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Compatibility of Agricultural Management Practices and Types of Farming in the EU to enhance Climate Change Mitigation and Soil Health

Impacts of soil management practices on crop productivity, on indicators for climate change mitigation, and on the chemical, physical and biological quality of soil

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General information

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Executive summary

Agricultural management practices are required to achieve high yields and to contribute to resource use efficiency. Furthermore, soil quality must be at least maintained and mitigation/adaptation to climate change (CC) will become increasingly important.

This work focuses on the analysis of the effects of improved practices on crop productivity, climate change and soil quality indicators, through an analysis of available European data sets and associated literature, mainly from long term experiments. It was carried out by five task groups, each group studying the effects of soil management practices on a particular goal - expressed in a set of indicators. The goals are crop productivity, mitigation of climate change (Carbon sequestration, reduction of greenhouse gases (GHG)), biological soil quality, chemical soil quality, and physical soil quality. This report merges the outcomes from the various task groups, highlights overriding patterns and discusses potential conflicts and synergies between the separate goals distinguished.

Each task group has identified suitable indicators, contributed to a comprehensive literature review and carried out data analyses. Data were taken both from literature and from own LTEs. Our evaluation was based on data derived from 291 mainly long-term field experiments (LTEs) - both from the partner countries and from the rest of Europe - which were included in an on-line database. Before the statistical analyses, comparisons between an assumed improved management practice and a baseline management were computed, forming either relative response ratios (RR), or absolute or relative differences for the single indicators. A multiple linear model using climate, soil texture/clay content, the duration of practice, the type of crop (for productivity indicators) and the investigated soil depth (for soil quality indicators) as nominal factors was performed to evaluate which conditions mostly affected the impact of a practice.

Based on this quantitative evaluation, the task groups carried out a qualitative assessment of agricultural management options. This report gives an overview, the more detailed results are provided in the deliverables D3.324 (Productivity), D3.334 (climate change mitigation, i.e. C-sequestration and reduction of greenhouse gases (GHG)), D3.344 (biological soil quality), D3.354 (chemical soil quality), and D3.364 (physical soil quality and conservation).

As expected, the indicator-based evaluation of agricultural management practices showed positive and negative effects. Overall (mean outcome across all data) none of the investigated practices could favourably contribute to all objectives, i.e. maintaining high yields and reducing cultivation costs, mitigating climate change and improving chemical, physical and biological soil quality.

Our analyses confirmed the results from practice and literature that suitable crop rotations are a precondition for good agricultural management. The inclusion of catch crops/cover crops/green manures in the crop rotation shows only positive or neutral effects on the investigated indicators.

Overall, the application of organic amendments was rated to be beneficial (sometimes neutral) regarding chemical, physical and, especially, biological soil indicators as well as on indicators for climate change. However, changed N dynamics and the importance of optimal application techniques require special attention by the farmer.

Measures that reduce tillage compared to conventional ploughing were appreciated differently by the respective task groups. In general, a total omission of tillage enhanced biological and chemical soil quality. (Shallow) Non-inversion tillage was additionally beneficial for CC indicators. For soil physical indicators, however, benefits of no-tillage depended very much on the farming system. This practice was rated as very unfavourable in permanent crops (bare exposed soil between rows). In contrast, NT (direct drilling) was evaluated as the best management practice for physical soil quality in annual arable crops, especially in the Mediterranean region, however, some tillage operations from time to time are suggested to alleviate the surface compaction. Non-inversion tillage, too, was rated unfavourable for physical quality in permanent crops. Additionally, all productivity indicators declined with reduced tillage, or showed neutral effects with tillage omission.

Management practices like weed control, specific measures for pest and disease control, water management and grassland management could not be evaluated due to insufficient data from LTEs. Furthermore, the evaluation of CC mitigation is often limited by the lack of data for continuous GHG emission measurements.

The most important single factor to influence the effect of any management practice seems to be the environmental zone (climate) in which the management practice is applied. For soil quality indicators, the responses often depend on the investigated soil depth. Furthermore, many effects on productivity and soil quality can be detected with statistical certainty only after many (more than 10) years, due to great temporal and spatial variations of weather and soil conditions.

The main conflicts between goals, in our view, relate to management practices that promote soil quality and C sequestration but may result in higher GHG emissions, especially of nitrous oxide. Examples are the incorporation of crop residues, the application of compost and slurry, and the omission of tillage.

More extensive assessments are still needed, which were not possible within the frame of this study. Entire life cycles of practices and farm inputs need to be considered, also beyond field and farm boundaries. Further, effects would have to be scaled per unit input to enable more precise comparisons among practices. Such more complete analyses should also consider alternative uses of farm produce, e.g. using crop residues to substitute for fossil fuels, versus incorporation to enhance soil organic carbon. Finally, the summation of beneficial and adverse effects that a practice may have on multiple indicators – as needed for an overall evaluation - remains a normative exercise when effects cannot be expressed in the same units.

Specific part

1 Introduction

Increasing crop production to feed a growing population was a major challenge to the agricultural community in the past few decades. As a result, management practices consisting of intensive tillage and high rate of fertilisation were used to increase crop production. Society must now accomplish the dual objectives of improving yield levels and food stability and of preserving the quality and quantity of ecosystem services. Farming practices which ensure a good use of resources, thus maintaining high yields, are to be promoted. Furthermore, best management practices are needed to maintain and improve physical, chemical and biological soil quality. Mitigation and adaptation to climate change will play a crucial role in the near future.

A reduction of tillage intensity, the adoption of green manuring, of crop residue incorporation and the substitution of mineral with organic fertilisers are among the most used farm management practices to maintain soil quality.

Reduced tillage techniques, aim to minimise soil inversion and soil structure disruption, to increase soil organic matter (SOM) by reducing residue and organic matter mineralisation (Lal and Kimble, 1997; West and Post, 2002; Holland, 2004; Alluvione et al., 2009, Alluvione et al., 2010). Although uncertainty remains as to the soil organic carbon (SOC)-sequestering efficacy of such techniques (Baker et al., 2007; Lal, 2009; Luo et al., 2010), there is no doubt about their fossil fuel-saving benefit. Leguminous green manure, crop residue incorporation and organic fertilisers from animal wastes are known to represent viable options as mineral N fertiliser substitutes (Bøckman, 1997; Eriksen et al., 1999; N'Dayegamiye and Tran, 2001; Tejada and Gonzalez, 2003; Tejada et al., 2008, Alluvione et al., 2013). In addition to stimulating microbial activity, increasing soil fertility, controlling pests, and reducing soil erosion, green manures and crop residues can prevent nutrient leaching outside the growing season and can supply N to the subsequent crop at low energy cost (Crews and Peoples, 2004; Cherr et al., 2006). Organic fertilisation has not only a low groundwater N pollution risk (Erhart et al., 2007), if applied at a rate that meets crop needs but also great potential for nutritive element recycling (Ikumo, 2005) and soil C sequestering and protection (Spaccini et al., 2002; Piccolo et al., 2004; Lynch et al., 2006).

Crop rotation has always been used in agriculture to maintain the soil fertility over years. Long-term studies have shown that crop rotations are essential to maintain high production levels (Mitchell et al., 1991), which can be assured in monoculture only by the use of mineral fertilisers and pesticides (Crookston et al., 1991; Bullock, 1992). Monoculture often results in yield decreases (Power and Follett, 1987; Peterson and Varvel, 1989).

No tillage practices are promoted mostly to reduce costs and labour, but also because they may have positive effects on soil physical properties such as aggregate stability (Rhoton et al., 1993; Ghuman and Sur, 2001), infiltration and soil water retention (Unger, 1994; Drury et al., 1999), number of biopores (Francis and Knight, 1993), and root growth (Martino and Shaykewich, 1994). There is little consensus as to whether tillage has any influence on the N balance of the soil (Mitsch et al., 1999; Smith et al., 1990).

Cover crops and catch crops are often used to reduce environmental problems caused by intensive cropping. They can take up mineral N during the winter period, in temperate climates (Lemaire et al., 2004). A soil cover can reduce wind and water erosion. When incorporated into the soil as green manures, they provide an extra source of energy and contribute to C-sequestration. Leguminous cover crops, in addition, fix N biologically and

may improve the soil N fertility (Kuo and Sainju, 1998; Vaughan et al., 2000; Gselman and Kramberger, 2008).

Several authors conclude that C sequestration for climate change is limited (e.g. Körschens et al., 2013 and 2013, Powlson et al., 2011), because the stored C quantities are often small, the beneficial management must be maintained over time (Spiegel, 2012, Dersch and Böhm, 2001) and fluxes of other GHGs, especially N₂O and CH₄ may be adversely changed. Powlson et al. (2012) reported SOC increases between 50 and 180 kg C ha⁻¹ yr⁻¹ per tonne of dry solids added in the form of different kinds of biosolids (cereal straw, farm manure, green compost, paper crumble, digested biosolids). They warn against mistaking soil C accumulation for net CO₂ extraction from the atmosphere, and see potential for CC mitigation only with compost application, because it avoids disposal to landfill and reduces N₂O emissions.

This report presents the results of an extensive meta-analysis on data from long term experiments, as well as the results of the associated literature review. Our study was performed to verify the hypotheses that “best management practices” are not only effective in maintaining high yields, in reducing cultivation costs, and in mitigating climate change, but also contribute to improving chemical, physical and biological soil quality.

The effects of agricultural practices can be assessed properly only in long-term experiments, where small changes can accumulate over the years to become detectable (as often occurs in soil organic matter changes), and interaction with meteorological variability can be assessed. Johnston (1994) stated that long-term or continuing experiments are the best practical way of assessing the sustainability of an agricultural system. However, it should be recognised that – by relying on those long-term experiments - new management practices, e.g. the application of biochar products or digestates, are hardly included in our evaluations.

This work focuses on the analysis of the effects of improved practices on crop productivity, climate change and soil quality indicators, through an analysis of available European data sets and associated literature, mainly from long term experiments. It was carried out by five task groups, each group studying the effects of soil management practices on a particular goal (expressed in a set of indicators). The goals are crop productivity, mitigation of climate change (C-sequestration, reduction of greenhouse gases (GHG)), biological soil quality, chemical soil quality, and physical soil quality. This report merges the outcomes from the various task groups, highlights overriding patterns and discusses potential conflicts and synergies between the separate goals distinguished. The underlying reports are Catch-C deliverables D3.324 (Zavattaro et al., 2014), D3.334 (Spiegel et al., 2014), D3.344 (D’Hose et al., 2014), D3.354 (Pecio et al., 2014), and D3.364 (Guzmán et al., 2014).

2 Materials and Methods

2.1 Indicators and Management practices

Each of the five task groups created an extensive list of possible indicators (MS321, 331, 341, 351, 361; numbers refer to milestones in the project workplan). Some indicators were shared among task groups. For example, soil organic carbon (SOC) is essential for chemical, physical and biological soil quality. However, for the topic of C sequestration by enhancing SOC stocks, which is discussed to mitigate climate change, SOC is very much a key indicator. Thus, SOC contents and SOC stocks were evaluated in the task group “Carbon sequestration and GHG emissions for CC mitigation”. The indicators are depicted in Tab. 3.1-1.

A standard list of management practices (MPs) was first developed (see Table in the Appendix) to enable a uniform approach across the task groups in WP 3. The same list served as a common frame for WP 4, too. Depending on the availability of data, the task groups used selected MPs for their indicator-based evaluations. Certain MPs served as a baseline (reference) management (bl) for the assessment of a presumably improved management practice (“BMP”), see Tab. 2.1-1. (We retained the original acronym for Best Management Practice from our workplan, in spite of our recognition that ‘improved’ could be a more appropriate qualification, even if still debatable.)

Tab. 2.1-1. Reference treatments and comparisons (in bold letters those comparisons that are reported within this report)

Code	Assumed improved management practice (“BMP”)	Baseline management practice (“bl”)
ROT	rotation	monoculture
ROT	rotation with tuber/root crops	rotation without tuber/root crops
ROT	rotation with legume crops	rotation without legume crops
ROT	rotation with grassland	rotation without grassland
Intercrop	intercropping	without intercropping
CatchCr	catch crops (harvested)	without CatchCr
GM	green manure (not harvested but left on field or incorporated)	without GM
NIT=MT and RT	minimum and reduced (shallow) non inversion tillage	ploughing (CT)
DNIT	deep non-inversion tillage to the depth of ploughing (in Belgium)	ploughing (CT)
NT	no tillage=direct drilling=sod seeding	ploughing (CT)
COMP	compost application	mineral N fertiliser (similar

		total N supply)
FYM	farmyard manure	mineral N fertiliser (similar total N supply)
S	bovine slurry	mineral N fertiliser (similar total N supply)
CR	incorporation of crop residues	removal of crop residues (includes selling, feeding and burning of crop residues)
IRR	high efficiency irrigation methods	surface irrigation
MIN	mineral fertilisation	no fertilisation
WEED	mechanical weeding	herbicides
GRASS	grazing	mowing
GRASS	grazing	growing of silage maize and other fodder crops in monoculture

Preferably, medium- and long-term effects of such practices on a set of indicators were considered important for the WP 3 evaluations. Therefore, mainly stabilised and long-term experiments (LTEs) situated in European countries were taken into consideration. For, e.g. CO₂, CH₄ and N₂O emissions, data from long-term experiments are scarce. For these variables shorter duration experiments (instead of LTEs) and laboratory experiments were included in the evaluation.

The data for evaluating the effects of the mentioned practices on the proposed indicators were collected from various sources: peer-reviewed scientific papers, national language scientific or technical papers, grey literature (project reports), unpublished data held by partners. However, peer-reviewed scientific journals provided most of the data.

2.2 Shared library and data base

Papers were first collected in a shared on-line library and then analysed by the different task groups. This activity resulted in a metadatabase (MS322, 332, 342, 352, 362), which was the starting point for developing, next, the Catch-C on-line shared database. The latter was constructed to store and retrieve data of single indicator values inserted by all project partners.

The on-line shared library on the Zotero free platform (www.zotero.org) was progressively filled by all partners. It contains 733 papers and allows all project partners an easy and fast access to original papers, which were used to fill the database.

Expected results from the literature were extensively provided in the reports (deliverables) D3.324, D3.334, D3.344, D3.354 and D3.364.

The data analysis was then conducted on the Catch-C online dataset which has been filled in by all the project's partners. Preliminary results of the data analyses carried out by the

different task groups have been provided earlier in the midterm report (MS 323 to 363). Furthermore, the above deliverables provide information on the data set (e.g. numbers of records regarding the indicators) used by the respective task groups and a list of European LTEs, which were used for the evaluations.

2.3 Data treatment

The data analyses were executed separately by the respective task groups. For each indicator a comparison between an assumed improved management practice (“BMP”) and a baseline management was carried out. The effect of some practice, with respect to the reference practice, was either expressed as the response ratio (RR) or as a difference or relative difference (DIFF or rel DIFF, see chapter 2.4 and Table 3.1-1). DIFF was chosen, when unscaled changes (e.g. number of earthworms) were more informative to express improvement or deterioration between the compared MPs.

$$RR = \frac{\text{Indicator treatment}}{\text{Indicator reference treatment}}$$

i.e. observed indicator value divided by the indicator value found in the reference treatment

$$DIFF = \text{Indicator treatment} - \text{Indicator reference treatment},$$

i.e. indicator value found in the reference treatment subtracted from observed indicator value.

Rel DIFF=

$$(\text{Indicator treatment} - \text{Indicator reference treatment}) / |\text{Indicator reference treatment}|$$

Relative differences were computed only for CH₄ emissions. Soils may act as a source or a sink regarding CH₄. So, unlike the other indicators, CH₄ fluxes were either positive or negative. As a result, the use of the alternative quantifiers (RR and DIFF) can be confusing. The detailed descriptions of the analyses of each indicator are provided in the respective reports from the task groups Zavattaro et al., 2014; Spiegel et al., 2014; Pecio et al., 2014; Guzmán et al., 2014; D’Hose et al., 2014).

Furthermore, each task group evaluated which conditions (sometimes referred to as co-variate factors) mostly affected the performance of each practice. The following factors were analysed:

- Climate (Environmental zones, ENZs, according to Metzger et al., 2005)
- Soil texture or clay content
- Duration of the experiment
- Sampling depth for selected soil parameters
- Kind of crop (Task « Productivity » and « CC Mitigation »)
- Kind of experiment (field or lab) for GHG emissions

Table 2.4-1 and Figure 2.4-1 indicate the factors considered in the analyses of the respective task groups.

Tab. 2.4-1. Levels of the four factors considered in the linear multiple regression. Climate types were those reported by Metzger et al., 2005. ALN = Alpine north, BOR = Boreal, NEM = Nemoral, ATN = Atlantic North, ATC = Atlantic Central, ALS = Alpine South, LUS = Lusitanian, CON = Continental, PAN = Pannonian, ANA = Anatolian, MDM = Mediterranean mountains, MDN = Mediterranean North, MDS = Mediterranean South.

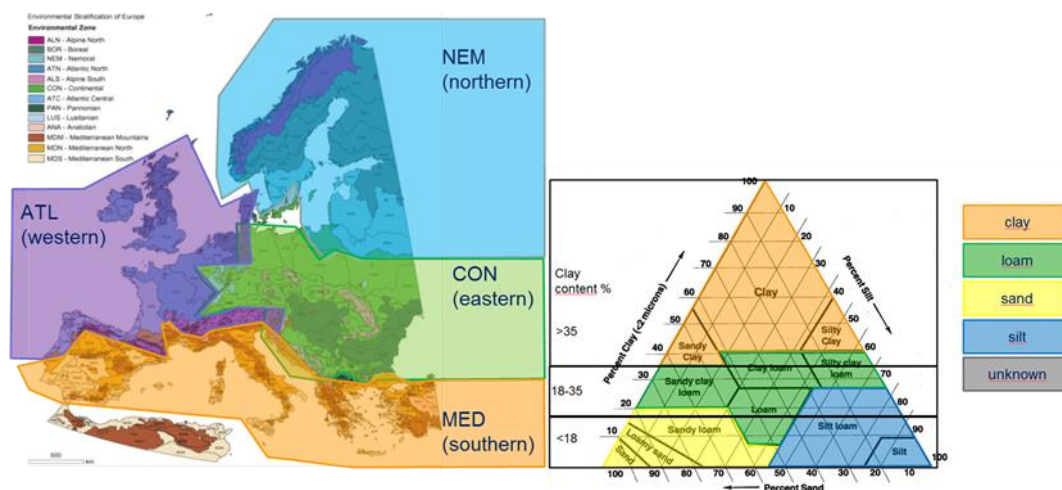
num.	climate	soil texture class	duration of practice	crop
1	northern	clay	low	barley

	(ALN, BOR, NEM)	(clay, sandy clay, silty clay)	(< 5 yrs)	
2	western (ATN, ATC, ALS, LUS)	loam (loam, clay loam, sandy clay loam, silty clay loam)	medium (5-10 yrs)	wheat
3	eastern (CON, PAN)	sand (sand, loamy sand, sandy loam)	high (11-20 yrs)	minor small grain cereals
4	southern (ANA, MDM, MDN, MDS)	silt (silt, silty loam)	very high (> 20 yrs)	grain legume
5		unknown	unknown	maize grain
6				maize/sorghum (total)
7				rapeseed
8				potato/beet
9				sunflower
10				legume/grass ley
11				vegetables
12				various (average)

Fig. 2.4-1. Levels of the four factors considered in the linear multiple regression. a) Climate (acronyms as in Tab. 2.3-1), from Metzger et al., 2005, modified according to Zavattaro et al., 2014; b) soil texture classes and clay content classes (modified according to Zavattaro et al., 2014).

a) Climate

b) texture



2.4 Statistical analyses

RR and (rel.) DIFF frequency distributions were tested for normality (Kolmogorov-Smirnov test) and their descriptive statistics were calculated.

A one-sample t-test (2 tails) was used to identify which RR means were statistically significantly different from 1 ($p < 0.05$), and which DIFF means were statistically significantly different from 0 ($p < 0.05$). Where effects are considered relevant but lack statistical significance, we refer to them as ‘a tendency’.

A multiple linear model (e.g. generalized linear model procedure of the SPSS software) using climate, crop, soil texture class and duration of practice as single nominal factors (without interactions) was performed to evaluate which conditions mostly affected the performance of each practice, separately. As mentioned above, climate, soil and duration of practice were

divided into 3 to 4 levels each. For the task group “productivity” 12 different crop types were considered. As not all soil texture and duration of practices were known from the literature, a separate class ‘unknown’ was also considered.

3 Results and Discussion

Tab. 3.1-1.: Mean (across LTE's) indicator responses of management practices compared to the respective baseline management practice as relative ratio (RR), as difference (DIFF) or as a relative difference (relDIFF). Significant responses at p<0.05 (one-sample t-test, 2 tails) are indicated with *.

Category of practice	Management practices/Indicators	Task group Productivity (P)				Task group Climate Change (CC)					Task group Chemical Soil Quality (SQC)						Task group Physical Soil Quality (SQP)					Task group Biological Soil Quality (SQB)									
		Yield (RR)	N uptake (RR)	NUE (RR)	N surplus (DIFF)	SOC concentrations (RR)	SOC stocks (RR)	CO ₂ emissions (RR)	N ₂ O emissions (RR)	CH ₄ emissions (rel DIFF)	pH (RR)	Ni cont (RR)	Ni stock (RR)	C/N (RR)	Nmin (RR)	K avail (RR)	P avail (RR)	Bulk density (RR)	Penetration resistance (RR)	Permeability (RR)	Aggregates stability (RR)	Runoff yield (RR)	Sediment yield (RR)	Earthworm number (DIFF)	Earthworm biomass (DIFF)	MBC (RR)	PPNEM (RR)	FUNGEM (RR)	BACNEM (RR)	BACPLFA (RR)	FUNGPLFA (RR)
Rotation	Monoculture (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Crop rotation	1.05*	1.03	1.38	-43.9	1.00	0.99				0.99	1.04		0.96*		0.76*	0.95	0.96	0.93*	1.41	1.09	0.29*									
	No intercropping (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Intercropping																														
	Without Green manure/catch crop/cover crop (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Cover crops																1.02*	0.68	1.45	1.18*	0.60*	0.56*									
	Harvested catch crop/cover crop	1.05*	1.19	1.19	-3.9						0.99	0.98	1.04*	0.99		0.81															
	Incorporated green manure	1.00	0.99	0.99	1.5																										
Catch crop/cover crop/ green manure					1.16	1.10	1.64	1.81*	0.95*																						
Tillage	Conventional tillage (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	No tillage	0.96	0.95	1.06	-4.2	1.03	1.07*	1.28*	3.24*	0.70	1.00	1.02	0.94	0.94	1.15	0.97	1.30*	1.11	0.84	0.55	0.87*	1.93*	2.46*	22*	39*	1.29*					
	Shallow non inversion tillage/reduced + minimum tillage	0.97*	0.91*	0.91*	12.6*	1.08*	1.06*	1.09	1.02	-0.13	1.00	1.07*	1.11*	0.97	0.87	1.46*	1.10*	1.00	1.35*	0.72*	1.12*	4.86	3.59	20*	13*	1.17*					
	Deep non-inversion tillage																						13	12*	1.1						
	Deep ploughing																1.03*	0.92	1.26	1.32*	1.77	0.30*									
	Direct drilling																1.02	1.32*	0.38*	1.88*	0.53	0.24*									
Nutrient management: mineral fertiliser and organic fertiliser	Mineral fertiliser (mineral N – baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Organic fertiliser- FYM	0.94*	1.00	0.92	23.9	1.23*	1.17*	1.04	0.83	-0.19	1.01	1.10*		1.12*	1.48*	1.28							320*	71*	1.29*	1.05	0.56*	2.14*	1.38*	1.08	
	Organic fertiliser-slurry	0.98	0.92*	0.92	28.2	1.21*	1.26*	1.32*	5.13*	60.3		1.13*		1.01	1.25*								283*	42*	1.35*	0.62*	0.56*	3.82	1.15	0.98	
	Organic fertiliser-compost	0.95	1.04	1.04	18.7	1.37*	1.31*	1.39	5.15	-0.84	1.07*	1.14*		1.03	1.09	1.04							75*	15*	1.25*	0.93	0.85	1.19	1.34*	1.07	
	No mineral fertiliser (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Mineral N fertiliser					1.07*	1.03		3.63*	9.02	1.00	1.02*		0.77	1.60*	2.33*	2.64*														
Residue management	Residue removal (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Residue incorporation	0.93*	0.95	1.36	-16.6	1.07*	1.07*	5.88*	12.08*	0.057		1.02*		1.07			1.01	1.36*		1.86*											
	Residue burning	1.03*	1.05	1.04	-6.2																										
Crop protection	Chemical control (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Mechanical control																0.99	0.79*	0.65*	1.15*											

Tab. 3.1-2. : Qualitative evaluation (based on Table 3.1-1) of management practices (++: very favourable effect;+: favourable effect; 0: neutral effect; -: unfavourable effect; --: very unfavourable effect; +/- favourable and unfavourable effects: compared to the baseline (reference) treatment (in grey cells))

Category of practice	Management practices/Indicators	Task group Productivity (P)				Task group Climate Change (CC)					Task group Soil Quality Chemical (SQC)						Task group Soil Quality Physical (SQP)					Task group Soil Quality Biological (SQB)										
		Yield (RR)	N uptake (RR)	NUE (RR)	N surplus (DIFF)	SOC concentrations (RR)	SOC stocks (RR)	CO ₂ emissions (RR)	N ₂ O emissions (RR)	CH ₄ emissions (rel.DIFF)	pH (RR)	Nt cont (RR)	Nt stock (RR)	C/N (RR)	N min (RR)	K avail (RR)	P avail (RR)	Bulk density (RR)	Penetration resistance (RR)	Permeability (RR)	Aggregates stability (RR)	Runoff yield (RR)	Sediment yield (RR)	Earthworm number (DIFF)	Earthworm biomass (DIFF)	MBC (RR)	PPNEM (RR)	FUNGEM (RR)	BACNEM (RR)	BACPLFA (RR)	FUNGPLFA (RR)	
Rotation	Monoculture (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Crop rotation	+	0	+	+	0	0			0	0		-		-	0	+	++	+	+	++		+	+	+	+/-	-	+	0	0		
	No intercropping (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Intercropping	-	+	+	+																											
	Without Green manure/catch crop/cover crop (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Cover crops																	--	+	+	++	++	++									
	Harvested catch crop/cover crop	+	+	+	0						0	0	+	0	0									+	+	+	+/-	+	+	+	0	
	Incorporated green manure	0	0	0	0																			++	++	++	+/-	0	+	++	0	
	Catch crop/cover crop/ green manure					+	+	0	-	-																						
Tillage	Conventional tillage (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	No tillage	0	-	0	0	+	++	-	--	-	0	0	0	++	0	++	-	+	-	--	-	-	+	+	+	+/-	+/-	+/-	0	0		
	Shallow non inversion tillage/reduced + minimum tillage	-	--	--	-	++	++	0	-	+	0	+	++	0	0	++	+	0	-	--	++	-	-	+	+	+	+/-	+/-	+/-	0	0	
	Deep non-inversion tillage																							+	+	0	+/-	+/-	+/-	0	0	
	Deep ploughing																	--	+	+	++	-	++									
	Direct drilling																	-	--	--	++	+	++									
Nutrient management: mineral fertiliser and organic fertiliser	Mineral fertiliser (mineral N – baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Organic fertiliser- FYM	-	0	-	-	++	++	0	+	+	0	++		++	++	+								++	++	++	0	-	++	++	0	
	Organic fertiliser-slurry	0	-	-	-	++	++	-	--	-	0	++		0	++	0								+	+	++	+	-	0	0	0	
	Organic fertiliser-compost	-	0	0	0	++	++	0	-	+	+	++		0	+	0									+	+	++	0	0	0	+	0
	No mineral fertiliser (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Mineral N fertiliser					++	+	0	--	-	0	+		0	++	++	++															
Residue management	Residue removal (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Residue incorporation	-	-	0	+	++	++	-	--	-		+		+		0	-	--		++				+	+	+	+/-	0	+	+	0	
	Residue burning	+	+	0	0																											
Crop protection	Chemical control (baseline)	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Mechanical control																+	++	--	++												
Water management irrigation-drainage	-	0	0	0	0																											

Table 3.1-1 shows mean values of the indicator responses compared to the respective baseline management practice (as relative ratio (RR), as difference (DIFF) or as a relative difference (relDIFF)) across all suitable LTEs. Table 3.1-2 indicates the qualitative evaluation based thereon, which will be discussed in detail in the following chapters (3.1 to 3.13). For these overall qualitative evaluations, statistical significances and, to a lesser extent, the size of effects and the author's expertise (especially for cells of Tab. 3.1-2 that were empty in Tab. 3.1-1) were taken into account. The effects of the changes of management practices were indicated in the following way:

- ++: very favourable effect
- +: favourable effect
- 0: neutral effect
- : unfavourable effect
- : very unfavourable effect of management practices.

3.1 Crop rotation

The comparison of rotation versus monoculture was performed for different LTEs, climate conditions, soil texture/clay contents and durations. Rotations analysed in this study were very variable in length or crops involved. The duration of a rotation varied from 2 to 6 years. Main crops were generally maize, wheat, barley or other small grains cereals, while secondary rotated crops were grain legumes (e.g. faba bean, pea), forage legumes (lucerne, clover, vetch), grass, root and tuber crops (e.g. potato, sugar beet), or minor cereals.

Rotation has a positive impact on the productivity of the major crops. Yield is increased by 5% on average (Tab. 3.1-1). However, while the main crop productivity can be increased in a rotation, the overall yield of the entire rotation is generally lower than that of the main single crop in monoculture. This could result in a reduction of farmers' income that is apparently not compensated by the gain of fertility. N efficiency indicators referred to the main crops are also improved.

Soil organic carbon is not affected by rotation, while total soil N tended to increase. Most soil physical properties are improved: reductions in bulk density, penetration resistance (-7%) and runoff yields (-71%) are observed and aggregate stability increases. Only the permeability decreases.

Soil biological properties are also improved, as an increase in earthworm number and biomass and in microbial biomass carbon indicate.

Therefore, rotation is a recommended practice under most of the considered viewpoints, however, due to a lack of data, no GHG emission comparisons could be included. There is an urgent need to gain such data in the near future.

3.2 Intercropping

In the condition of European agriculture intercropping means growing two crops at the same time for at least part of their cycle, typically undersowing of legume cover crops in growing winter wheat. No analyses could be performed due to the lack of data, at least no yield reduction is expected when using this practice.

3.3 Catch crops (harvested) and green manure (not harvested)

3.3.1 Task group results under consideration of co-variate factors

Catch-crops are fast-growing crops sown to reduce nutrient losses when the main crop is absent from the field. Cover crops are generally planted to prevent soil erosion, again in the absence of the main crop. When the biomass produced is incorporated into the soil (or left at the soil surface, in the case of no tillage), then this practice is called green manure. Leguminous catch crops can supplement nitrogen (N) by fixing N_2 from the atmosphere. Non-leguminous catch crops exploit the residual nitrogen left after harvest of the main crop and their value as green manure can be as high as that of leguminous crops. All these practices are here considered altogether and compared to rotations without them.

An increase in yield of 5% was found when catch/cover crops are included in the crop rotation. Additionally, a statistically insignificant increase in N uptake and N use efficiency (NUE) and a reduction in N surplus (Tab. 3.1-1) could be observed, even when N fertiliser is applied at the same rate. Chemical N supply can be reduced, especially when a legume is used as a cover crop. However, several studies found that cover crops may cause an initial decrease in yield of the subsequent crop and a positive effect in later years (e.g. Torstensson and Aronsson (2000)). SOC concentrations and stocks tended to increase. As in many cases in which a source of easily degradable organic matter is applied, CO_2 and N_2O emissions are increased. CH_4 emissions increased as well. Cover crops are beneficial to soil physical characteristics: our results show that as a result of cover crops, the soil penetration resistance decreased. When dealing with tree crops, bulk density is increased although permeability improves in response to cover crops. Furthermore, aggregate stability is increased, while runoff and erosion are reduced.

Based on literature results (e.g. Thoden, 2011), the effect of green manure crops on plant-parasitic nematodes is various and depends on their host status for the plant-parasitic species present. When green manure crops are good hosts the infestation levels rise considerably and can reach damage levels. The choice of the green manure crop should therefore be a tailor made decision, to fit local conditions of field and rotation. In general, however, we can conclude that green manure crops often enhance growing conditions of the following crop, and make that crop less sensitive to nematode damage.

3.3.2 Conflicts (trade-offs) and synergies

The cultivation of catch/cover crops, both when harvested and when used as a green manure revealed positive or neutral effects on the investigated indicators for productivity and soil quality and can, thus, be confirmed as a recommended practice regarding these objectives. However, concerning climate change mitigation, elevated GHG emissions may outreach the positive effect of SOC increases.

3.4 No Tillage – NT

3.4.1 Task group results under consideration of co-variate factors

The practice of No-tillage (NT) was compared to conventional tillage (ploughing in most cases), see Tab. 3.1-1. NT has been studied all throughout Europe, especially in southern and western countries. Reasons to adopt no tillage are mostly economic (to save fuel, machinery and labour costs) or to protect the soil (from compaction, erosion, excessive mineralisation).

The positive effects of no-till are often others than to increase productivity. However, the overall analysis showed a tendency for a yield decrease.

Among the tested factors, soil texture class was the only one which appeared to significantly affect yield response. Only in silt soils yield increases occurred with NT.

On average, no-tillage increased SOC concentrations and SOC stocks by 3% and 7%, respectively. The overall CO₂ emissions rose by 28%, however, great differences occurred between field and lab studies, the latter revealing lower increases (the median decreased). Possible contradictions between a concurrent rise in CO₂ emissions and SOC may be explained by the fact that the increases in SOM may exceed the increase in CO₂ emissions—caused by heterotrophic respiration mostly by soil microorganisms (Janzen, 2004). Furthermore, NT resulted in an overall significant more than 3fold increase of N₂O emissions. Based on only few experimental results, NT showed slightly higher CH₄ emissions, however, in the majority of measurements the soil acted as a sink for CH₄.

SOC concentrations increased under NT only in ATL and MED, whereas they decreased in the CON zone. The SOC concentrations tended to increase in heavy-textured soils and to decrease in coarse-textured soils. The highest increases occurred in the soil depths ≤ 10 cm.

The increases of N₂O emissions without tillage were statistically significant higher in the ATL climate compared to MED. This does not entirely confirm the findings of van Kessel et al. (2013), who found higher N₂O emissions in the first 10 years (this was also a tendency here) and in dryer climates. CH₄ emissions increased in the first 5 years and afterwards decreased.

Among soil chemical indicators only available phosphorus (Pavail) gave a significant response to No-tillage. Pavail increased, on average, by 30%. This is largely attributed to the accumulation of fertiliser and manure-P in the topsoil, in absence of mechanical soil mixing.

Significant effects occurred for sampling depths on the RR for pH, with slightly decreased pH values in the top soil. One reason could be the accumulation of organic matter, increased microbial activity and an enhanced production of organic acids (Spiegel et al., 2007). Another may be the acidifying effect of fertilisers (not mixed into soil in absence of tillage). The other significant effects, e.g. of experimental duration on RR of N_i stocks, for texture on RR of Kavail and for all factors (climate, texture and duration) on RR of Pavail, could not be readily explained and may be due to the unbalanced data structure (Pecio et al., 2014).

The task group on soil physical quality provided NT data for permanent crops with bare soil and no tillage operations, and in these LTEs a chemical control of weeds was carried out. NT induced soil degradation, indicated by, e.g. higher bulk density RR, lower aggregate stability and permeability, and increased runoff and sediment yields due to natural soil compaction. This compaction is not easily alleviated by the surface harrowing at shallow depth. Bulk density, runoff and sediment yield increased significantly in clay soils.

Furthermore, the task group on soil physical quality reported direct drilling as the best management practice for arable crops (Guzmán et al., 2014). This practice, however, increased slightly bulk density and penetration resistance and decreased permeability. Thus, some tillage operations from time to time are suggested to alleviate the surface compaction. On the other hand, direct drilling increased aggregate stability, and lowered runoff yield and sediment yield.

NT significantly increased earthworm number and biomass, the effect on nematode populations is reported very differently in the literature. It was reported that the effect of tillage on nematode populations is very limited and variable. Populations depend far more on crop rotation, cover/green manure crops and the build-up and distribution of organic matter.

3.4.2 Conflicts (trade-offs) and synergies

The practice of NT was appreciated by the working groups very differently. Beneficial effects (Tab. 3.1-2) were stated regarding chemical and biological indicators. Main benefits are increases of plant available nutrients and SOC and an improvement of soil biota. Furthermore, no significant yield decreases compared to conventional tillage occurred, NUE was better and N surplus decreased. However, these positive and neutral effects were more than outweighed by an increase of the GHG emissions (CO_2 , N_2O , CH_4) and by a deterioration of physical soil conditions. The latter was - due to a lack of data in other regions - mainly confined to Mediterranean areas with their long, hot and dry summer period.

3.5 Non-inversion Tillage – Minimum tillage

In our first evaluations we have differentiated between reduced and minimum tillage (see Glossary) compared with conventional ploughing. However, there was no clear distinction between the definitions of these two management practices, so we summarised them into “non-inversion tillage” (NIT). Only the task group “Productivity” preferred the term “minimum tillage”, because in their LTE’s analysed, not all reduced and minimum tillage practices were non-inversion techniques. Another deviation – from our convention to pool all non-inversion tillage practices – was made for a number of Belgian LTE’s on soil biology. There, a differentiation between shallow and deep non-inversion tillage was made.

3.5.1 Task group results under consideration of co-variate factors

Minimum tillage influenced all productivity indicators unfavourably, i.e. yields, N uptake, NUE and N surplus (Tab. 3.1-1 and Tab. 3.1-2). Less negative effects (also compared to the full omission of tillage) could be stated regarding CC indicators. Overall, with shallow non inversion tillage SOC concentrations and stocks increased significantly (favourable), CO_2 and N_2O emissions increased only slightly. However, these (unfavourable) increases occurred only in the first 5 years, after longer periods the CO_2 and N_2O emissions decreased with NIT compared to conventional ploughing revealing RRs below 1. Furthermore, the nutrient contents (N_t , plant available P and K) increased. N_{min} contents tended to decrease. Nevertheless, the overall evaluation of soil chemical quality was positive (more distinct than for NT). As mentioned in D3.354 (Pecio et al., 2014), the near surface accumulation of P (and other nutrients, e.g. N_t) can be an advantage for early crop growth under favourable moisture conditions. However, under dry conditions the nutrients may be inaccessible for plant uptake and prone to erosion and runoff losses. For the physical indicators the evaluation was less consistent. Minimum tillage resulted in a significantly improved aggregate stability (favourable). However, the penetration resistance was significantly higher and the permeability significantly lower, runoff yields and sediment yields were distinctly higher (all unfavourable) compared to conventional ploughing, thus leading to an overall deterioration of physical quality and soil conservation. These findings show that increased aggregate stability does not necessarily pay off in terms of reduced runoff and erosion. Finally, based on the investigated LTEs, minimum tillage had no pronounced effect on bulk density.

Similar to NT, shallow non-inversion tillage significantly increased earthworm number and biomass, for deep non-inversion tillage only earthworm biomass was significantly increased compared to CT. Overall, all kinds of tillage reduction increased microbial biomass C (MBC) in the order $\text{NT} > \text{Shallow NIT} > \text{deep NIT}$ compared to CT. However, significant differences with soil depth occurred. While both, Shallow NIT and NT resulted in a distinct increase of

the MBC in the topsoil layer (0-10cm) compared to ploughing, the – less pronounced – reverse effect has been observed in the subsoil (10-30 cm).

3.5.2 Conflicts (trade-offs) and synergies

Similar to NT, (shallow) non-inversion tillage enhanced the chemical and biological quality of the top soil, all evaluations done in comparison to CT (Tab. 3.1-2). NIT led to less physical soil deterioration than NT in arable systems. For tree crops, there were insufficient data to evaluate the effect of NIT on physical parameters. It must be emphasised that also the indicators of GHGs emissions responded - with lower average increases of CO₂ and N₂O emissions and less CH₄ emissions compared to CT - more favourably to NIT than to NT. However, all productivity indicators showed significant deterioration compared to CT, and mostly worse than under NT.

Although omission of tillage may have positive effects on indicators other than productivity, it is productivity – and especially its monetary consequences – that is the major driver for farming. This may be a reason, why NIT is not commonly accepted by the farmers. However, for an overall assessment, the savings of fuel, labor and, possibly, fertiliser costs, which depend on farm and site conditions, must be further taken into account.

3.6 Mineral N fertilisation

3.6.1 Task group results under consideration of co-variate factors

The task group SQC has investigated the effects of mineral fertilisation (N, P, K) compared to the omission on their indicators (pH, N_t content, C to N ratio (C/N), N_{min}, plant available P and K), see Tab. 3.1-1. The CC task group has only evaluated (high) N fertiliser rates versus 'no fertilizer', for consequences on SOC (concentrations and stocks) and GHG emissions. Comparisons between organic manures and mineral fertilisers (the latter serving as reference) are presented in Sections 3.7-3.9 of this report.

The strongest overall responses to fertiliser application occurred for the indicators available P and K and N_{min}. The N_t content enhanced only slightly but significantly. The increase of N_{min} contents was more distinct in the first 30 cm soil depth, the eastern climate zone and after more than 10 experimental years. The two latter facts were also the case for available K.

The application of mineral nitrogen fertiliser increased, based on the mean value, the SOC concentrations significantly by 7% and the SOC stocks tended to increase (by 3%), compared with N omission. Our evaluations revealed an overall significant, more than 3.5-fold increase of N₂O emissions. Strong variations, between increase and decrease, were observed for all these indicators.

There is an ongoing discussion about the effect of mineral N fertilisation on SOC. Results of Austrian long-term field experiments showed that appropriate mineral N fertilisation resulted in a slight SOC increase (Dersch und Böhm, 2001). In contrast, studies from US report a decrease of organic matter following mineral N fertilisation (Khan et al., 2007). Worldwide evaluations of field experiments show a retardment of degradation or a marginal increase of SOM with mineral N (Ladha et al., 2011).

In general, the application of mineral N-fertilisers, regardless of its type, leads to elevated N₂O emissions in the field (e.g. Abdalla et al. (2012)). This occurs, because a higher amount of available nitrogen allows higher concentrations of nitrate or other nitrogen compounds, being involved in denitrification processes depending on site conditions (Weier et al., 1993). At intermediate water filled pore space values (65%), nitrous oxide emissions are reported to

peak (Sehy et al., 2003). Consecutive N_2O measurements at the same site in different years have shown that there is a wide range of emission values within similar treatments (Flechard et al. 2007). Emission data of different sites throughout the United Kingdom of the same year were compiled by Smith et al. (2012) and identified a high variation in the fluxes as well. It seems that weather conditions at and after the fertiliser application determine the N_2O emission rates in a strong way.

However, the main focus should not only be on the total applied N but also on the amount of N not used by the crops and, thus, the timing of fertilisation. Any extension of the time period in which an ammonium-containing fertiliser is prone to nitrification, or a nitrate-containing fertiliser to denitrification, in absence of a growing crop that can act as a strong sink for N, increases the N_2O -emission probability. Furthermore, NUE and operation income will decrease. The application of fertilisers containing nitrification inhibitors may contribute to a reduction in N_2O -emissions. Since hardly any scientific measurement data exist, we strongly recommend to implement more continuous GHG emission measurements in field experiments to allow appropriate evaluations.

3.6.2 Conflicts (trade-offs) and synergies

Mineral N fertilisation plays a crucial role in terms of productivity, because N is the most important limiting factor for the growth of crops. Optimal N fertilisation management places special demands on the skill of the farmer with respect to the fertilisation form, amount, timing, kind of application, knowledge of soil-plant processes (see chapter 3.6.1) etc. This is necessary to minimise N losses to the water and to the atmosphere.

3.7 Fertilisation with compost

3.7.1 Task group results under consideration of co-variate factors

The final composition, i.e. the chemical and biophysical characteristics, of the composts depends on the basic materials. The evaluation comprised very different kinds of compost (e.g. plant, biowaste, sludge), thus, the results showed a great variability. Compared to a similar N fertilisation level using mineral fertilisers, the RR revealed an average non-significant 5% yield decrease with compost application (Tab. 3.1-1). Furthermore, SOC concentrations and stocks were significantly enhanced by 37% and 31%, respectively. A limited amount of GHG emission measurements showed increased CO_2 and N_2O emissions in ATL and CON (only CO_2) and decreased emissions in the MED climate.

Compost amendments resulted in an increase of earthworm number and biomass - however, (far) less so than with FYM and slurry. Compost application tended to decrease plant-parasitic and fungivorous nematodes and to enhance bacterivorous nematodes. On an individual basis, compost effects on soil biota were reported to depend on the C/N ratio of the organic amendment. Those with lower C/N, indicating more readily mineralisable compounds, will preferentially be used by soil bacteria, those with higher C/N ratio will be mainly decomposed by fungi (Marschner et al., 2003).

The application of composts enhanced average pH and N_t content significantly and tended to increase plant available K contents, the C/N ratio and N_{min} contents and in the soil. These increases of N indicators fit very well to the findings of the productivity task group. They stated – albeit based on few comparisons only in the ATC climate - that the N uptake and the N use efficiency were enhanced with compost application as well, coherent with decreasing

N surplus in the same specific cases. One short-term trial in MED climate, however, showed an increased N surplus (N input minus removal) in response to compost application. The most important influencing factors were the duration of practice (e.g. for yields, pH) and the climate (e.g. yields). Yield and pH increases after compost application only occurred after (more than) 5 years of compost application. SOC increases were highest in the upper 10 cm soil depth and became more pronounced after more than 10 experimental years. The reduction of plant-parasitic nematodes due to compost was more effective in a sandy soil (decrease by 9%) than in a silt soil, where almost no effect was observed.

3.7.2 Conflicts (trade-offs) and synergies

With compost organic material is applied to soils. Depending on the amounts of organic matter and its nutrient contents, compost application will result in an increase of SOC and plant nutrients, especially N, which is primarily beneficial for productivity in the long-term and for soil quality. However, the mineralisation of organic matter will lead to a retarded nutrient, especially N, discharge. Thus, our analyses confirmed findings of the literature that composts act as “slow release” fertilisers with a well-known slow but nevertheless effective N mineralisation, which should be adequately controlled. Based on only few comparisons, our evaluations have shown a decrease of CH₄ and an increase of N₂O emissions. Despite the above mentioned trade-offs, compost application can be recommended as BMP.

3.8 Farmyard manure application

3.8.1 Task group results under consideration of co-variate factors

We compared FYM application versus mineral N fertilisers, based on the same amounts of total N, except for the chemical indicators where comparisons were on ‘equal plant available nutrients’ basis. On average of 60 long-term experiments (>10years), a significant yield reduction by 6% was observed after FYM application (Tab. 3.1-1). However, this seems to be due to the great data variability, because the mean effect on yield found for each crop group was positive– except for legumes/grass ley (RR 0.97). Vegetables and potato benefited more of manure additions than wheat and barley. Climate and soil texture class significantly affected the RR of yields. Results obtained in northern Europe on fodder maize were extremely positive (RR1.56), although the absolute yield was rather low (<5.5 t ha⁻¹ of DM in the manured plots). Conversely, 8 cases in the Atlantic climate showed a reduction in marketable production (RR 0.74). Coarse-textured soils, where mineralisation proceeds faster, created more favourable conditions for manured treatments. Summer crops tended to benefit more from the N mineralisation of organic fertilisers, because their N uptake patterns are more synchronous with the mineralisation curve of organic manures. Furthermore, statistically insignificant reductions of NUE and increases in N surplus (calculated as N input minus N removal) could be shown.

SOC concentrations and stocks increased significantly. Also a slight insignificant increase in CO₂ emissions could be stated, whereas N₂O emissions slightly decreased, CH₄ emissions behaved differently in two field experiments.

Biological soil quality indicators, such as earthworm number, earthworm biomass and microbial populations and chemical soil quality indicators (Nt and Nmin contents, plant available K) were positively affected after (long-term) FYM application. The C/N increase was significantly higher in the soil depth 0-10 compared to 10-30 cm. This fact also indicates conclusively that adding FYM - with assumed higher C/N ratios than arable soils -

significantly changes (chemical) soil indicators revealing changes in soil organic matter dynamics

3.8.2 Conflicts (trade-offs) and synergies

FYM fertilisation was positively evaluated due to the yield increases for all investigated crops (except for legumes/grass ley) and improvements in chemical and biological soil quality, decreases of N₂O emissions were measured as well (Tab. 3.1-2). However, the build-up of total and plant available mineral nitrogen seemed to result in an N surplus, the decrease of the NUE indicated slow release N sources. These dynamics should be taken into account to avoid N losses to the groundwater and the atmosphere. The positive effects, stated by almost all task groups, led to an overall favourable assessment of FYM application as BMP.

3.9 Slurry application

3.9.1 Task group results under consideration of co-variate factors

We compared slurry application versus mineral N fertilisers, based on the same amounts of total N, except for the chemical indicators where comparisons were on 'equal plant available nutrients' basis. Application of cattle slurry resulted in similar yields (RR 0.98), a decrease of N uptake by 8%, and similar values of NUE and N surplus (calculated as N input minus N removal) compared to a similar rate of mineral N (Tab. 3.1-1).

Crop yield responses to slurry application were mainly influenced by the soil texture class. Best results were obtained in coarse-textured soils (RR1.07 in sandy soils) and poorer results in silt soils (RR 0.73), thus confirming that no yield decrease is expected in conditions that promote mineralisation.

Cattle slurry application resulted in a significant SOC increase. However, based on a limited amount of comparisons, the emissions of all analysed GHGs (CH₄, CO₂, and N₂O) increased as well. On average CO₂ emissions increased by 32 % and N₂O emissions were enhanced 5-fold, but these figures are based on a limited amount of comparisons (5 and 9, respectively). Additionally, N_t (+13%) and N_{min} contents (+25%) increased significantly. As stated, however, these latter indicators were assessed on 'equal plant available nutrient' basis.

Similar to FYM (and compost), the amendment of cattle slurry lead to an improvement of biological soil quality, as earthworm number, earthworm biomass and microbial biomass C increased significantly. Furthermore, plant-parasitic nematodes favourably decreased and the amount of fungivorous nematodes was significantly reduced as well. This indicates a change in the mineralisation patterns (less fungi driven) and cannot be allocated to the scheme favourable/unfavourable.

3.9.2 Conflicts (trade-offs) and synergies

Slurry application improved SOC and other chemical and, above all, biological soil indicators (Tab. 3.1-2). It affected crop yields neither positively nor negatively. However, all investigated N indicators showed a change in the N dynamics compared to mineral N application. Although a build-up of total and plant available mineral nitrogen pools was observed, N uptake was reduced and consequently N surplus was slightly increased. Furthermore, the simultaneous decrease in N uptake and NUE suggests the danger for N losses into the ground water with NO₃ enrichments. Another pollution risk that should be mentioned, although it was not investigated here, is the ammonia loss, which can be remarkable if slurry is not rapidly incorporated into the soil.

GHG (CO₂ and N₂O) emissions increased significantly, however, the relevant enhanced N₂O emissions were measured in a limited amount of (three) field experiments comprising 7 comparisons. Improved application time and techniques are options to reduce environmental and climate (at least indirect N₂O emissions) relevant N losses to the water and the atmosphere for this MP that, on the other hand, has positive effects on soil quality. Thus, the qualitative evaluation of the single task groups (Tab. 4.1-1) qualified slurry application as a favourable MP, if the manure management (storage, spreading) is carried out properly (e.g. Sommer et al., 2009).

3.10 Crop residue incorporation

3.10.1 Task group results under consideration of co-variate factors

The incorporation of crop residues - compared to the removal of crop residues from the field - resulted in an overall 7% crop yield decrease and a slight decrease in N uptake (Tab. 3.1-1). Furthermore, an increase of SOC by 7%, of N_t contents by 2% and a significant increase of the C to N ratio was observed. However, the GHG emissions, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), were significantly enhanced as well. Based on few experimental results, the residue incorporation showed beneficial effects regarding earthworm abundance and weights. Crop residue incorporation resulted in an unfavourable overall increase of penetration resistance by 36% and a beneficial increase of aggregate stability by 86%. The increase in penetration resistance was highest in the 11 to 30 cm soil depth. The increases of aggregate stability were even more pronounced in long lasting experiments (>10 years) and in silty soils. The bulk density decreased in Southern countries (RR 0.96).

The increase of SOC tended to be highest in the northern ENZ (attributed to retarded mineralisation), in soils with high clay contents and after longer experimental duration (>20 years). The incorporation of cereal crop residues showed a significantly lower increase of CO₂ and N₂O emissions compared to leafy crop residues. The increases of CO₂ field emissions were significantly higher in the ATL (western) compared to the MED (southern) climate. In contrast, N₂O field emissions were more enhanced in the MED experiments with soils containing higher clay contents compared to the ATL experiments with coarsely textured soils. That fits well with the observation that – albeit based on one to two comparisons - incorporation of crop residues gave strongest responses of N_t contents (increasing) and C/N (decreasing) in the southern environmental zones.

The increase of SOC concentration and stocks as well as for N_t contents were higher with longer duration (> 10 years) of this management practice compared to short-term application.

3.10.2 Conflicts (trade-offs) and synergies

The separate task groups detected unfavourable effects of crop residue incorporation (e.g. some yield decreases, increases of GHG emissions and of penetration resistance) as well as beneficial increases of SOC, N_t, aggregate stability and of earthworm number and/or biomass. Thus, the qualitative evaluation (Tab. 3.1-2) stated neutral to positive overall effects of this MP compared to the removal of crop residues. Finally, this practice can be further recommended as a BMP.

3.11 Burning of crop residues

3.11.1 Task group results under consideration of co-variate factors

Burning of crop residues was addressed only by the productivity task group (Tab. 3.1-1). It is a cheap technique to remove crop residues from the field and still widely adopted by farmers in Mediterranean areas. It has been studied in some LTEs where it was compared with incorporation but not with removal (and therefore could not be used for this analysis). The 9 cases reported were mainly located in Atlantic climate.

Burning had an overall slightly positive but significant effect on yield, +3%, with a very limited variability around this value. N uptake was also slightly (but not significantly) increased and consequently N surplus was slightly reduced (see Tab. 3.1-1).

3.11.2 Conflicts (trade-offs) and synergies

Burning of crop residues surprisingly resulted in an improvement of all productivity indicators. However, many adverse effects of crop residue burning are known, e.g. impacts on aerosol properties, increases of greenhouse gas (GHG) emissions, such as CO₂, CH₄ and N₂O. Thus, the emissions of these GHGs associated with the burning of residues are taken into consideration in the national GHG inventories (IPCC, 2006).

In some European countries or provinces the burning of crop residues is not allowed.

3.12 Irrigation

Due to D3.324 (Zavattaro et al. 2014) no evidence was found of long-term experiments or medium-term experiments (less than 5 years), regarding the comparison between irrigation systems, and in particular sprinkler or drip irrigation, compared with surface distribution methods. Some studies compare irrigation with a control without irrigation (e.g. Flink et al., 1995).

Dersch and Böhm (2001) observed losses of 2.4 t carbon per ha caused by additional irrigation compared to the rain fed system for sugar beet and maize in a rotation with cereals in a 21 years period in the Pannonian climate.

No other publications were found comparing different kinds of irrigation regarding the listed CC indicators and the indicators of the other task groups.

3.13 Crop protection

The mechanical control of weeds was compared to the chemical control of weeds to evaluate a possible difference – only - in soil physical properties.

Mechanical weed control had beneficial effects on soil physical properties, as the soil penetration resistance was reduced and the aggregate stability improved. However, also the permeability was significantly lower, while the bulk density was not found to be significantly different (Guzmán et al., 2014).

4 Conclusions

Tab. 4.1-1. : Overall qualitative evaluation (++: very favourable effect;+: favourable effect; 0: neutral effect; -: unfavourable effect; --: very unfavourable effect) of management practices

Category of practice	Management practices/Indicators	Qualitative evaluation of the task groups				
		Productivity	Climate change mitigation	Soil chemical quality	Soil physical quality	Soil biological quality
Rotation	<i>Monoculture (baseline)</i>					
	Crop rotation	++	0	0	++	+
	<i>No intercropping (baseline)</i>					
	Intercropping	0				
	<i>Without Green manure/catch crop/cover crop (baseline)</i>					
	Cover crops				++	
	Harvested catch crop/cover crop	+		0		+
	Incorporated green manure	0				++
	Catch crop/cover crop/ green manure		-			
Tillage	<i>Conventional tillage (baseline)</i>					
	No tillage	0	-	+	--	+
	Shallow non inversion tillage/reduced + minimum tillage	--	+	++	--	+
	Deep non-inversion tillage					0
	Deep ploughing				+	
	Direct drilling				++	
Nutrient management: mineral fertiliser and organic fertiliser	<i>Mineral fertiliser (mineral N – baseline)</i>					
	Organic fertiliser- FYM	-	++	++		++
	Organic fertiliser-slurry	-	0	++		+
	Organic fertiliser-compost	0	+	+		++
	<i>No mineral fertiliser (baseline)</i>					
	Mineral N fertiliser		0	++		
Residue management	<i>Residue removal (baseline)</i>					
	Residue incorporation	0	0	+	0	+
	Residue burning	+				
Crop protection	<i>Chemical control (baseline)</i>					
	Mechanical control				+	
Water management irrigation-drainage	-	0				

Tab. 4.1-2: Three BMPs suggested by each task group

Suggested BMPs for P	Suggested BMPs for CC	Suggested BMPs for SQC	Suggested BMPs for SQP	Suggested BMPs for SQB
Crop rotation	FYM application	FYM application	Crop rotation	FYM application
Catch crop (harvested)	Crop rotation	Non-inversion tillage	Cover crops	Compost application
Burning crop residues	Non-inversion tillage	Compost application	Direct drilling	Incorporation of a green manure crop

The indicator-based evaluation of agricultural management practices carried out as comparisons between an improved (“BMP”) and a prevalent current practice showed positive and negative effects (Tab. 4.1-1). As expected, none of the investigated practices could comply with all objectives simultaneously, i.e. maintaining high yields and reducing cultivation costs, mitigating climate change and improving chemical, physical and biological soil quality. Furthermore, often substantial variation in the responses of one indicator to the same practice between LTEs occurred, which we could not explain with the help of our covariate factors. Not only the size of the response varied, but the response itself was sometime favourable, sometimes unfavourable.

Our analyses confirmed the results from practice and literature that a suitable crop rotation is a precondition for good agricultural management (Tab. 4.1-2). The inclusion of catch crops/cover crops/green manures in the crop rotation shows overall positive or neutral effects on the investigated indicators.

Overall, the application of organic amendments was rated to be beneficial/neutral regarding chemical, physical and, especially, biological soil indicators. Among the indicators for climate change mitigation, SOC is favourably promoted, but some amendments (e.g. slurry) enhance CO₂ and N₂O emissions (in a limited amount of measurements). Changed N dynamics and the importance of optimal application techniques require special attention by the farmer, and further experimentation is needed to assess the trade-off between SOC increments and GHG losses.

Reducing tillage compared to conventional ploughing was appreciated differently by the respective task groups. In general, a total omission of tillage (NT) enhanced biological and chemical soil quality. (Shallow) Non-inversion tillage - i.e. a reduced number and depth of cultivation passes and avoidance of inversion, in short, less soil disturbance - was again good for biological and chemical quality, but was in addition also beneficial for CC indicators. For soil physical indicators, however, benefits of no-tillage depended very much on the farming system. This practice was rated as very unfavourable in permanent crops (bare exposed soil between rows). In contrast, NT (direct drilling) was evaluated as the best management practice for physical soil quality in annual arable crops, especially in the Mediterranean region (Tab. 4.1-2), however, some tillage operations from time to time are suggested to alleviate the surface compaction. Non-inversion tillage, too, was rated unfavourable for physical quality in permanent crops. Additionally, all productivity indicators were scarcely,

but significantly adversely affected by reduced tillage, whereas they showed neutral (n.s.) effects with no tillage.

Management practices like weed control, specific measures for pest and disease control, water management and grassland management could not be evaluated due to insufficient data from long-term experiments.

Furthermore, the evaluation of CC mitigation is often limited by the lack of data from – preferably - continuous GHG emission measurements. Thus, more long-term field studies are needed to better assess the CO₂, (CH₄) and, especially, N₂O emissions following favourably rated MPs such as reducing tillage, the addition of organic fertilisers and crop residue incorporation. Additionally, in these experiments SOC should be measured, as well. This could enable overall balances of CO₂-C equivalent emissions, which was also requested by DEFRA, 2010.

The most important factor affecting the impact of a management practice seems to be the environmental zone (climate). For soil quality indicators the responses often depend on the investigated soil depth, too. Furthermore, many effects for productivity and soil quality can be detected with statistical certainty only after many (more than 10) years, due to great temporal and spatial variations of climate and soil conditions.

Furthermore, this study has shown that ‘best’ or ‘better’ or ‘improved’ MPs do hardly exist if all goals are considered simultaneously. Best practice’ is largely determined by context and by the specific goals that the farmer - or the consumers or the civil environment - wish to maximise. Furthermore, ‘overall best’ cannot be defined without assigning normative judgements to these goals, which lies beyond the scientific perspective.

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Acronyms

BMP	Best management practices
CH ₄	Methane
CO ₂	Carbon dioxide
CT	Conventional tillage
ENZ	Environmental zones
MP	Management practice(s)
N	Nitrogen
NT	No tillage
NIT	Non-inversion tillage
NUE	Nitrogen use efficiency
N ₂ O	Nitrous oxide
RR	response ratio(s)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
DIFF	differences
rel DIFF	relative differences

Appendices

Definitions/Descriptions for the used terms of the management practices:

Category of practice	Sub-category of practice	Management practice	Definitions/descriptions
A. Rotation	A1.crop rotation	Monoculture	The growing of a single arable crop species on a field year after year, for at least 9 to 10 years.
		Rotation with cereals	The growing of different species of crops in a crop rotation with >50% coverage with cereals.
		Rotation with legume crops	The growing of different species of crops in a crop rotation with >25% coverage with legume crops.
		Rotation with tuber or root crops	The growing of different species of crops in a crop rotation with >25% coverage with tuber or root crops.
		Rotation with fallow land	The growing of different species of crops in a crop rotation with >25% fallow.
		Rotation with grassland	The growing of different species of crops in a crop rotation with >50% grassland.
	A2. intercropping/green manure/catch crop	Intercropping	The growing of two or more different arable crops simultaneously in different rows in the same field.
		Rotation with cover/catch crops	The growing of different species of crops in a crop rotation with >25% coverage with cover/catch crops. Double cropping (two different crops grown on the same area in one growing season) is here included. Cover/catch crops are harvested.
		Rotation with green manures	The growing of different species of crops in a crop rotation with >25% coverage with green manure crops. Green manure crops are incorporated into the soil.
B.Grassland management		Permanent grazing	Continuous feeding on standing vegetation by livestock.
		Rotational grazing	Rotational feeding (i.e. changing the grazed parcels) on standing vegetation by livestock.
		Zero grazing	No grazing but only mowing to harvest grass.
C. Tillage		Conventional tillage	The conventional tillage consists of ploughing the soil (e.g. \pm 30 cm), which causes turning, loosening, crumbling and aeration of the topsoil. This should result in a clean field surface.
		No / Zero tillage	No tillage.

		Shallow non inversion tillage/reduced tillage	Tillage without inversion, at a reduced depth (e.g. 5-15 cm), with specific equipment (e.g. grubber/cultivator) more than once a year . About 30% of soil cover after seeding (or the incorporation of organic matter >1120 kg/ha).
		Shallow non inversion tillage/minimum tillage	Tillage without inversion, at a reduced depth (e.g. 5-10 cm), with specific equipment (e.g. rotovator) only once a year . About 30% of soil cover after seeding (or the incorporation of organic matter >1120 kg/ha).
		Deep non inversion tillage	Tillage without inversion, on a soil depth of ± 30 cm and with specific equipment (e.g. grubber/cultivator) more than once a year. About 30% of soil cover after seeding (or the incorporation of organic matter >1120 kg/ha).
		Deep ploughing	The deep ploughing describes the use of the plough, where the soil is ploughed > 35 cm. It causes a turn, loosening, crumbling and aeration of the topsoil and parts of the subsoil. Furthermore, deep ploughing is used as a measure for agricultural land improvement or cultivation of peat.
		Direct drilling	Direct drilling results in sowing without tillage. The residues of the plant material remain usually as mulch in the field.
		Contour ploughing	Parallel ploughing to the contours of hill slopes.
		Terrace farming	The term describes the use of graded terrace steps of sloped land, used to farm on hills and mountainous area.
		Controlled traffic farming	Controlled traffic farming means using similar traffic lanes for different application within one year and the same traffic lanes between years , often applying a navigation system.
E. Crop protection	E1. Crop protection - weeds	Mechanical weeding	The mechanical weeding uses technical tools to bury, cut or uproot the existing weeds. For this mechanical method, straight-row planting is essential.
		Herbicide application	The application of herbicides to combat weeds and protecting crops.
	E2. Crop protection - pests	Push-pull strategies	Push-pull technology is a method of biological pest control. Within cultures, crops are cultivated with repellent effects and outside the cultures crops are grown with attractive effects. This makes it possible to pull or to push the insects from the crops.
		Patches or stripes of natural vegetation	Patches or stripes of natural vegetation are included in the field. They serve as a refuge for beneficial insects for biological pest control, for promotion of soil-field weeds, and to avoid erosion and prevent leaching of

			nutrients.
		Pheromones application	The application of pheromones to influence plant growth.
		Insecticide application	The application of insecticides to protect crops.
		Fungicide application	The application of fungicides to protect crops.
		Nematode application	The application of nematodes to protect crops.
		Soil fumigation	After covering the soil the application of gaseous pesticides by specialized devices are used to control pests inside the soil.
		Soil solarization	Covering the soil to trap solar energy and heat the soil to control pests.
F. Water management	F1. Water management - irrigation	Surface irrigation	Application of water to the field by surface irrigation.
		Drip irrigation	Application of water under low pressure through a piped network in a pre-determined pattern, applied as a small discharge to each plant or adjacent to it and adjustable by irrigation nozzles.
		Sprinkler irrigation	Application of water to the field by sprinkler irrigation.
	F2. Water management - drainage	Subsurface drainage	Artificial systems of furrows, ditches, pipes, etc. to improve drainage of excess water from the sub-soil.