	Critical load exceedance by sulphur and nitrogen	Progress in management of contaminated sites	New settlement area established on previously developed land	Status of site identification	Cation exchange capacity	Bioavailability of pollutants			
Soil salinisation	Salt profile where Soil Salinisation is assessed	Exchangeable Sodium Percentage (ESP) [%] to assess	the potential salt sources (groundwater or											

	in Total Salt Content [%] and Electrical Conductivity [dS m^{-1}]	sodification	irrigation water) and vulnerability of soils to salinisation/sodification measured in Salt content [mg l^{-1}] or SAR [dimensionless].										
Desertification	Climate (air temperature, aridity index, climate quality index, drought, drought index, effective precipitation, potential evapotranspiration, rainfall, rainfall erosivity,	Water (groundwater depth, water quality)	Runoff (dam sedimentation, drainage density, erosivity (RDI), flooding frequency, floodplain and channel morphology, impervious surface area, rainfall-runoff	Soils (acidified area, drainage, erosion risk (RDI), infiltration capacity, organic matter in surface soil, organic matter in surface soil, organic matter mixing with	Vegetation (Area of matorral, Biodiversity conservation, Deforested area, Drought resistance, Ecosystem resilience, Erosion protection, Forest fragmentation, Vegetation cover, Vegetation cover type,	Fire (burned area, fire frequency, fire risk, forest and wild fires, fuel models, wild fire incidence)	Agriculture (expenditure on water, family size, farmer's age, farm ownership, farm size, forest productivity, fragmentation of land parcels, gross margin index,	Land management (agri-enviromental management, fire protection, forest management quality, management quality index, organic farming, reclamation of affected	Land use (area of cultivated & semi-natural vegetation, area of marginal soil used, land abandoned from agriculture, land use evolution, land use intensity, land use	Cultivation (area of hillslope cultivated, fertilizer application, mechanisation index, tillage direction, tillage depth, tillage operations)	Water use (aquifer over exploitation, external water resources, groundwater exploitation, hydrological regulation (artificial), irrigated area, irrigation intensity and	Tourism (penetration of tourist eco-labels, tourism contribution to local GDP, tourism change, tourism intensity)	Macro economics (employment index, GDP per capita, accessibility, unemployment rate, value added by sector

	rainfall seasonality, wind speed)		relationship, runoff threshold (RDI), soil permeability)	depth, parent material, rock fragments, salinization potential, slope aspect, slope gradient, soil crusting, soil depth, soil erosion (USLE), soil erosion (measured), soil loss index, soil quality index, soil stability index, soil structure, soil surface stability, soil texture, soil type, sater storage capacity)	Vegetation quality index)		traditional agricultural products, net farm income, parallel employment)	soils, reclamation of mining areas, soil erosion control measures, soil & water conservation measures, sustainable farming, terraces (presence of))	type, natural vegetation, period of existing land use type, shannon's diversity index, urban sprawl)		seawater intrusion, irrigation percentage of arable land, irrigation potential realised runoff water storage, water consumption by sector, water leakage, wastewater recycling, water scarcity, water availability)		

Flooding	Flood frequency, duration	Extent of inundated area	Water level thresholds exceeded	Loss of crops due to inundation of fields	Loss of crops due to siltation of fields	Soil anaerobic condition s								
Landslides	Displacem ent of mass	Land abandoned from agriculture	Soil properties (depth, texture, structure)											
Decline in soil biodiversity	Indicators for species diversity (species richness)	Indicators for biological functions (variety and number of taxa that undertake contrastin g functional roles in the soil.												