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Assessment of Benefits of Conservation Agriculture on Soil Functions in Arable Production Systems in Europe

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Abstract: Conventional farming (CONV) is the norm in European farming, causing adverse effects on some of the five major soil functions, viz. primary productivity, carbon sequestration and regulation, nutrient cycling and provision, water regulation and purification, and habitat for functional and intrinsic biodiversity. Conservation agriculture (CA) is an alternative to enhance soil functions. However, there is no analysis of CA benefits on the five soil functions as most studies addressed individual soil functions. The objective was to compare effects of CA and CONV practices on the five soil functions in four major environmental zones (Atlantic North, Pannonian, Continental and Mediterranean North) in Europe by applying expert scoring based on synthesis of existing literature. In each environmental zone, a team of experts scored the five soil functions due to CA and CONV treatments and median scores indicated the overall effects on five soil functions. Across the environmental zones, CONV had overall negative effects on soil functions with a median score of 0.50 whereas CA had overall positive effects with median score ranging from 0.80 to 0.83. The study proposes the need for field-based investigations, policies and subsidy support to benefit from CA adoption to enhance the five soil functions.

Keywords: soil functions; conservation agriculture; conventional farming; zero tillage; environmental zones

1. Introduction

Soil is vital for the provision of soil-based ecosystem services that are essential for human wellbeing. These soil-based ecosystem services are the outcomes of the complex interplay of soil properties, environment, land use management and their interactions [1–3] of which five key soil functions are identified; (a) primary productivity; (b) water regulation and purification; (c) carbon sequestration and regulation; (d) habitat for functional and intrinsic biodiversity; and (e) nutrient cycling and provision [4]. These five soil functions contribute to agricultural productivity, as well as the provision of other regulating and supporting ecosystem services. Soil management is a key driver that will determine whether soils are capable of supplying these multiple functions, which underscores the significance of soil custodianship [5]. As soils provide a suite of soil functions, optimization of one function can have trade-offs with other soil functions. The objective of enhancing individual soil function viz. primary productivity function in the agriculture sector at the cost of other soil functions will depend on the local demands for the other soil function (e.g., clean drinking water) or national or regional demands (e.g., national carbon sequestration targets) [6]. Due to the competing demands for different soil functions, there is a need for an integrated, or holistic assessment, of the suite of five soil functions in order to mitigate trade-offs and to optimize supply which contrasts with efforts that focus only on individual soil functions. This study builds upon earlier reviews [7,8] and assesses the five soil functions concurrently and the optimization of same, so that one soil function is not maximized at the cost of other soil functions.

Conventional farming (CONV) refers to mono-cropping, inversion tillage and residue removal, which is often, although not always, associated with contributing to adverse effects on soil functions. Conservation Agriculture (CA) practice constitutes no-till combined with residue retention and crop rotation [9–11], as an alternative to optimize the provision of soil functions. In a framework of soil custodianship, CA is practiced to optimize available resources (soil, water and biological) whilst minimizing external inputs [12] and soil degradation [13]. Despite reported benefits, such as improved soil fertility, crop growth, better water infiltration, increased biological activity, decreased soil erosion and reduced labour, machinery use and fuel costs, CA is practiced only in 25.8% of European agricultural lands, well below the land areas of similar continental farming landscapes [12,14,15]. Hence, there is a need to assess the effects of CA and CONV practices on soil functions in order to better understand their potentials to optimize soil functions and to provide evidence to support more sustainable outcomes.

Due to the knowledge gaps on outcomes of CA adoption [15], there is a need to assess the impacts of CA and CONV practices on the five soil functions to guide recommendations for sustainable land uses and policy making [16,17]. As the effects of CA and CONV practices are dependent upon environmental zones [18], out of the 13 environmental zones in Europe [19], four environmental zones viz. Atlantic North, Continental, Pannonian and Mediterranean North were identified to represent the major environmental zones in Europe. Hence, the objective was to assess the effects of CA and CONV practices on the five soil functions in four major environmental zones in Europe.

2. Materials and Methods

2.1. Identification of Environmental Zones and Treatments

Based on climate, soil and vegetation and land cover, Europe is classified into 13 environmental zones [19] and a representative population of studies from identified environmental zones, representing major production systems in LANDMARK project [20], were used to extrapolate results for the

zones investigated. Of the 13 environmental zones, four environmental zones were identified viz. Atlantic North, Continental, Pannonian and Mediterranean North (Figure 1). Atlantic North includes mountains and uplands in Western Scandinavia and narrow coastal plains [21]. It is characterised by glacial deposits and oceanic climate with tundra vegetation in the north and grasslands in the high mountains and arable agriculture in the areas near the coastlines. Continental zone covers a large area including lowlands from Central and Eastern Europe and Balkan countries. The zone has variable land cover due to inherent geology and soil types with a huge annual temperature range and high precipitation during the summer. The Pannonian Zone covers the lowlands, valleys and mountain in the middle and the lower Danube basin and the Black Sea lowlands. The zone experiences a warm continental climate with early summer precipitation and it is a dominant arable agriculture zone converted from grasslands. The Mediterranean North Zone covers lowlands of the northern and central Mediterranean, but also hills and low mountains in the south. The zone is characterised with warm dry summers and precipitation in the winter months and water availability is the main constraint for agriculture in this zone [21]. Hence, these four environmental zones were selected with the aim of assessing the dominant environmental zones in Europe.

In each environmental zone, the effects of CA and CONV practices on five soil functions were assessed in annual cereal crop production systems. Six treatments were identified as common treatments across the environmental zones to compare the effects of CA and CONV over five soil functions. The six treatments compared were (i) conventional farming (CONV) (ii) No-tillage (iii) reduced tillage (iv) crop rotation (v) residue retention and (vi) conservation agriculture (CA). The six treatments were defined as:

1. Conventional farming (CONV) practice constitutes mono-cropping, ploughing to 20–30 cm depth to prepare the land for sowing and crop residue removal
2. No-tillage is a practice of directly sowing in the stubble, by cutting narrow slots for seeding
3. Reduced tillage, whereby near-surface soil (5–10 cm) is physically disturbed with discs, chisels or field cultivar, resulting in loose topsoil. A significant proportion of crop residues are retained on the soil surface equivalent to 30–60% soil coverage by residue.
4. Crop rotation which involves growing different crops in sequence in a field in 4–5 year crop rotation including cover/catch crops depending upon the environmental zone
5. Residue retention is a practice, where crop stubble, straw or other crop debris is left on the field, and is then incorporated when the field is tilled or left on the soil surface
6. CA is a combination of (i) no-tillage, (ii) crop rotation and (iii) residue retention

CONV is the control practice of intensively managed winter wheat (*Triticum aestivum* L.) monoculture with mineral fertilizer and pest and disease control with chemicals and residue removal. The treatment effects were evaluated on five soil functions and soil functions were defined as below [1,4,22]:

- i. Primary Productivity: The productive capacity of a soil to produce plant biomass for human use, providing food, feed, fibre and fuel within natural or managed ecosystem boundaries
- ii. Carbon sequestration and regulation: The capacity of a soil to store carbon in a non-labile form with the aim to mitigate increases in atmospheric CO₂ concentrations
- iii. Water regulation and purification: The capacity of a soil to receive, store and conduct water for subsequent use and the prevention of both prolonged droughts, flooding and erosion. Water purification is the capacity of a soil to remove harmful compounds (e.g., volatile organic compounds and heavy metals) from the water that it holds
- iv. Nutrient cycling and provision: The capacity of the soil to receive and retain nutrients, to make and to keep nutrients available for crop uptake and to facilitate recovery of plant-available nutrients over these nutrients into harvested crops

- v. Habitat for functional and intrinsic biodiversity: The multitude of soil organisms and processes, interacting in an ecosystem, making up a significant part of the soil's natural capital, providing society with a wide range of cultural services and unknown services.

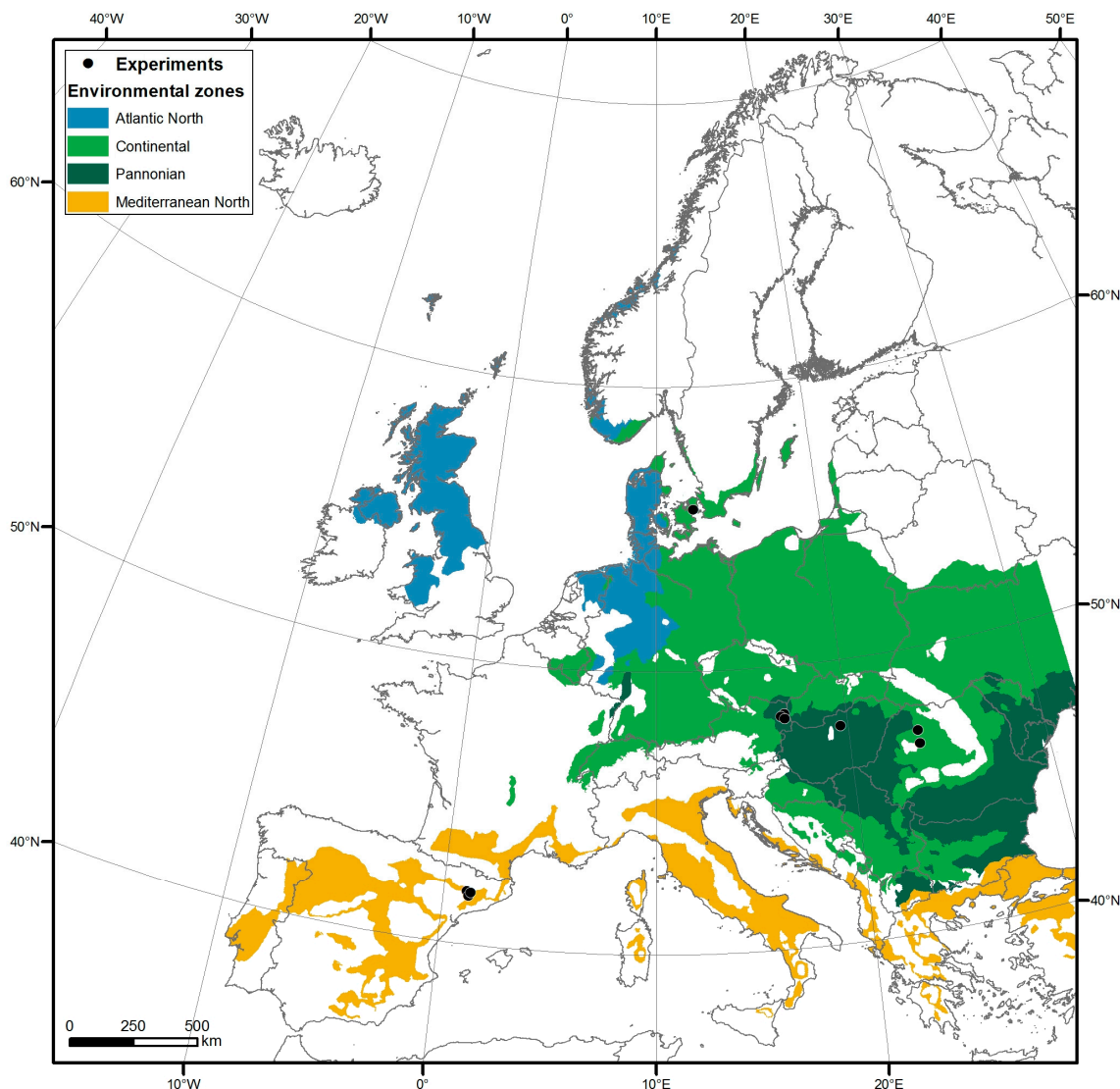


Figure 1. Map of the four major environmental zones with locations of the on-site long term experiments, in LANDMARK consortium countries viz. Ireland, Denmark, Netherlands, Hungary, United Kingdom, Belgium, France, Germany, Austria, China, Brazil, Switzerland, Romania, Sweden, Slovenia, Italy and Spain.

For the literature search, key search strings were tillage, minimum tillage, soil functions, conventional tillage, conservation agriculture, soil properties, crop rotations, residue retention, Atlantic, Continent, Pannonian and Mediterranean. The resulting papers were subjected to the following criteria for inclusion in the study:

- i. Experiment period was a minimum of 2 years prior to the date of response variable (e.g., grain yield) measurement
- ii. At least two treatment levels were included in the trial design (e.g., minimum tillage vs. conventional tillage or residue retention vs. removal)
- iii. Experiments were conducted in any of the selected environmental zones in Europe [19]

- iv. Only annual cereal crops (wheat, barley, oat etc.) production systems were taken into account.
- v. Other field crops were only considered within the crop rotation such as associated companion undersown grass, maize, rapeseed, legumes, root crops (potato and beets) and catch/cover crops
- vi. A minimum of three replicates per treatments were required.

2.2. Soil Function Scoring by the Subject Matter Experts

The five soil functions were scored at a coarse scale of environmental zones and the four environmental zones identified, representing the major environmental zones in Europe. The identified environmental zones are justified to represent wide differences in climate, land uses, management practices and soils [19]. For each of the four environmental zones, a team of 2–4 subject matter experts were assigned to the respective environmental zones, to provide one consolidated scoring of the effects of six treatments of CA and CONV practices on five soil functions in annual cereal production systems. The team of subject matter experts from each environmental zone used a common list of 10–22 references (Table 3) to agree on a common scoring by each team. The consolidated scoring of each soil function was based on the mix of three methods consisting of a minimum of 2–3 papers per treatment, expert knowledge and on-site long-term experiments. The on-site long term experiments, were the combined food and energy production system in Denmark, Fuchsenbigl tillage trial and the Rutzendorf crop residue incorporation trial in Austria, a soil tillage field experiment in Romania, a cultivation experiment in Hungary, and the tillage management effects on soil water conservation, organic matter and crop productivity sites in Agramunt, Selvanera and El Canós in Spain. The on-site long-term experiments were very useful data sources for scoring soil functions, especially in cases, where data was scarce. Although the treatment effects may vary within a single farm due to interactions between management, climate and soil variables, the consolidated scoring provided general direction of treatment effects for comparison across the four major environmental zones in Europe. The information available on the five soil functions varied significantly across the zones and hence the scoring of some commonly quantified soil functions (e.g., primary productivity, soil carbon sequestration etc.) may be based on more extensive number of studies compared to the other soil functions, the information of which can be scarce to non-existent.

In this study, the soil function scoring may be biased, to a certain extent, based on the particular studies the experts were aware of, depending on the field experiments available at the local experimental farm or research environments. We have mitigated this bias by taking account of the soil function scoring from at least 2–4 subject matter specialists from each environmental zones. As our aim was to assess the general effects of the CA and CONV practices on soil functions, our analysis provided a broad acceptance of views on effects rather than context-specific treatment effects. The study is an attempt to provide a framework on the direction of change in soil functions due to management practices for the land managers to adjust land use and management practices in order to meet the demand for soil functions.

The scoring of the soil functions were carried out in the following three steps. Firstly, a set of three indicators were identified for each of the five soil functions (see Table 1) and the team of subject matter experts provided the scorings on indicators. Secondly, indicator scorings were aggregated over soil functions and hence the performance of a single soil function was considered as the median score of three indicators and this methodology was followed for all the five soil functions (Table 3). Thirdly, soil function median scores were aggregated over each of the six treatments, which provided the performance of each treatment over five soil functions (Table 3). Median, a measure of central tendency, is used to describe the data spread in ordinal dataset (scoring dataset).

The scorings were carried out using a Likert-type scale ranking [23] and arranged in an incremental order; viz. high negative effect (−2), low negative effect (−1), no effect (0), low positive effect (+1) and high positive effects (+2). These scorings were carried out at indicator level for each of the soil functions, which were subjected to positive reassignment between 1–5 scale as shown in Table 2.

The positive reassignment is required to rank the scoring as a precondition for data normalization. Following positive reassignment, scores were normalized to between 0–1 (Table 2) by dividing each score with five, assigning equal weights to each score [24]. For example, for the primary productivity function, the three parameters under primary productivity were scored between –2 to +2 followed by conversion of the scoring to 1–5 scale, which was subsequently normalized by dividing by 5 to arrive at scores between 0–1 [24]. The median scores aggregated over soil functions and treatments were interpreted as negative effect ($0 < 0.60$), no effect (0.60) and positive effect (>0.60) corresponding to –2 to –1, 0 and +1 to +2 scoring values respectively.

Table 1. Three indicators identified for each of the five soil functions.

Soil Function Indicators	Primary Productivity	Carbon Sequestration and Climate Regulation	Water Regulation and Purification	Nutrient Cycling and Provision	Habitat for Functional and Intrinsic Biodiversity
1.	Increase in grain yield	Increase in stable soil organic matter (humus)	Increase in the water holding capacity of soil	Reduction of soil erosion	Increase of above ground biodiversity
2.	Improvement in grain quality (e.g., protein content)	Increase in reactive soil organic matter	Enhance water infiltration into soil matrix	Reduction of NO ₃ leaching	Increase of soil biodiversity
3.	Increase in biomass yield (grain + aboveground biomass)	Incorporation of plant residues	Reduce groundwater contamination	Reduction of phosphorus leaching	Increase earthworm count

Table 2. Soil function scoring rules [24].

Directional Change	Value Range	Positive Re-Assignment	Normalized Scores
High positive effect	2	5	1
Low positive effect	1	4	0.8
No effect	0	3	0.6
Low negative effect	–1	2	0.4
High negative effect	–2	1	0.2

2.3. Statistical Analysis

The aggregated median values of the five soil functions for each of the six treatments were subjected to Kruskal-Wallis non-parametric test [25] to determine the differences between the six treatments on the five soil functions. Kruskal-Wallis non-parametric test is used to test if the samples originate from the same distribution to compare two or more independent samples of equal or unequal size [25]. Test Statistic H [26] was calculated on the median score and H critical value at 95% significance was the basis for significant differences across the treatments. Statistic H was found to be higher than H critical indicating that the treatment median scores were significantly different ($p \leq 0.05$) between the treatments. Median scores were assigned with alphabet letters (a, b, c, d and e) and scores with no common letters are significantly different.

3. Results

3.1. Effects of CA and CONV Practices on Five Soil Functions in Atlantic North Environmental Zone

In the Atlantic North environmental zone, soil functions were affected in both directions viz. positively and negatively by application of CONV practices whereas only positive effects were recorded due to CA (Table 3). The differential treatment effects of CONV on the five soil functions indicated that there were trade-offs where one soil function was enhanced at the risk of decreasing another soil function. The CONV scored significantly lower median values (0.33; Table 3) indicating that the practice

had overall negative effects (<0.60) on soil functions. In contrast, the CA and its component practices scored significantly higher median values (0.87–1.0) indicating positive effects on soil functions.

Across the treatments, CONV had negative effects on four out of the five soil functions except for a positive effect on primary productivity function (0.87) (Table 3). CA and its component practices had varying positive effects (>0.60) on all five soil functions except primary productivity in no-tillage and residue retention treatments (0.47). Crop rotation had the highest positive effect on primary productivity (0.93), whereas CA and no-tillage had the highest positive effect on carbon sequestration (1.0). No-tillage and residue retention had the highest positive effect on water retention and regulation (1.0) whereas the no-tillage and crop rotation had the highest positive effect on nutrient retention and cycling. No-tillage had the highest positive effect on habitat for functional and intrinsic biodiversity (Table 3). Hence, no-tillage had the highest positive effects on four soil functions followed by crop rotation with highest positive effects on two soil functions (Table 3).

3.2. Effects of CA and CONV Practices on Five Soil Functions in Pannonian Environmental Zone

In the Pannonian zone, the median scores were significantly lower (0.53; Table 3) in CONV indicating overall negative effects on soil functions. In contrast, CA and its component practices had significantly higher median score (0.67–0.80) indicating positive effects on soil functions (>0.60) compared to the CONV practice.

Across the treatments, CONV had a positive effect on the water regulation and provision function, with no effect on primary productivity function and with negative effects on the other three soil functions (<0.60) (Table 3). CA and its component practices had varying positive (>0.60) and neutral effects on each of the five soil functions except negative effects on primary productivity (0.47). Crop rotation had the highest positive effects on primary productivity whereas CA had the highest positive effect on carbon sequestration (Table 3). Residue retention had highest positive effects on water regulation and provision whereas crop rotation, residue retention and CA had highest positive effects on nutrient regulation and cycling. No-tillage had the highest positive effect on habitat for functional and intrinsic biodiversity function. Some treatments had positive effects on a greater number of soil functions than other treatments. For example, crop rotation, residue retention and CA had highest positive effects on at least two soil functions (Table 3), whereas no-tillage had highest positive effect on only one soil function.

3.3. Effects of CA and CONV Practices on Five Soil Functions in Mediterranean North Environmental Zone

In Mediterranean North, the impacts of CA and CONV treatments differed widely from negative effects (<0.60) to highly positive effects (>0.60 –1) (Table 3). Among the treatments, CONV had significantly lower median score (0.53) indicating overall negative effects on soil functions. In contrast, CA and its component tillage practices had significantly higher median scores (0.80–0.93) indicating overall positive effects on soil functions.

Of the treatments, CONV had negative effects on three soil functions viz. carbon sequestration, water regulation and cycling and habitat for functional and intrinsic biodiversity whereas, of the CA and its component tillage practices, only residue retention had a negative effect on primary productivity. No-tillage had the highest positive effect on primary productivity followed by crop rotation, whereas, CA had highest positive effects on carbon sequestration followed by residue retention (Table 3). Residue retention had the highest positive effects on water regulation and cycling function followed by no-tillage whereas, residue retention had the highest positive effects on nutrient cycling and regulation. No-tillage and CA had the highest positive effects on habitat for functional and intrinsic biodiversity compared to other CA and CONV practices. Hence, CONV contributed to negative effects on three of the five soil functions whereas, the CA and its component practices, had a negative effect only in primary productivity due to residue retention.

Table 3. Scorings of CA and CONV practices (1–6 as described above) on five soil functions in Atlantic North, Pannonian, Mediterranean North and Continental environmental zone. Studies (no) is the number of studies per soil function in each environmental zone.

Soil Functions/Treatments	Primary Productivity	Carbon Sequestration and Climate Regulation	Water Regulation and Purification	Nutrient Cycling and Provision	Habitat for Functional and Intrinsic Biodiversity	Median	References
Atlantic North— Studies (no)	(6)	(4)	(3)	(5)	(2)		
Conventional farming	0.87	0.33	0.20	0.20	0.35	^a 0.33 (0.20,0.87)	[27–30]
No-tillage	0.47	1.00	1.00	1.00	0.95	^b 1.00 (0.47,1.0)	[7,28,31–33] (expert opinion)
Reduced tillage	0.73	0.80	0.80	0.80	0.80	^c 0.80 (0.73,0.80)	[31,34,35]
Crop rotation	0.93	0.73	0.87	1.00	0.90	^d 0.90 (0.73,1.0)	[36–38] (expert opinion)
Residue retention	0.47	0.73	1.00	0.87	0.80	^c 0.80 (0.47,1.0)	[24,39,40] (expert opinion)
Conservation agriculture	0.73	1.00	0.93	0.87	0.85	^d 0.87 (0.73,1.0)	[6,7,33,41] (expert opinion)
Pannonian	(8)	(13)	(4)	(8)	(3)		
Conventional farming	0.60	0.53	0.67	0.53	0.40	^a 0.53 (0.40,0.67)	[42–53] (expert opinion)
No-tillage	0.60	0.87	0.67	0.73	0.93	^b 0.73 (0.60,0.93)	[43,44,46–52] (expert opinion)
Reduced tillage	0.60	0.67	0.67	0.60	0.80	^c 0.67 (0.60,0.80)	[42,47–49] (expert opinion)
Crop rotation	0.80	0.80	0.73	0.80	0.80	^e 0.80 (0.73,0.80)	[48,53–55] (expert opinion)
Residue retention	0.67	0.80	0.80	0.80	0.80	^{bde} 0.80 (0.67,0.80)	[46,56–58] (expert opinion)
Conservation agriculture	0.47	1.00	0.73	0.80	0.80	^{bd} 0.80 (0.47,1.0)	(expert opinion)

Table 3. Cont.

Soil Functions/Treatments	Primary Productivity	Carbon Sequestration and Climate Regulation	Water Regulation and Purification	Nutrient Cycling and Provision	Habitat for Functional and Intrinsic Biodiversity	Median	References
Mediterranean North	(3)	(9)	(3)	(8)	(5)		
Conventional farming	0.73	0.53	0.33	0.67	0.20	^a 0.53 (0.20,0.73)	[59–69] (expert opinion)
No-tillage	0.87	0.87	0.93	0.87	1.00	^b 0.87 (0.87,1.0)	[59–64,66–70] (expert opinion)
Reduced tillage	0.73	0.80	0.80	0.80	0.80	^c 0.80 (0.73,0.80)	[60,63,66]
Crop rotation	0.80	0.80	0.73	0.80	0.80	^c 0.80 (0.73,0.80)	[59,67,71]
Residue retention	0.47	0.93	1.00	0.93	0.93	^{bd} 0.93 (0.47,1.0)	[62,65] (expert opinion)
Conservation agriculture	0.73	1.00	0.73	0.87	1.00	^d 0.87 (0.73,1.0)	[60,63,66]
Continental	(5)	(5)	(4)	(5)	(1)		
Conventional farming	0.40	0.60	0.40	0.60	0.47	^a 0.47 (0.40,0.60)	[50,72–74]
No-tillage	0.80	0.87	0.93	0.80	0.73	^{bd} 0.80 (0.73,0.93)	[72,75–78]
Reduced tillage	0.80	0.80	0.93	0.80	0.73	^b 0.80 (0.73,0.93)	[78–81] (expert opinion)
Crop rotation	0.93	0.87	0.80	0.87	0.87	^e 0.87 (0.80,0.93)	[78,82] (expert opinion)
Residue retention	0.80	0.87	0.93	0.80	0.73	^{bd} 0.80 (0.73,0.93)	[83] (expert opinion)
Conservation agriculture	0.93	0.87	0.80	0.80	0.80	^{cd} 0.80 (0.80,0.93)	[83–86] (expert opinion)

Bold numbers indicate the negative effects (<0.6) on soil functions. Median scores are presented as Median (minimum, maximum) and median scores with no common superscript letters are significantly different at $p = 0.05$.

3.4. Effects of CA and CONV Practices on Five Soil Functions in Continental Zone

In the Continental zone, the median scores of CA was significantly higher (0.80–0.87; Table 3) indicating positive effects on soil functions compared to CONV with significantly lower median value of 0.47 indicating negative effects (Table 3). Across treatments, CONV had no positive effects (<0.60) on soil functions at all, with only negative (<0.60) to no effect (0.60) on five soil functions (Table 3). In contrast, CA and its component practices had only positive (>0.60) effects on the five soil functions. Crop rotation and CA had the highest positive effects on primary productivity whereas CA, no-tillage, crop rotation and residue retention had the highest positive effect on carbon sequestration (Table 3). Residue retention, reduced tillage and no-tillage had highest positive effects on water regulation and provision whereas crop rotation had highest positive effects on nutrient regulation and cycling. Crop rotation had the highest positive effect on habitat for functional and intrinsic biodiversity function. Hence, CA and its component tillage practices had particularly positive effects on the soil functions compared to CONV with neutral to negative effects on soil functions.

3.5. Comparison of CA and CONV Practices on Five Soil Functions in Atlantic North, Pannonian, Mediterranean North and Continental Environmental Zones

Comparing the CA and CONV across environmental zones, there were consistent differences between the CONV and CA and its component practices. CONV had overall negative effects on soil functions across the environmental zones with median score value of 0.50 (Table 3). In comparison, CA and its component tillage practices had overall positive effects on soil functions across the environmental zones with median score values ranging from 0.80 to 0.83 (Table 3).

Comparing the differences in effects due to application of the six treatments, the magnitude of positive effects over soil functions differed between environmental zones. In Atlantic North, Continental and Pannonian zone, crop rotation had the highest positive effects on soil functions compared to CA and its component practices whereas in Mediterranean North, no-tillage had the highest positive effects on soil functions (Table 3). The data clearly indicated that the same practice can have varying consequences in terms of positive and negative effects on the suite of soil functions and hence the suitability of enhancing one particular soil functions or bundle of soil functions is context-specific.

4. Discussion

4.1. Integration of Soil Function Scoring Data

The study is an attempt to deliver a framework to indicate the direction of changes in soil functions due to different land management so that land managers can adjust land use and management practices in order to meet the demand for soil functions. The impacts of CA and CONV on soil functions are important to resolve, as there is conflicting evidence of management effects on soil functions. The difference in effects are attributed to multiple factors as soil functions are the outcomes of interactions of climate, land use, management practice and soils [1,4,87]. Due to multiplicity of factors above, it is a challenging task to quantify soil functions and be precise for a given land use, management practice, climate and soils.

CA and CONV are contrasting practices in terms of crop rotation, crop residue management and soil disturbance from no-till and/or reduced tillage to conventional moldboard ploughing to 20–30 cm. The management practices had differential effects on soil physical, biological and chemical attributes affecting the soil functions. Overall, in our study, CONV had consistent negative effects on soil functions with a median score of 0.50 across environmental zones, in concurrence with Stavi et al. [24], where conventional production system scored 0.52 compared to 0.69 and 0.72 in integrated production system and CA respectively. The negative effects of CONV are attributed to undue emphasis on primary productivity neglecting the provision of other soil functions, explicit from the scorings [28,60]. The positive effects of CA and its component practices were attributed to, in

general, synergistic provision of the five soil functions [7,48] although primary productivity declined in some environmental zones [39,70]. For example, in Mediterranean zone, positive effects of CA on primary productivity varied depending on rainfall when compared with CONV and CA performed better than CONV in dry years [59].

4.2. CA and CONV Treatment Effects on Soil Functions

CA practice consists of three core measures viz. no-till, crop rotation and residue retention [8]. However, all the three core measures are applied with different modifications in different socio-economic contexts based on the relevance of different soil functions in a particular environmental zone, which makes the comparison of performance of CA across the environments difficult [33]. Furthermore, the main effects of the three core measures, applied in isolation or in different combinations are difficult to separate and there is a wide variation in effects of management and the associated impacts on the suite of soil functions depending on the environmental context [41]. For example, in Mediterranean environments, the overall effects of CA is positive in combination with crop residue. However, when only crop residue effect is accounted for, it may lead to transitory nitrogen immobilization, decreasing nitrogen supply at the initial grow stages, particularly in nitrogen vulnerable zones with restriction in nitrogen fertilization [60]. Similarly, CONV is also practiced in different forms in terms of timing, depth and intensity of tillage, the combinations of which can have differential effects on soil functions in diverse environments [6].

A recent global meta-analysis of no-till compared to CONV assessed 5463 paired observations in 610 studies in 48 crops and 63 countries and reported that no/minimum tillage, in general, reduced crop yields while in some areas, produced yields equivalent to CONV [88]. This compares well with our study where, no-tillage reduced yields in Atlantic North [29], increased yields in Mediterranean North [60] and Continental whereas equivalent yields were produced with reduced tillage compared to CONV in Pannonian [51]. More importantly, positive crop yield responses were recorded only when combined with crop rotation and residue cover [88] and this was true in the Pannonian and Continental zone [83]. Except Pannonian zone, CA provided positive yield responses in other zones, particularly in Mediterranean climate due to higher moisture retention and minimized soil erosion [89,90]. In general, the CA yield penalty is found for the first 1–2 years after conversion to CA methods, but is subsequently similar to conventional practice yields over the next 3–9 years, while declining after 10+ years, probably due to weed pressure, pests and disease build-up [91]. A recent meta-analysis of 100 study comparisons reported increase in carbon sequestration in 54 cases due to no-tillage/zero tillage compared to CONV [41]. In another recent meta-analysis, comparison of 184 comparisons, shallow non-inversion tillage increased the carbon stock by 143 g C m⁻² compared to deep inversion tillage [28]. This is in line with our findings that no-tillage increased the carbon sequestration in the four environmental zones. However, some recent studies have argued that the effects of no-tillage are highly complex, involving many factors and should not be generalized [18,92]. Apart from the aforementioned benefits, the main drivers of CA adoption are economic benefits due to cost reduction of tillage, machinery and labour inputs [7].

The impact of agricultural practices on habitat for functional and intrinsic biodiversity is explicit but, poorly addressed in CA that combine tillage, soil cover and crop rotation. There is no consensus on how to assess this soil function and most of the studies are still segmented with a specific approach on microorganisms, mesofauna or macrofauna. The increase in habitat and biodiversity with no-till or reduced tillage, crop rotation, residue retention and CA is mainly linked to changes in soil carbon and soil physicochemical properties. Similarly, water regulation and purification, and nutrient cycling and provision functions are not addressed well and hence, there is a need to include the effects on the five soil functions to realistically assess the impacts of a measure.

4.3. Research Gaps on CONV and CA Practices

The studies on soil functions due to CA are incomplete within the European soil research landscape with some environmental zones having more exhaustive data compared to other zones with sparse data [30]. For example, in Atlantic North, the scoring of the five soil functions due to CA was based on four studies whereas in Pannonian zone, the same was scored only with expert opinion (Table 3). The literature search revealed that majority of the studies collect data on crop yields (22 studies) and carbon sequestration (31 studies) whereas other soil functions are less prioritized lacking information on those soil functions (Table 3). The main gaps are emphasis on one or two soil functions, trade-offs with other soil functions, modified practices or measures in field, lack of stakeholder information and a need for a soil function assessment at farm scale. For example, primary productivity has been the main goal of land use by farmers and emphasis on this individual soil function has compromised the balance of provision of other soil functions that the soils provide. The reason is that the farmers' main goals are grain and biomass yields for income but do not get rewarded for the non-marketable soil functions viz. nutrient cycling and provision, water regulation and purification and habitat for functional and intrinsic biodiversity, which are the core supporting and regulating functions backstopping primary productivity. Hence, there is no incentive to enhance non-marketable soil functions. Another important factor is the temporal factor (e.g., years of CA practice) on soil functions that needs to be taken into account as it has significant implications on the five soil functions [93]. Hence, there is a need to take account of the five soil functions rather than individual soil functions, by policy support at national to European scale to enhance provision of the five soil functions. For example, in Norway and Germany, CA practice is eligible for subsidy support [39], which has encouraged adoption of CA and such policy support will contribute, indirectly, to enhanced provision of the five soil functions. CA adoption does pose challenges due to increased weeds and competition for the use of crop residues for other purposes, such as fodder and energy production and hence loss of income to the farmers. Indeed, one of the main criticisms of conservation agriculture is the increase in herbicide use. Developing research on alternatives for weed management would facilitate the development of conservation agriculture (especially in increasingly constrained pesticide regulation environment) and limit its potential effects on the quality of water resources. However, there are other compelling reasons for CA adoption viz. reduced machinery and labor use, reduced erosion, which needs to be taken into account for realistic cost-benefit assessment. The information on the economics of CA adoption on and the underlying benefits on the five soil functions, need to be made available to the farmers, land managers, advisory services and policy makers to influence their decision based on evidence-based examples from the locally relevant applied CA field practices.

5. Conclusions

The current study has revealed that the existing field studies on CA and CONV practices assessed only individual soil functions and there is a growing need to determine the management effects on the suite of five soil functions. The study shed light on the current weakness of skewed research with emphasis on individual soil functions and there is need to incorporate the five vital soil functions, when assessing the effects of a management practice. Given that the research environment is highly compartmentalized in the research centers and universities, the study provided insight into need for transdisciplinary approaches to determine the five soil functions in field investigations so that objective assessment of a particular measure can be provided to the farmers, land managers and policy makers for informed decision-making.

Our study found significant differences of CA and CONV management effects on five soil functions across the four major environmental zones in Europe. Across environmental zones, overall CONV had consistent negative effects on soil functions whereas CA and its component practices had overall positive effects on soil functions. The study identified a need for more field-based investigations in Europe to provide further evidence of benefits of CA adoption. There is need for concerted efforts

from researchers to provide the evidence of CA benefits on five soil functions and the policy-making bodies to encourage CA adoption through policies and subsidy support.

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