Funded by the European Union

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

Impacts of soil management on physical soil quality

Deliverable reference number: D3.364

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Submission date: 2015/06/18 (revised)







This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289782
Project duration: January 2012 - December 2014

The CATCH-C project aims at identifying and improving the farm compatibility of sustainable soil management practices for farm productivity, climate-change mitigation, and soil quality. The project is carried out by a consortium of 12 partners, led by Stichting Dienst Landbouwkundig Onderzoek (DLO), The Netherlands.

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Disclaimer:

This publication has been funded under the CATCH-C project (Grant Agreement N° 289782) within the 7th Framework Programme for Research, Technological Development and Demonstration, Theme 2 – Biotechnologies, Agriculture & Food. Its content does not represent the official position of the European Commission and is entirely under the responsibility of the authors.

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General information

Task(s) and Activity code(s):	Task 3.6, A 3.6.1-A 3.6.4
Input from (Task and Activity codes):	
Output to (Task and Activity codes):	WP4, WP5, WP6
Related milestones:	MS 3.6.1-MS 3.6.3

Suggested citation:

Guzmán G., Sáenz de Rodrigáñez M., Vanwalleghem T., Vanderlinden K., Laguna A., Giráldez JV. 2015. Compatibility of Agricultural Management Practices and Types of Farming in the EU to enhance Climate Change Mitigation and Soil Health: Impacts of soil management on physical soil quality. CATCH-C, www.catch-c.eu, pp. 38.

Executive summary

The rational use of soil requires the selection of management practices that take advantage of the beneficial functions of plant growth, water and nutrient storage, and pollutant removal by filtering and decomposition without altering its properties. Use of the soil implies its disturbance. The soil itself is resilient although its resilience is not strong enough to overcome the effects of human impact, either in agriculture or other soil uses.

Tillage is an ancestral agronomic practice to condition the soil for preparing a seedbed, to remove weeds and to incorporate organic residues accelerating their conversion into organic matter. However tillage has some shortcomings as well: topsoil inversion or disturbance does not have the same effect under different conditions. With the development of herbicides by the chemical industry in the nineteen seventies, new reduced tillage systems emerged: reduced, minimum, and zero-till or direct drilling, which were progressively adopted by farmers worldwide. The benefits of reduced tillage, or conservation agriculture on soil quality were soon evident; without stubble burning, soil organic carbon was not easily lost into the atmosphere. Soil losses decrease by the protection of standing stubble and no-removed weeds in early Fall, saving more water, which has meant greater crop yields in dry years.

One recommendable management practice is tillage reduction, but is such a practice a fixed universal rule? Is there a set of reduced tillage practices suited to the different climates, soil, and agronomic zones in the European Union, to which this report could act as a document for planning assessment? Many studies and recommendations originate from the US. Are these also valid under European conditions?

Agricultural management practices do not affect soil physical quality (SPQ) unilaterally. Soil physical quality also determines which management options are, or should be, in place. We hypothesize that a large proportion of these management effects on SPQ is a result of indirect mechanical or chemical disturbance of the soil matrix, for example, as a result of compaction by machinery wheels or associated with soil tillage involved in the different management options.

Tillage is expected to exert the largest impact on soil physical quality (SPQ) indicators, since mechanical disturbance of the soil matrix implies a new geometry, and, consequently, a different set of pore walls and menisci, which changes the forces with which water is

retained. A new distribution of pore sizes modifies the water retention curve, and the hydraulic conductivity curve of the soil. Therefore, tillage drastically changes the indicators.

The aim of this report was (i) to evaluate the effect of different soil management practices on soil physical quality, (ii) to identify synergies and trade-offs and (iii) to propose the best management practices which promote the conservation of SPQ in agricultural areas. This assessment was carried out by exploring key indicators of physical soil quality. The analysis was based on experimental data, mainly from Europe, published in selected articles on the topic of SPQ. The aim of this study was the assessment and comparison of management practices for a more rational use of natural resources in the near future.

From the available data of the European long term experiments, we conclude that the most advantageous practices for SPQ are organic fertilization, minimum tillage (non-inversion tillage) and the use of plant covers in permanent (tree) crops for water erosion control.

Other management systems are less convenient, such as no tillage in permanent crops. On the contrary, no tillage in arable crops (direct drilling) presents clear benefits as compared to conventional tillage, under the Mediterranean conditions.

Is it important to notice that given the multiple factors on which soil quality is based and the variability in space and time of the environmental agronomic factors, these results must be taken within the context of the available information explored here, and are limited to soil physical properties only.

Specific part

1 Introduction

The rational use of soil requires the selection of management practices that take advantage of the beneficial functions of plant growth, water and nutrient storage, and pollutant removal by filtering and decomposition without altering its properties (*e.g.* Buchan 2010). Each of these functions in itself causes alterations in the soil. Plant roots spread themselves through pores, meso- and macropores, and deform their walls or open new conduits. Water absorption or extraction can cause expansion or shrinkage and induce stress in the solid matrix, or create conditions that produce compaction, surface crusting, or deformation of wet aggregates by liquid phase sintering (Or 1996), while water borne sediments or pollutants clog pores. The soil itself is, however, resilient to these effects. However, this resilience is not strong enough to overcome the effects of human impact, either on agriculture or other soil uses. Soil is a natural resource in relation to which humans can act as a parasite as appropriately expressed by Hyams (1952).

One of the crucial steps in civilization was the transformation of man from hunter, gatherer, and scavenger to stock breeder and farmer (*e.g.* Childe 1951). This step started with the introduction of tillage, a rudimentary way of conditioning the soil to form a seed bed, protected from sun beams, holding water to induce germination, with a free exchange of gases with the atmosphere, to receive oxygen, and to remove emergence-restricting surface crusts, and to open conduits for the growth and development of seedling roots. Other additional objectives of tillage were weed removal and residue incorporation.

However, tillage has its shortcomings as well: topsoil inversion or disturbance does not have the same effect under different conditions. There is an optimal condition, tilth mellowing (Utomo and Dexter 1981), where soil can be tilled without any irreversible alteration of its structure. Excessive tillage or tillage out of this -essentially- optimal moisture range, may have negative consequences on long-term structural stability, apart from additional effects, such as soil displacement by agricultural implements, known as tillage or mechanical erosion even more intense than, and comparable with, water erosion (*e.g.* Heckrath et al. 2005), pest dispersal as in the case of broom rape (López-Granados and Garcia-Torres 1993). All these effects were enhanced by the introduction of mechanization into the farm leading to what Faulkner (1943) denominated a plowman’s folly.

With the new development of herbicides by the chemical industry in the 1970`s new reduced tillage systems emerged: reduced, minimum, and zero-till or direct drilling, which were progressively adopted by farmers worldwide. The benefits of reduced tillage, or conservation agriculture on soil quality were soon evident; without stubble burning, soil organic carbon was not so easily lost into atmosphere. Soil losses decreased due to the protection of standing stubble and no-removed weeds in early Fall, saving more water, which led to greater crop yields in dry years (*e.g.* Ordóñez-Fernández et al. 2007). Additionally, farmer production costs were significantly reduced.

One recommendable management practice is tillage reduction, but is such a practice a fixed universal rule? Is there a set of reduced tillage practices suited to the different climates, soil, and agronomic zones in the European Union, to which this report could act as a document for planning assessment? Many studies and recommendations originate from the US. Are these also valid under European conditions?

Agricultural management practices do not affect soil physical quality (SPQ) unilaterally. Soil physical quality also determines which management options are, or should be, in place. We hypothesize that a large proportion of these management effects on SPQ is a result of indirect mechanical or chemical disturbance of the soil matrix, for example, as a result of compaction by machinery wheels or associated with soil tillage involved in the different management options.

Tillage is expected to exert the largest impact on soil physical quality (SPQ) indicators, since mechanical disturbance of the soil matrix implies a new geometry, and, consequently, a different set of pore walls and menisci, which changes the forces with which water is retained. A new distribution of pore sizes modifies the water retention curve, and the hydraulic conductivity curve of the soil, as can be seen, for example, in Leij et al. (2002), or Moroizumi and Horino (2004). Therefore, tillage drastically changes those indicators. Effects of crop rotation, nutrient management, crop protection and water management on SPQ cannot be considered as being as relevant as those due to tillage.

The aim of this report is (i) to evaluate the effect of different soil management practices on soil physical quality, (ii) to identify synergies and trade-offs and (iii) to propose the best management practices which promote the conservation of SPQ in agricultural areas. This assessment was carried out by exploring key indicators of physical soil quality. The analysis was based on experimental data, mainly from Europe, published in selected articles on the topic of SPQ. The aim of this study was the assessment and comparison of management practices for a more rational use of natural resources in the near future.

2 Materials and Methods

The effects of several management practices on physical soil quality were evaluated based on an inventory of available literature on experiments carried out in European countries. A careful screening was performed of international and national peer-reviewed literature, vernacular scientific or technical papers, project reports and unpublished data. Some cases where the available data were insufficient or non-representative for allowing statistical analysis were discarded. Relevant information on each document and measurements of the different indicators available in the bibliography were collected in a shared on-line library and analysed with the help of an on-line database by the different task groups.

Table 2-1 presents the management practices evaluated in this project that hold a relation to soil physical quality indicators.

Tab. 2-1. List of practices studied in WP3 for SPQ

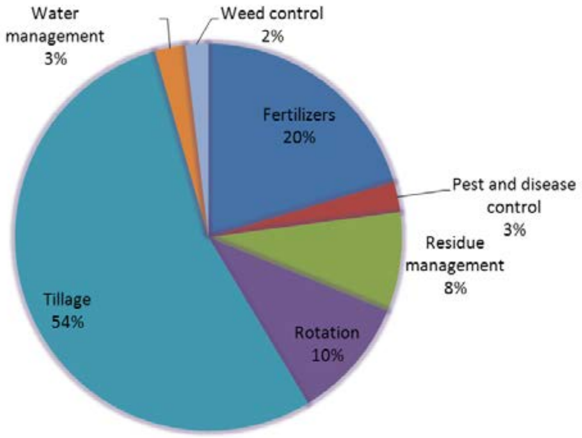
Rotation	Monoculture (baseline treatment) Crop rotation (**CR**)
Crop protection: weeds	Chemical control (baseline treatment) Mechanical control (**MCW**)
Fertilization	Mineral fertilization (baseline treatment) Organic fertilization (**OF**)
Residue management	Residue removal (baseline treatment) Residue incorporation (**IR**)
Tillage	Conventional tillage (baseline treatment) No Tillage (**NT**) Minimum tillage (**MT**) Cover crops (**CC**) Deep ploughing (**DP**)

Soil erosion is one of the major concerns for SPQ, especially in permanent crops located in Mediterranean climate countries due to some management practices which leave large areas of bare soil, due to intensive weed control. These practices worsen erosion risk in marginal soils with a low organic matter content located on steep slopes. The use of cover crops, acting as vegetative filters or buffer strips is a soil and water conservation practice, widely adopted in semiarid regions (Maetens et al. 2013). These crops are not harvested. For that reason, cover crops as a management practice is compared with tillage operations in SPQ studies.

2.1 Shared library

The on-line shared library created during this study on the Zotero free platform (www.zotero.org) contains more than 700 items among papers, PhDs, Master Thesis, videos, etc.), 22.4% of which include information for SPQ as is shown in Fig. 2.1-1.

Fig. 2.1-1. Distribution of the bibliography search from the Zotero library.



2.2 Database

Data from literature contained within the Zotero library were entered by the CATCH-C members and stored in a customized on-line database. Relevant information on productivity, climate change and biological, chemical and physical soil quality was recorded. The dataset consisted of 3059 records with data on physical soil quality (bulk density, penetration resistance, permeability, runoff and sediment yield). The list of European and non-European LTEs used in this study is shown in Tab. 2.2-1.

Tab. 2.2-1. Long term experiments (LTEs) in the database reporting soil physical indicators. The letter in management practices columns indicates the type of relevant indicators that they reported (according to paragraph 2.3): bd = bulk density, pr = penetration resistance, pe = permeability, as = aggregates stability, ry = runoff yield and sy = sediment yield. The letter in characteristics columns indicates climate classes: N (northern), W (western), E (eastern) and S (southern); soil texture classes: C (clay), I (silt), A (sand), L (loam) and U (unknown); duration of the trial: L (low), M (medium), H (high), V (very high) and U (unknown); sampling depth: T (top), M (medium), D (deep) and U (unknown).).

LTEs	**Management practices**								**Characteristics**			
	no tillage	**minimum tillage**	**cover crops**	**deep ploughing**	**organic fertilization**	**incorporation of residues**	**rotation**	**mechanical weeding**	**climate class**	**soil txt class**	**duration**	**depth of sampling**
Alameda del Obispo	bd, pr, pe, as, ry								S	I	L	T, M, D
Apelsvoll/Kise		bd							N	A	H	T, M
Aragón	as	as							S	L	H	U
Askov					bd, pe				W	A	VH	T, U
Benazacón			bd, pe, as, ry, sy					as, ry, sy	S	A	L	T,M
Boigneville	bd								W	L	V	U
Bonlez			ry, sy						W	A	L	-
Braunschweig FV4		bd, pe							E	I	H	D
Broadbalk					bd				W	L	VH	T
Brody	bd, pr	bd, pr							E	A	M	T, M
Castro del Río			ry						S	L	L	-
CEBAC (Murcia)	ry, sy								S	L	L	-
Cordoba	bd								S	A	V	M,D
Coria del Rio		bd, pr, pe				bd, pr, pe		bd, pr, pe	S	L	L	T, M
Darmstadt					bd				E	A	VH	U
DK-Foulum	bd, pr	bd, pr							W	A	M	M
Edinburgh South Road	bd, pe, as								W	A	L	T
Edinburgh2		pe, as							W	L	L	U
El Ardal (Murcia)	ry, sy		ry, sy						S	I	L	-
ES-Olite	bd					bd			S	L	M	T
Extremadura	pr, as		pr, as			pr, as		pr, as	S	L	L	T,M
Fidenza					bd				S	L	H	U
Finca La Pluma (Las Cabezas de San Juan, Sevilla)	pr								S	C	L	T,M
Finca Serfica (Carmona, Sevilla)	pr								S	C	L	T,M
Göttingen HohesFeld		bd							W	I	V	T, M, D
Hangaar		bd, pe, as, ry, sy							W	A	L, M	T, M, D
Heestert		bd, pe, as		bd, pe, as					W	I	L, M	T, M, D
Herent		bd							W	I	L	D
Hoogveld-Bertembos		bd, pe, as, ry, sy							W	A	L	T, M, D
Huéscar (Granada)	pe, as	pe, as	pe, as						S	L	L	U
Huldenberg		bd, pe, ry, sy		bd, pe, ry, sy					W	I	L	D
Huldenberg3		bd, pe, ry, sy							W	I	M	D
Jaen	bd		bd			bd			S	L	V	T, M
Jerez de la Frontera						ry			S	L	L	-
Kortrijkdorp		bd, pe, as, ry, sy							W	A	L, M, H	T, M, D
Kruishoutem		bd, pe, as		bd, pe, as					W	A	M	T, M
Kruishoutem_compost					bd, as, ry, sy				W	A	M	T

La Higuerela (tillage x rotation)	bd, pr	bd, pr						S	L	M, H	T, M
Lange weide		bd, pe, as, ry, sy						W	I	L, M	T, M, D
Leefdaal		ry, sy						W	I	L	-
Lierde		pe, ry, sy						W	I	L	M
Loddington		ry, sy						W	C	L	-
LTE 7 BOPACT		bd, as			as			W	A	L	T, M
LTE 8 VEGTILCO		bd						W	A	L	T, M
LTE 9 FARMCO					bd, pr, as			W	A	M	T
LTE 10_Ferti					pe, as			W	L	L	T
LTE 16 TOMEJIL_	pr	pr						S	C	H	T, M, D
LTE 17 CONCHUELA	bd, pr, pe, as, ry, sy		bd, pr, pe, as, ry, sy					S	C	L, M, H	T
LTE 18 Effects of different tillage treatments		bd, pe						E	A	H, V	T, M, D
LTE 26 GarteSud		bd						W	I	V	T, M, D
LTE Denmark					bd			E	L	VH	T
Madrid (Alcalà de Henares)	as	as				as		S	A	H	T,M
Maulde	bd, as	bd, as						W	I	M	U
NARDI	pr	pr		pr				E	L	L	T,M
Nieuwe stal		bd, pe, as						W	I	M	T, M, D
Nodebais			ry, sy					W	I	L	-
Nueva Carteya			ry					S	I	L	-
Obejo			ry					S	I	L	-
Pedrera (Sevilla)			bd, pe, as				bd, pe, as	S	L	L	T,M
Pisa		bd, pr						S	I	L	T, M, D
Pisa 3	bd							S	L	L	T,M
Torredonjimeno	ry, sy							S	L	L	-
Radinghem		bd, pe, as						W	I	H	T, M
Santaella2	bd, pr, pe						bd, pr, pe	S	L	H	T,M, D
Scottish Crop Research Institute, Invergowrite, Dundee	bd	bd		bd				W	A	M	T, M, D
Tänikon	bd	bd						E	U	L	T, M
Vlaco.B97					pe			W	L	H	U
Vlaco.M97					pe, as			W	L	M	U
Walshoutem		bd, ry, sy						W	I	L	D

2.3 Main indicators

Table 2.3-1 contains the indicators proposed in a first stage for assessing SPQ. As a result of data insufficiencies or non-representativeness not all these indicators were included in the final analysis as detailed below.

Table 2.3-1. Initial proposal of SPQ indicators.

Indicator	Concept	Units
Aggregate stability, friability	Mean weight diameter (MWD), stability index (SI)	mm, %
Clay dispersion	Readily dispersible clay	NTU g^{-1} L^{-1}
Density (bulk density, packing density, total porosity)	Dry bulk density	Mg m^{-3}
Erosion	Mass of eroded soil	t ha^{-1} yr^{-1}
Infiltration, permeability of topsoil	Infiltration	mm h^{-1}
Least limiting water range (LLWR)	Water retention curve (WRC)	mm
Penetration resistance	Penetration resistance measurement	MPa
Runoff	Volume of runoff water	mm yr^{-1}
Runoff coefficient	Runoff as % of rainfall	%
S-index, indicator for general soil physical degradation	Water retention curve (WRC)	-
Saturated and unsaturated hydraulic conductivity	Saturated and unsaturated hydraulic conductivity	cm s^{-1}
Sediment delivery(field)	Sediment delivery rate	t ha^{-1} yr^{-1}
Sediment delivery(rivers)	Sediment delivery ratio (SDR)	-
Soil depth	Distance from soil surface to bedrock or impervious layer	m
Soil structure	Aggregate size classes or distribution	mm
Water storage capacity, water holding capacity at various pF	Water retention curve (WRC)	mm

After searching for information on soil physical properties in the scientific literature, a preliminary list of indicators (Table 2.3-2.) was proposed, based on the number of available data and expert knowledge.

Tab. 2.3-2. Number of records in the CATCH-C database reporting SPQ indicators.

Indicators	No. of records	No. of LTEs
Bulk density	1039	64
Penetration resistance	993	20
Permeability	108	13
Ks	126	18
Erosion	72	9
Sediment yield	111	14
Runoff	93	13
Runoff coefficient	125	17
WSA	54	5

WSA-micro	62	6
WSA-macro	62	6
Aggregate stability	214	21

Many of the records were excluded from the analysis because they could not be compared with the baseline treatment. Finally, six key indicators were retained by merging some of the indicators related to the same physical property:

Bulk density: The mass of dry soil per unit bulk volume represents the degree of weathering of the parent rock, and colonization by flora and fauna (e.g. Pielou 1998 § 2.2). Conversely, bulk density also indicates the degree of deterioration caused by improper agricultural management reducing void space, destroying macropores responsible for fast fluid transfer and root pass through the soil, in what is known as compaction.

Penetration resistance: More specifically, penetration resistance attempts to represent the potential difficulties that plant roots may meet with when growing and exploring soil pores. The usual measurement method has some shortcomings but it is commonly accepted as an estimator of the plant rooting conditions of soils.

Permeability: The permeability data are often confusing. Permeability is an ill-defined term. The Soil Science Society of America defines permeability as '*The ease with which gases, liquids, or plant roots penetrate or pass through a bulk mass of soil or a layer of soil*'. The intrinsic permeability is the hydraulic conductivity corrected with the kinematic viscosity of the fluid. Since it includes the acceleration of the gravity in the denominator, it is measured in Darcy, or m^2. Nevertheless, intrinsic permeability is not usually found in soil quality-related articles. We should use the term saturated hydraulic conductivity and, when available, field saturated hydraulic conductivity, due to the difficulties in representing field conditions in disturbed soil samples in the laboratory. The complete hydraulic conductivity curve, relating it either to the water content or to the matric component of soil water potential, could have provided better information on the soil. However, this information is not always included in articles.

Aggregates stability: Soil structure is not as stable under wet as under dry conditions. It is difficult to measure the stability of soil structure, as pointed out by Amezketa (1999) and Nimmo and Perkins (2002), due to the interaction between force and rupture, which determines the aggregate size. Usually, wet-aggregate stability is measured with a wet-sieving apparatus. The results of the sieving method are presented in several forms. In a seminal work, Le Bissonnais (1996) suggested the use of seven size classes or the mean weight diameter to characterize the results of the sieving process. Coughlan et al. (1973 a,b) presented the sieving results in eight size classes. To prevent the problems of the different size groups, the use of a probability distribution function, pdf, like the lognormal pdf was proposed by Gardner (1956). Alternatively, the Weibull pdf has been successfully adopted in the description of fragmentation processes in several fields, as in the case with the data of Coughlan et al. (1973 a,b), Gabriels and Moldenhauer (1978), Loch and Donnollan (1989), or Le Bissonnais and Arrouays (1997) among many others. In this way, all the reported data of sieving to assess stability of aggregates can be placed on a common base.

Runoff yield: In this analysis, runoff volume or water yield has been adopted as an indicator of the water infiltration capacity of a soil. Since runoff volume depends, among other factors, on the volume of rainfall, the term runoff coefficient seems more appropriate. Rate and duration of the rain should be considered but, unfortunately, these data are not usually available in the publications.

Sediment yield: The amount of sediment measured at the outlet of a plot, farm or watershed is related to soil resistance, to the action of erosive agents, water, wind, or agricultural implements, and to ongoing degradation. Instead of the absolute value, mass of sediment, the specific yield, mass of sediment produced per unit area would be more representative, even though this magnitude is not always provided in articles.

The selected indicators are widely accepted by different authors such as Arshad et al. 1996. Nevertheless, the measurement method is one of the most important problems of the interpretation of the various values of SPQ indicators found in the literature in addition to the expected differences due to the climate, soil, vegetation and agronomic practice (*e.g.* Van den Putte et al. 2010). Considering these limitations, Table 2.3-3 presents the final list of retained indicators and corresponding number of records and LTEs available.

Tab. 2.3-3. List of the retained indicators and available number of records and LTEs.

MP		BD		PR		PE		AS		RY		SY	
		LTEs	n	LTEs	n	LTEs	n	LTEs	n	LTEs	n	LTEs	n
Crop system	Crop rotation	3	20	1	5			2	22				
Weed control	Mechanical control of weeds	2	10			2	7	2	16	2	9	1	1
Fertilization	Organic fertilization	7	14	1	3	3	13	5	16	1	3	1	6
Residue management	Incorporation of crop residues	1	2							2	7	1	3
Tillage	Minimum tillage	30	361	7	255	13	68	12	51	12	37	12	38
	No tillage	16	99	10	240	4	11	7	54	4	27	4	24
	Deep ploughing	3	41	2	47	1	2			1	2	1	2
	Cover crops	4	38	2	13	3	10	3	21	7	37	4	27

2.4 Data treatment and statistical analysis

Since the data originated from different studies and were collected for different purposes, a wide variety of methodological approaches was found. These different methodologies were not always clearly described in the original reports. Therefore, we had to recur to meta-analysis (Hedges et al. 1999, Borenstein et al. 2009).

Once all records from the dataset were classified by the indicators described in Table 2.3-3., a careful review was carried out to homogenise and merge indicators when possible (*e.g.* runoff coefficient and runoff yield) and to select valid records for the analysis, as shown in Tab. 2.3-3. Management practices assigned to each experiment were also checked to make sure that the same criterion was followed by all partners.

From this data control, two main limitations were immediately observed with respect to the SPQ analysis. One was the scarcity of physical indicators measured in field trials outside Mediterranean countries, while the second one was the scarcity of indicator data regarding SPQ that assess management practices other than tillage operations. In spite of their importance and as a result of limited data availability and the high variability of conditions and strategies adopted in the different trials, their analysis and comparison with baseline treatments was not feasible.

Baseline treatments for each management practice were discussed and defined in order to calculate response ratios (RR) in each of the experiments of the dataset:

$$RR = \frac{Indicator_{treatment}}{Indicator_{baseline\,treatment}}$$

Descriptive statistics or RR and represented by indicator and management practice to detect outliers of the data. Records coming from just only one LTE were not analyzed.

A one-sample t-test ($p < 0.05$) was used to identify which RR means were significantly different from 1.

A linear model (analysis of variance) using climate zones, soil textural class, duration of the trial and depth of sampling, as single nominal factors was used to evaluate which conditions mostly affected the performance of each practice, separately. The linear model is described in Table 2.4-1. A pairwise Bonferroni test was used to separate means of single factors ($p<0.05$). All the statistical approaches were performed using the software Statistix (Analytical Software, 1996).

Tab. 2.4-1. Levels of the five factors considered in the linear multiple regression. Climate types were those reported by Metzger et al. 2005 grouped as Northern (Alpine north, Boreal, Nemoral), Western (Atlantic North, Atlantic Central, Alpine South, Lusitanian), Eastern (Continental, Pannonian) and Southern (Anatolian, Mediterranean mountains, Mediterranean North, Mediterranean South). Soil textural classes were described in detail in previous sections of this report.

Climate(ENZ)	Soil texture class	Duration of practice	Depth of sampling
N. Northern (ALN, BOR, NEM)	**C.** Clay (clay, sandy clay, silty clay)	**L.** Low (< 5 yrs)	**T.** Top (<11 cm)
W. Western (ATN, ATC, ALS, LUS)	**L.** Loam (loam, clay loam, sandy clay loam, silty clay loam)	**M.** Medium (5-10 yrs)	**M.** Medium (11-30 cm)
E. Eastern (CON, PAN)	**S.** Sand (sand, loamy sand, sandy loam)	**H.** High (11-20 yrs)	**D.** Deep (>30 cm)
S. Southern (ANA, MDM, MDN, MDS)	**Si.** Silt (silt, silty loam)	**VH.** Very high (> 20 yrs)	**U.** Unknown
	U. Unknown	**U.** Unknown	

3 Results and Discussion

3.1 Crop rotation

3.1.1 Results expected from the literature

Diversified crop rotations resulted in similar or greater grain yields, mass of harvested products, and farmer income than those of the conventional system, a monoculture, despite reductions in agrichemical inputs. Weeds were suppressed effectively in all systems. Nevertheless, freshwater toxicity in the management practice that included a large variety of crops was two orders of magnitude lower than the analog of the conventional system. More diverse cropping systems can use small amounts of synthetic agrichemical inputs as powerful tools with which to tune, rather than drive, agroecosystem performance, while meeting or exceeding the performance of less diverse systems (Davis et al. 2010).

Aggregate dynamics varies among different crops, crop rotations and cover crops (Jarecki and Lal, 2003). The effect of different crops reflects the crop chemical composition (Martens, 2000), rooting structure and ability to alter the chemical and biological properties of the soil (Chan and Heenan, 1996). These effects tend to be short-lived under conventional tillage regimes (Chan and Heenan, 1996). In some soils, rotations may not affect aggregate stability (Filho et al. 2002).

3.1.2 Data analysis

Tab. 3.1.2-1 and Tab. 3.1.2-2: Compared to monoculture, crop rotation induces soil compaction. This could be explained by the continuous pass of different types of agricultural machinery that induces a compaction that reduce the size of macro-pores and thrust the resulting fragments downwards blocking other pores. This effect was observed specially at the long term (>20 yr), loamy soils and top 10 cm. As compared to monoculture, crop rotation has a negative effect on aggregate stability. This can be explained by the compaction produced by the machinery, the timing of agricultural operations, under different soil moisture conditions from autumn to spring drilling, etc. A reduction was observed at the top 10 cm of soil.

Tab. 3.1.2-1. Main descriptive statistics for the available indicators in crop rotation compared to monoculture.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	3	20	0.95	1.24	1.04	1.03	0.08	**0.02**
pr RR	1	5	1.36	1.54	1.43	1.40	0.07	
as RR	2	22	0.05	1.15	0.77	0.90	0.35	**0.01**

Tab. 3.1.2-2. Results of the analysis of variance of indicators in crop rotation compared to monoculture.

BD	**Duration**	**n**	**mean**		**PR**	**Duration**	**n**	**mean**		**AS**	**Duration**	**n**	**mean**	
	L	5	1.05	**b**		**L**	5	1.43			**L**	5	0.78	a

M			
H			
VH	3	1.20	**a**
U	12	1.00	**c**
ENZ	**n**	**mean**	
N			
W	8	1.11	**a**
E			
S	12	1.00	**b**
Texture	**n**	**mean**	
C			
L	8	1.11	**a**
S	12	1.00	**b**
Si			
Depth	**n**	**mean**	
T	8	1.11	**a**
M	12	1.00	**b**
D			
U			

M		
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	5	1.43
E		
S		
Texture	**n**	**mean**
C		
L	5	1.43
S		
Si		
Depth	**n**	**mean**
T	5	1.43
M		
D		
U		

M			
H	17	0.76	a
VH			
U			
ENZ	**n**	**mean**	
N			
W	5	0.78	a
E			
S	17	0.76	a
Texture	**n**	**mean**	
C			
L	22	0.77	
S			
Si			
Depth	**n**	**mean**	
T	14	0.68	a
M	6	0.92	a
D	1	0.92	a
U	1	0.97	a

3.2 Crop protection: weeds

3.2.1 Results expected from the literature

Weed control by tillage sometimes poses serious problems when farmers develop the Plowman’s Folly properly described by Faulkner (1943), by applying as many harrow passes as possible, with the subsequent degradation of topsoil structure. The definition of weeds has been examined by agronomists like Harlam (1975, cap. 4). In many languages, weeds are literally bad grasses, but weeds protect the soil when no other plants are able to do so. In some European climate zones, such as the Mediterranean, weed control becomes critically important during early Spring when the atmospheric water supply fades out and soil water is quickly lost by evapotranspiration.

3.2.2 Data analysis

Tab. 3.2.2-1 and Tab. 3.2.2-2: In the Mediterranean area, mechanical weed control seems to affect soil bulk density. A decrease of bulk density in the top soil (< 10 cm) was found although for deeper layers, an increase was detected. This practice does not present important differences compared to chemical control although negative effects were found. No clear conclusion can be reached due to the lack of available data. For the aggregate stability a somewhat similar effect was observed but the paucity of available records precludes a more sound statement. An increase of runoff generation is detected with the mechanical weed control, which could be again attributed to soil compaction due to the machinery used. No clear conclusion can be reached due to the lack of available data.

Tab. 3.2.2-1. Main descriptive statistics for available indicators in mechanical control of weeds compared to chemical control of weeds.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	2	10	0.86	1.33	1.01	0.98	0.16	0.80
pe RR	2	7	0.20	1.85	0.68	0.40	0.57	0.18
as RR	2	16	0.60	1.50	1.01	0.98	0.26	0.89
ry RR	2	9	0.59	2.81	1.67	1.40	0.76	**0.03**
sy RR	1	1		2.61				

Tab. 3.2.2-2. Results of the analysis of variance of indicators in mechanical control of weeds compared to chemical control of weeds.

Duration	**n**	**mean**	
L	10	1.01	
M			
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W			
E			
S	10	1.01	
Texture	**n**	**mean**	
C	10	1.01	
L			
S			
Si			
Depth	**n**	**mean**	
T	5	0.91	**b**
M	5	1.12	**a**
D			
U			

PE

Duration	**n**	**mean**	
L	7	0.68	
M			
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W			
E			
S	7	0.68	
Texture	**n**	**mean**	
C	7	0.68	
L			
S			
Si			
Depth	**n**	**mean**	
T	3	0.85	a
M	4	0.55	a
D			
U			

AS

Duration	**n**	**mean**	
L	16	1.01	
M			
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W			
E			
S	16	1.01	
Texture	**n**	**mean**	
C	16	1.01	
L			
S			
Si			
Depth	**n**	**mean**	
T	8	0.98	a
M	8	1.04	a
D			
U			

RY

Duration	**n**	**mean**	
L	8	1.53	a
M	1	2.81	a
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W			
E			
S	9	1.67	
Texture	**n**	**mean**	
C	9	1.67	

SY

Duration	**n**	**mean**
L	1	2.61
M		
H		
VH		
U		
ENZ	**n**	**mean**
N		
W		
E		
S	1	2.61
Texture	**n**	**mean**
C	1	2.61

L
S
Si

L
S
Si

3.3 Nutrient management: fertilization

3.3.1 Expected results from the literature review

Inorganic fertilizers might decrease SOC concentration (e.g. Steiner et al. 2007), reduce aggregation, and reduce microbial communities compared to manure and organic or composted fertilizers. However, using chemical fertilizers often improves soil structure in comparison to unfertilized soils (Munkholm et al. 2002). The primary effect of improved nutrient management is to increase not only plant productivity but also SOC and, consequently, biological activity (Haynes and Naidu, 1998). Fertilizer use also improves residue quality and quantity, but this does not necessarily increase the SOC pool (Halvorson et al. 2002). Fertilizer applications alter soil pH and the electrolyte concentrations in soil, which can exert adverse effects on soil structure (Haynes and Naidu, 1998).

On the other hand, compost additions to soil improve soil structure and lower bulk density. Composting materials can increase macroaggregation and rhizospheric aggregate stability (de León- González et al. 2000, Caravaca et al. 2002).

3.3.2 Data analysis

Tab. 3.3.2-1 and Tab. 3.3.2-2: Regarding organic fertilization, in the absence of more data, farm yard manure, green manure, compost, etc., were grouped under the general heading of organic fertilization in order to be compared with mineral fertilization. However, most of the data came from farm yard manure trials in the Atlantic climate zone. Despite not many data were available, in all the cases evaluated, organic fertilization reduced significantly bulk density, penetration resistance and aggregates stability. For the case of the aggregates stability, it was increased mainly at the top soil (< 10 cm) and in loamy soils.

Tab. 3.3.2.1. Main descriptive statistics for available indicators in organic fertilization compared to mineral fertilization.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	7	14	0.89	1.07	0.96	0.96	0.04	**0.01**
pr RR	1	3	0.98	1.08	1.02	1.00	0.05	
pe RR	3	13	1.02	8.40	4.12	2.17	1.02	**0.00**
as RR	5	16	1.13	4.18	2.30	2.21	1.10	**0.88**
ry RR	1	3	0.76	0.80	0.78	0.79	0.02	
sy RR	1	6	0.67	0.97	0.85	0.89	0.13	

Tab. 3.3.2-2. Results of the analysis of variance of indicators in organic fertilization compared to mineral fertilization.

BD

Duration	n	mean	
L			
M	6	0.96	a
H	2	0.90	a
VH	6	0.98	a
U			
ENZ	**n**	**mean**	
N			
W	8	0.96	a
E	4	0.90	a
S	2	0.96	a
Texture	**n**	**mean**	
C			
L	9	0.96	a
S	5	0.96	a
Si			
Depth	**n**	**mean**	
T	11	0.97	a
M			
D			
U	3	0.94	a

PR

Duration	n	mean
L		
M	3	1.02
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	3	1.02
E		
S		
Texture	**n**	**mean**
C		
L	3	1.02
S		
Si		
Depth	**n**	**mean**
T	3	1.02
M		
D		
U		

PE

Duration	n	mean	
L	5	4.17	a
M	4	5.20	a
H	3	5.41	a
VH	1	1.02	a
U			
ENZ	**n**	**mean**	
N			
W	13	4.53	
E			
S			
Texture	**n**	**mean**	
C			
L	12	4.83	a
S	1	1.02	a
Si			
Depth	**n**	**mean**	
T	5	4.17	a
M			
D			
U	8	4.76	a

AS

Duration	n	mean	
L	6	2.69	a
M	10	2.07	a
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W	16	2.30	
E			
S			
Texture	**n**	**mean**	
C			
L	13	2.53	a
S	3	1.33	a
Si			
Depth	**n**	**mean**	
T	13	2.53	a
M	3	1.33	a
D			
U			

RY

Duration	n	mean
L		
M	3	0.78
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	3	0.78
E		
S		
Texture	**n**	**mean**
C		
L		
S	3	0.78
Si		

SY

Duration	n	mean
L		
M	6	0.85
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	6	0.85
E		
S		
Texture	**n**	**mean**
C		
L		
S	6	0.85
Si		

3.4 Residue management

3.4.1 Results expected from the literature

Effects on SPQ are expected to occur through soil organic carbon (SOC), which is affected by N fertilization and the use of organic fertilizers or crop residues. SOC increases aggregate stability, reduces bulk density and enhances infiltration and water retention.

Wilhelm et al. (2004) report that the actual amount of feedstock (stover), that could be removed has been estimated at from 20% (Nelson, 2002) to about 30% (McAloon et al. 2000) the total based on the need for adequate surface cover to control soil erosion.

Removal of crop residue must be constrained by the need to retain sufficient surface cover to keep soil loss by erosion within tolerable limits (Larson, 1979, Nelson, 2002).

Mulches improve structure, reduce evaporative water losses, protect against raindrop impact and increase aggregate stability (Layton et al. 1993), modify thermal and moisture regimes and stimulate the biodiversity of the soil. The return of plant residues to soil benefits soil structure (Martens, 2000), depending on the amount and quality of the residue.

3.4.2 Data analysis

Tab. 3.4.2-1 and Tab. 3.4.2-2: Residue incorporation reduced the runoff generated due to the change of soil roughness and micro-topography compared to the removal of residues, especially at the surface (< 10 cm) and loamy soils.

Tab. 3.4.2-1. Main descriptive statistics for available indicators in incorporation of residues to soil profile compared to residue removal.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	1	3	0.9	0.98	0.94	0.94	0.06	
ry RR	2	7	0.04	1.14	0.53	0.54	0.42	**0.03**
sy RR	1	3	0.29	0.88	0.60	0.62	0.29	

Tab. 3.4.2-2. Results of the analysis of variance of indicators after incorporation of residues into the soil profile compared to residue removal.

BD	**Duration**	**n**	**mean**	**RY**	**Duration**	**n**	**mean**		**SY**	**Duration**	**n**	**mean**
	L				**L**	5	0.46	a		**L**		
	M	2	0.94		**M**					**M**		
	H				**H**	2	0.70	a		**H**	3	0.60
	VH				**VH**					**VH**		
	U				**U**					**U**		
	ENZ	**n**	**mean**		**ENZ**	**n**	**mean**			**ENZ**	**n**	**mean**
	N				**N**					**N**		
	W				**W**	3	0.85	a		**W**	3	0.60
	E				**E**					**E**		
	S	2	0.94		**S**	4	0.29	a		**S**		
	Texture	**n**	**mean**		**Texture**	**n**	**mean**			**Texture**	**n**	**mean**

C		
L	2	0.94
S		
Si		

Depth	**n**	**mean**
T	2	0.94
M		
D		
U		

C	3	0.85	a
L	4	0.29	a
S			
Si			

C	3	0.60
L		
S		
Si		

3.5 Tillage

3.5.1 Results expected from the literature

The baseline for the study was set as the average conditions found in the simplest treatment, Conventional tillage, under its multiple forms found in the literature, from different geographical areas, climates, and agronomic circumstances.

Minimum/reduced tillage in Mediterranean tree crops quickly increased crop yields, especially due to the reduction of root damage by the tillage implements, like disk harrow in the shallow root systems. Nevertheless, agricultural operations like soil preparation, surface compaction under the canopy to collect the falling olive fruits during their harvesting, and the harvest itself induced intense soil compaction with surface crusts. This resulted in short incipient ponding times and low post-ponding water infiltration rates during rain events with increased water and sediment yields (Gómez et al. 2004). In general, they found that the implementation of conservation techniques (conservation tillage /cover crops) on cropland reduced by 20% the exceedance probability of soil losses ranging from 5-12 Mg ha^{-1} yr^{-1}, while no clear differences in the cumulative probability density functions of runoff coefficient could be observed.

Cover crops are known to reduce N leaching and erosion but their establishment is not always easy. The plant species chosen for the cover crop must be able to -reproduce itself using its own seeds for the next agricultural year. The plant must obtain a large ground cover in a short period, before the autumn rains occur. In addition to its residue -once killed in early Spring- it must go on protecting the soil until early summer. Cover crops increase (i) C input to the soil, (ii) CEC, (iii) aggregate stability, and, consequently, water infiltration capacity, reduce soil losses by erosion, and recycle nutrients.

Other conservation techniques such as minimum tillage and/or cover crops are generally less effective in reducing runoff than in reducing soil loss, which might be a major issue in drought-prone regions where envisaged soil conservation techniques should simultaneously enable optimal crop-use of the scarce natural water resources. In addition, the results of Maetens et al. (2012) provide evidence that no tillage and conservation tillage become less effective in reducing runoff with time, while this effect is not observed for soil loss. This could be a result of increasing compaction with time. These results also help to identify possible barriers for adoption of soil conservation techniques by farmers under certain circumstances. For example, although conservation tillage or cover crops are often recommended in olive orchards on a sloping terrain, certain farmers may still feel the need to till the soil to reduce bulk density, improve infiltration, and diminish runoff, in order to enhance crop water-supply.

3.5.2 Data analysis: No Tillage

Tab. 3.5.2-1and Tab. 3.5.2-2: This management practice induces soil consolidation, indicated by the bulk density and penetration resistance ratios. Furthermore, other indicators such as, permeability, runoff and sediment yields are aggravated under this practice due to soil natural compaction. This compaction is not easily alleviated by surface harrowing at a shallow depth. No tillage induces a certain degradation of the top soil structure as has been detected by an increase in bulk density especially at the short term. At the same time, runoff and sediment yield significantly increase at the medium term (5-10 yr) and loamy soils. The only indicator that seems to be improved by this practice is the aggregates stability especially at the short term (< 5 yr) and in sandy soils.

Tab. 3.5.2-1. Main descriptive statistics for indicators in no tillage compared to conventional tillage.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	16	99	0.33	1.39	1.04	1.04	0.14	**0.01**
pr RR	10	240	0.17	9.26	1.54	1.16	1.36	**0.00**
pe RR	4	11	0.01	2.16	0.74	0.66	0.74	0.28
as RR	7	54	0.10	4.59	1.44	1.27	0.88	**0.00**
ry RR	4	27	0.22	5.80	1.90	1.16	1.63	**0.01**
sy RR	4	24	0.10	8.50	1.92	1.00	2.55	0.09

Tab. 3.5.2-2. Results of the analysis of variance of indicators in no tillage compared to conventional tillage.

BD	**Duration**	**n**	**mean**		**PR**	**Duration**	**n**	**mean**		**PE**	**Duration**	**n**	**mean**	
	L	18	1.08	a		**L**	125	1.32	**b**		**L**	2	1.09	a
	M	36	1.04	a		**M**	16	2.18	**a**		**M**	5	0.45	a
	H	29	1.02	a		**H**	99	1.73	**ab**		**H**	4	0.95	a
	VH	9	1.05	a		**VH**					**VH**			
	U	7	1.01	a		**U**					**U**			
	ENZ	**n**	**mean**			**ENZ**	**n**	**mean**			**ENZ**	**n**	**mean**	
	N					**N**					**N**			
	W	34	1.08	a		**W**	4	1.55	a		**W**	4	0.24	a
	E	7	1.03	a		**E**	6	1.70	a		**E**			
	S	58	1.01	a		**S**	230	1.54	a		**S**	7	1.03	a
	Texture	**n**	**mean**			**Texture**	**n**	**mean**			**Texture**	**n**	**mean**	
	C	3	0.97	a		**C**	162	1.45	**b**		**C**			
	L	48	1.05	a		**L**	54	2.08	**a**		**L**	5	1.26	**a**
	S	45	1.04	a		**S**	24	0.98	**b**		**S**	6	0.32	**b**
	Si	3	0.99	a		**Si**					**Si**			
	Depth	**n**	**mean**			**Depth**	**n**	**mean**			**Depth**	**n**	**mean**	
	T	46	1.06	a		**T**	94	1.21	**b**		**T**	3	1.14	a
	M	31	1.01	a		**M**	84	1.58	**ab**		**M**			
	D	14	0.99	a		**D**	62	2.00	**a**		**D**			

U	8	1.10	a

U			

U	8	0.60	a

AS	**Duration**	**n**	**mean**	
	L	30	1.73	**a**
	M	7	1.06	**ab**
	H	11	0.75	**b**
	VH	6	1.72	**ab**
	U			
	ENZ	**n**	**mean**	
	N			
	W	3	1.31	
	E			
	S	51	1.45	
	Texture	**n**	**mean**	
	C			
	L	23	1.04	**b**
	S	31	1.74	**a**
	Si			
	Depth	**n**	**mean**	
	T	34	1.48	a
	M	13	1.24	a
	D			
	U	7	1.62	a

RY	**Duration**	**n**	**mean**	
	L	23	1.41	**b**
	M	4	4.75	**a**
	H			
	VH			
	U			
	ENZ	**n**	**mean**	
	N			
	W			
	E			
	S	27	1.90	
	Texture	**n**	**mean**	
	C	12	1.11	**b**
	L	12	3.03	**a**
	S	3	1.85	**b**
	Si			

SY	**Duration**	**n**	**mean**	
	L	21	1.83	a
	M	3	2.59	a
	H			
	VH			
	U			
	ENZ	**n**	**mean**	
	N			
	W			
	E			
	S	24	1.92	
	Texture	**n**	**mean**	
	C	6	0.38	a
	L	15	2.88	a
	S	3	0.21	a
	Si			

3.5.3 **Data analysis: Minimum Tillage**

Tab. 3.5.3-1 and Tab. 3.5.5-2: Minimum tillage in this study is defined as a light tillage with no inversion of soil profile. The number of plough passes varies from one to three, depending on the rain sequence during the year. It has a beneficial effect on most of the indicators as permeability, aggregate stability, and runoff and sediment yields. Compared to conventional tillage, non-inversion tillage presented higher values of bulk density, especially down to a depth of 10 cm. This negative effect was also observed at the long term (> 20 yr). Penetration resistance increases were mainly observed at the short term, in loamy and sandy soils. Positive effects are higher in loamy soils for the rest of indicators.

Tab. 3.5.3-1. Main descriptive statistics for indicators in minimum tillage compared to conventional tillage.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	30	361	0.72	2.29	1.02	1.01	0.13	**0.00**
pr RR	7	255	0.10	8.80	1.65	1.16	1.47	**0.00**
pe RR	13	68	0.01	7.00	1.23	0.82	1.46	0.19
as RR	11	51	0.04	2.21	1.12	1.09	0.38	**0.02**
ry RR	12	37	0.07	3.10	0.94	0.76	0.07	0.55
sy RR	12	38	0.01	3.67	0.76	0.40	0.84	0.08

Tab. 3.5.3-2. Results of the analysis of variance of indicators in minimum tillage compared to conventional tillage.

BD

Duration	**n**	**mean**	
L	120	1.01	**b**
M	152	1.01	**b**
H	43	1.02	**b**
VH	43	1.11	**a**
U	3	0.97	**b**
ENZ	**n**	**mean**	
N	3	1.04	a
W	234	1.03	a
E	36	1.03	a
S	88	1.01	a
Texture	**n**	**mean**	
C	6	1.03	a
L	298	1.03	a
S	51	1.00	a
Si	6	1.01	a
Depth	**n**	**mean**	
T	125	0.98	**b**
M	149	1.06	**a**
D	84	1.03	**a**
U	3	1.03	**ab**

PR

Duration	**n**	**mean**	
L	110	1.72	a
M	44	1.92	a
H	101	1.47	a
VH			
U			
ENZ	**n**	**mean**	
N			
W	4	1.59	a
E	27	1.36	a
S	224	1.69	a
Texture	**n**	**mean**	
C	85	1.29	**b**
L	129	1.79	**a**
S	41	1.98	**a**
Si			
Depth	**n**	**mean**	
T	61	1.49	a
M	77	1.65	a
D	117	1.74	a
U			

PE

Duration	**n**	**mean**	
L	18	1.46	a
M	29	1.10	a
H	14	0.98	a
VH	7	1.79	a
U			
ENZ	**n**	**mean**	
N			
W	50	1.21	a
E	14	1.40	a
S	4	1.02	a
Texture	**n**	**mean**	
C			
L	60	1.25	a
S	4	0.93	a
Si			
Depth	**n**	**mean**	
T	2	1.95	a
M	11	1.68	a
D	4	2.39	a
U	51	1.02	a

AS

Duration	**n**	**mean**	
L	13	1.31	**a**
M	20	1.18	**ab**
H	18	0.92	**b**
VH			
U			
ENZ	**n**	**mean**	
N			
W	37	1.23	**a**
E			
S	14	0.85	**b**
Texture	**n**	**mean**	
C			
L	47	1.11	a
S	4	1.30	a
Si			
Depth	**n**	**mean**	
T	22	1.05	a
M	5	0.98	a

RY

Duration	**n**	**mean**	
L	25	0.95	a
M	9	0.93	a
H	3	0.85	a
VH			
U			
ENZ	**n**	**mean**	
N			
W	32	0.92	a
E			
S	5	0.57	a
Texture	**n**	**mean**	
C	9	0.67	a
L	28	1.02	a
S			
Si			

SY

Duration	**n**	**mean**	
L	26	0.78	a
M	9	0.75	a
H	3	0.60	a
VH			
U			
ENZ	**n**	**mean**	
N			
W	33	0.86	a
E			
S	5	0.09	a
Texture	**n**	**mean**	
C	10	0.37	a
L	28	0.90	a
S			
Si			

D			
U	24	1.22	a

3.5.4 Data analysis: Cover Crops

Tab. 3.5.4-1and Tab. 3.5.4-2: Although in some cases soil covers induce greater water yields due to soil consolidation, from this study it can be observed that vegetation covers are beneficial for soil because it enhances most of the indicators. Cover crops increase the aggregate stability, reducing resistance to penetration, especially in loamy soils. Runoff yields are lower compared to those under conventional tillage, which is clearer in loamy soils and at the medium term (5-10 yr).. The reduction of sediment yield was more evident in loamy soils and at the medium term (5-10 yr).

Tab. 3.5.4-1. Main descriptive statistics for indicators in cover crops compared to conventional tillage.

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	4	38	0.73	1.17	1.02	1.03	0.10	0.25
pr RR	2	13	0.26	1.31	0.64	0.51	0.35	**0.00**
pe RR	3	10	0.30	3.00	1.74	1.93	1.12	0.06
as RR	3	21	0.67	1.67	1.05	1.07	0.26	0.36
ry RR	7	37	0.00	1.29	0.55	0.50	0.37	**0.00**
sy RR	4	27	0.00	1.08	0.39	0.30	0.33	**0.00**

Tab. 3.5.4-1. Results of the analysis of variance of cover crops compared to conventional tillage.

BD	**Duration**	**n**	**mean**		**PR**	**Duration**	**n**	**mean**		**PE**	**Duration**	**n**	**mean**	
	L	12	1.02	a		**L**	13	0.64			**L**	9	1.64	a
	M	6	1.03	a		**M**					**M**	1	2.63	a
	H	5	1.03	a		**H**					**H**			
	VH	15	1.01	a		**VH**					**VH**			
	U					**U**					**U**			
	ENZ	**n**	**mean**			**ENZ**	**n**	**mean**			**ENZ**	**n**	**mean**	
	N					**N**					**N**			
	W					**W**					**W**			
	E					**E**					**E**			
	S	38	1.02			**S**	13	0.64			**S**	10	1.74	
	Texture	**n**	**mean**			**Texture**	**n**	**mean**			**Texture**	**n**	**mean**	
	C	10	1.00	a		**C**					**C**	7	1.66	a
	L	28	1.02	a		**L**	1	0.26	a		**L**	3	1.94	a
	S					**S**	12	0.67	a		**S**			
	Si					**Si**					**Si**			

Depth	n	mean	
T	28	1.01	a
M	10	1.06	a
D			
U			

Depth	n	mean	
T	13	0.64	
M			
D			
U			

Depth	n	mean	
T	7	1.70	a
M	3	1.85	a
D			
U			

AS

Duration	n	mean	
L	17	1.06	a
M	4	1.02	a
H			
VH			
U			

ENZ	n	mean	
N			
W			
E			
S	21	1.05	

Texture	n	mean	
C	16	1.06	a
L	5	1.04	a
S			
Si			

Depth	n	mean	
T	13	1.03	a
M	8	1.09	a
D			
U			

RY

Duration	n	mean	
L	30	0.58	a
M	5	0.25	a
H	2	0.78	a
VH			
U			

ENZ	n	mean	
N			
W	12	0.59	a
E			
S	25	0.53	a

Texture	n	mean	
C	11	0.67	a
L	24	0.49	a
S	2	0.48	a
Si			

SY

Duration	n	mean	
L	20	0.40	a
M	5	0.27	a
H	2	0.67	a
VH			
U			

ENZ	n	mean	
N			
W	11	0.45	a
E			
S	16	0.36	a

Texture	n	mean	
C	1	0.75	a
L	26	0.38	a
S			
Si			

3.5.5 Data analysis: Deep ploughing

Tab. 3.5.5-1and Tab. 3.5.5-2: Compared to conventional tillage, deep ploughing slightly increased bulk density. The lateral compression of soil by the implement blades could compact the soil leaving macropores and the more dense soil matrix in between. Our results could indicate that bulk density was measured in the compacted soil matrix. Sandy soils and deeper layers (> 30 cm) seem to suffer a higher compaction. Compared to conventional tillage, deep ploughing increased penetration resistance. This indicator is strongly linked to soil depth. For deeper soil layers (> 30 cm) this resistance is higher.

Tab. 3.5.5-1. Main descriptive statistics for indicators in deep ploughing compared to conventional tillage

Ind.	LTEs	n	Min.	Max.	Mean	Median	Stdv	t-test
bd RR	2	41	0.89	1.19	1.01	0.98	0.08	0.61

pr RR	2	47	0.18	8.87	1.57	1.06	1.77	**0.03**
pe RR	1	2	0.69	2.33	1.51	1.51	1.16	
ry RR	1	2	1.31	1.79	1.55	1.55	0.34	
sy RR	1	2	1.29	1.43	1.36	1.36	0.10	

Tab. 3.5.5-2. Results of the analysis of variance of indicators in deep ploughing compared to conventional tillage.

BD

Duration	**n**	**mean**	
L	1	1.01	**ab**
M	20	1.04	**a**
H	20	0.97	**b**
VH			
U			
ENZ	**n**	**mean**	
N			
W	17	1.04	**a**
E			
S	24	0.98	**b**
Texture	**n**	**mean**	
C			
L	25	0.98	**b**
S	16	1.04	**a**
Si			
Depth	**n**	**mean**	
T	15	0.96	**b**
M	16	1.00	**b**
D	10	1.08	**a**
U			

PR

Duration	**n**	**mean**	
L	6	1.04	a
M	6	1.01	a
H	35	1.76	a
VH			
U			
ENZ	**n**	**mean**	
N			
W			
E	6	1.04	a
S	41	1.65	a
Texture	**n**	**mean**	
C	6	1.04	a
L	41	1.65	a
S			
Si			
Depth	**n**	**mean**	
T	14	0.75	**b**
M	16	1.00	**b**
D	17	2.79	**a**
U			

PE

Duration	**n**	**mean**	
L	2	1.51	
M			
H			
VH			
U			
ENZ	**n**	**mean**	
N			
W	2	1.51	
E			
S			
Texture	**n**	**mean**	
C			
L	2	1.51	
S			
Si			
Depth	**n**	**mean**	
T			
M			
D	1	2.33	-
U	1	0.69	-

RY

Duration	**n**	**mean**
L	2	1.55
M		
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	2	1.55
E		
S		
Texture	**n**	**mean**
C		
L	2	1.55
S		
Si		

SY

Duration	**n**	**mean**
L	2	1.36
M		
H		
VH		
U		
ENZ	**n**	**mean**
N		
W	2	1.36
E		
S		
Texture	**n**	**mean**
C		
L	2	1.36
S		
Si		

5

4 Conclusions

The best management practices are those that minimize soil disturbance while at the same time enhancing plant establishment on the soil surface, since the plant is the best soil conservation element.

Table. 4-1 presents the summary of the RR means for the six SPQ indicators in each of the management practices evaluated.

Tab. 4-1. Summary of main effects of practices on SPQ indicators based on the RR. Values in bold are significant at $p < 0.05$. Baseline treatments are in italics. CT: Conventional tillage (plowing), MT: minimum tillage, NT: no-tillage, DP: deep plowing, CC: cover crops without tillage.

MP		BD	PR	PE	AS	RY	SY
Crop system	*Monoculture*	*1.00*			*1.00*		
	Rotation	**1.04**			**0.77**		
Residues management	*Removal*					*1.00*	
	Incorporation					**0.53**	
Weed control	*Chemical*	*1.00*		*1.00*	*1.00*	*1.00*	
	Mechanical	1.01		0.68	1.01	**1.67**	
Fertilization	*Mineral*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
	Organic	**0.96**		**4.53**	2.30		
Tillage	*CT*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
	MT	**1.02**	**1.65**	1.23	**1.12**	0.94	0.76
	NT	**1.04**	**1.54**	0.74	**1.44**	**1.90**	1.92
	DP	1.01	**1.57**				
	CC	1.02	**0.64**	**1.74**	1.05	**0.55**	**0.39**

There is a marked strong difference between agriculture in the different climate zones, especially between the two zones separated by the Alps parallel. This can be appreciated by simply considering the number of papers containing information on SPQ indicators.

The different behavior can be attributed to the effect of the Mediterranean climate with its long, hot, dry summer period. Non-Mediterranean agriculture also has soil physical problems but possibly the main factor responsible for the differences from the Mediterranean agriculture problems is the lower water content in the latter, which implies higher averaged temperatures as well.

Table 4-2. presents the overall qualitative evaluation of SPQ based on the positive, negative, or neutral effects of each MP thought the different indicators assessment.

Tab. 4-2. Overall qualitative assessment of MPs, as compared to reference (reference treatment in italics). CT: Conventional tillage (plowing), MT: minimum tillage, NT: no-tillage, DP: deep plowing, CC: cover crops without tillage.

MP		BD	PR	PE	AS	RY	SY	OVERALL SPQ
Crop system	*Monoculture*							
	Rotation	--			--			0
Residues management	*Removal*							
	Incorporation					++		0
Weed control	*Chemical*							
	Mechanical	-		-	+	--		-
Fertilization	*Mineral*							
	Organic	++		++	+			++
Tillage	*CT*							
	MT	--	--	+	++	+	+	++
	NT	--	--	-	++	--	-	--
	DP	-	--					0
	CC	-	++	++	+	++	++	++

The evaluation was made in the following way:

\+ positive effect

++ positive effect and significant differences ($t < 0.05$)

\- negative effect

-- negative effect and significant differences ($t < 0.05$)

0 + and - are in a balance or the RR = 1 or no data available

An overall evaluation equal to 0 implied a neutral judgment and in some cases, an overall evaluation equal to 0 was assigned when data were lacking.

Considering the trends observed in the Tab. 4-2 one could conclude that the best management practices are:

- Organic fertilization
- Minimum tillage
- Cover crops

Mechanical weed control seems to be a negative practice for soil physical quality mainly because of the compaction produced by machinery. Other management systems are less convenient, according to the table, such as no tillage. Other practices such as crop rotation, residue incorporation to soil profile or deep ploughing have been evaluated as neutral because the dataset available for this analysis did not allow to obtain a clear conclusion about them.

This was due either to the lack of adopted indicators values or to the number and representativeness of records of each indicator.

Our analysis of no-tillage data covers both herbaceous and permanent crops. Although this distinction was not made in our presentation of outcomes in this report, we wish to clarify that for Mediterranean conditions a clear difference exists between the soil responses (to no-tillage) for the two crop types. Whereas the compaction effects of farm operations cannot be alleviated in permanent crops, the mechanical operations under herbaceous crops are less aggressive to soil structure. This means that direct drilling (the common name for no-till in herbaceous cropping systems) is more beneficial than conventional tillage for physical soil quality standards. The main advantages of direct drilling to preserve soil quality are: (i) the maintenance of the stubble during the summer and early autumn keeps the large surface cracks open improving the water infiltration into the soil of the first rain events, as well as it reduces soil losses due to water erosion in the same period; (ii) the stubble cover attenuates the water losses by direct evaporation from the soil until the crop canopy covers the surface; (iii) during this period soil biodiversity is conserved; (iv) the production cost under direct drilling is usually lower than in conventional tillage (Lyon and Farrow, 1995); (v) the crop productivity is not lower than under conventional tillage, and in dry years (annual rainfall below 400 mm) yield is usually greater than under conventional tillage. This result was also found by Pittelkow et al. (2015), under the heading of dry conditions, corresponding to a high aridity index (average annual potential evaporation-precipitation ratio).

In contrast, in permanent (tree) crops, the compaction of soil under no-tillage enhances runoff and erosion, especially during years with frequent rain events. Therefore, the use of cover plants (cover crops, weeds) between the trees is the best management practice to protect the soil and, consequently, water. Occasional tillage to alleviate compaction could be a beneficial complement for this combined practice (no-till with cover crops).

One alternative management practice could be the adoption of vegetation filters downstream to retain soil, sediment and chemicals, and vegetation barriers as wind breaks to mitigate the evaporation enhancement of the gusts of hot winds. In this way, biodiversity could be encouraged.

Is it important to notice that given the multiple factors on which soil quality is based and the variability in space and time of the environmental agronomic factors, these results must be taken within the context of the available information explored here, and are limited to soil physical properties only.

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6 Glossary

General:

BMP: best management practice
LTE: long term experiment
RR: response ratio
SPQ: soil physical quality

Indicators:

bulk density (bd)
permeability (pe)
penetration resistance (pr)
aggregates stability (as)
runoff yield (ry)
sediment yield (sy)

Management practices:

crop rotation (CR)
mechanical control of weeds (MCW)
residue incorporation (IR)
organic fertilization (OF)
minimum tillage (MT)
cover crops (CC)
deep ploughing (DP)

Variables:

Climate: northern (N), western (W), eastern (E), southern (S)
Soil textural class: clay (C), silt (Si), loam (L), sand (S), unknown (U)
Depth: top (T), medium (M), deep (D), unknown (U)
Duration: low (L), medium (M), high (H), very high (V), unknown (U)
Soil textural class: clay (C), silt (I), loam (L), sand (A),