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INVITED ORIGINAL RESEARCH PAPER

Long-term effects of soil management practices on selected indicators of chemical soil quality

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Abstract

The study was conducted in scope of Catch-C project "Compatibility of agricultural management practices and types of farming in the EU to enhance climate change mitigation and soil health" (7FP), realized in 2012–2014 by the consortium of partners from 10 European countries (http://www.catch-c.eu). This work reports the effects of soil management practices – under different soil and climatic conditions – on the selected soil chemical quality indicators, based on the analysis of data extracted from literature on long term experiments (LTEs) in Europe, as well as from LTEs held by the Catch-C consortium partners. The dataset related to soil chemical quality indicators consisted of 1044 records and referred to 59 long-term trials. The following indicators of chemical soil quality were analyzed: pH, N total content, N total stock, C:N ratio, N mineral content, P and K availability. They are the most frequently used indicators in the European literature on long-term experiments collected in the Catch-C project database. Soil organic carbon, however, the most important indicator was not presented here, due to it was covered by a separate study on indicators for climate change mitigation. The indicators were analyzed using their response ratio (RR) to a management practice. For a given treatment (management practice), this ratio was calculated as the quotient between the indicator value obtained in the treatment, and the indicator value in the reference treatment. The examples were: rotation (with cereals, with legume crops, with tuber or root crops, with grassland) vs. adequate monoculture, catch/cover crops vs. no catch/cover crops, no-tillage and no-inversion tillage vs. conventional tillage, mineral fertilization vs. no fertilization, organic fertilization (compost, farmyard manure, slurry) vs. mineral fertilization at the same available nitrogen input, crop residue incorporation vs. removal. All tested practices influenced soil chemical quality indicators. Both positive and negative effects were observed. When the RR values of seven soil chemical quality indicators were considered in an overall evaluation – based on their significance level, the number of indicators positively affected, and the size of the effects – the best practices among those tested were: farmyard manure application, no-inversion tillage, compost application, mineral fertilization, and no-tillage.

Keywords

soil management practices; chemical soil quality; long-term experiments; meta-analysis

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 rates of fertilization were used to increase crop production.

A major challenge for agriculture now is to ensure security of food. Increasing production, possible due to intensive tillage or the use of high doses of mineral fertilizers, can lead to adverse ecological effects, including disorders of the basic functions of the soil. According to the idea of sustainable agriculture, efficient production of safe and high quality food should be accompanied by special care of the environment. Therefore, the best agronomic practices, which, on one hand, allow efficient use of natural resources, and on the other, contribute to maintaining or even improving soil fertility are still sought. A reduction of tillage intensity, the adoption of green manuring, crop residue incorporation and the substitution of mineral with organic fertilizers are among the most used farm management practices to maintain soil quality.

Reduced tillage techniques, aim to minimize soil inversion and soil structure disruption, and to increase soil organic matter (SOM) content by reducing the decomposition of residues and organic matter processes [1–3]. While the efficiency of soil organic carbon (SOC) sequestration is still studied [4,5], the benefits from fossil fuel savings are undoubted. Leguminous green manure, crop residue incorporation and organic fertilizers from animal wastes are known to represent viable options to substitute mineral N fertilizer [6,7]. 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 to the subsequent crop at low energy cost [8,9]. Organic fertilization has not only a low groundwater N pollution risk [10], if applied at a rate that meets crop needs but also great potential for nutritive element recycling [11] and soil C sequestering and protection [12,13].

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 [14] stated that long-term or continuing experiments are the best practical way of assessing the sustainability of an agricultural system. However, it should be recognized 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.

Catch-C ("Compatibility of agricultural management practices and types of farming in the EU to enhance climate change mitigation and soil health") project was conducted 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 in improving chemical, physical and biological crop quality. In this paper we analyze the effects of soil management practices on selected soil chemical quality indicators.

Material and methods

The study was conducted by an extensive meta-analysis of data extracted from literature on long term experiments (LTEs) in Europe, as well as from LTEs held by the Catch-C consortium partners from 10 European countries. The set relevant to document soil management effects on chemical soil quality indicators consisted of 1044 records referred to 59 long-term trials [15]. The indicators studied were pH, N total content (N_t) and N stock (N_{tS}), C:N ratio, N mineral content (N_{min}), K available (K_{avail}) content, P available (P_{avail}) content. Soil organic carbon, however, the most important indicator, is not presented here, due to it was covered by a separate study on indicators for climate change mitigation [16].

The management practices analyzed in this work considered: crop rotation, catch/cover crops (either harvested or incorporated into the soil as green manure), no-tillage and no-inversion tillage, mineral and organic fertilization with compost, farmyard manure, or slurry, and incorporation of crop residue into the soil.

The effect of a practice on a given indicator was expressed as the response ratio (RR). For a given treatment (management practice), this ratio was calculated as the quotient between the indicator value obtained in the treatment, and the indicator value in the reference treatment. The examples were: rotation (with cereals, with legume crops, with tuber or root crops, with grassland) vs. adequate monoculture, catch/cover crops vs. no catch/cover, no-tillage and no-inversion tillage vs. conventional tillage, mineral fertilization vs. no fertilization, organic fertilization (compost, farmyard manure, slurry) vs. mineral fertilization at the same available nitrogen input, crop residue incorporation vs. removal. The comparisons were made by ensuring that all factors different than the other one tested were equal in the two treatments under comparison (e.g., two tillage treatments were compared within the same rotation). The response ratio RR was greater than 1 when the studied management practice increased the value of the indicator in comparison to the reference treatment. In this paper we will refer to the RR value of indicator x as RR(x).

All statistical analyses were performed with the help of the package Statgraphics Centurion v. XVI. RR frequency distributions were tested for normality and their descriptive statistics were calculated. A one-sample Student t-test (2-tails) was used to identify which RR means were significantly different from 1 ($p < 0.05$). Next, a multiple linear model with climate, soil type, sampling depth and duration of practice as a single nominal factor (without interactions) was used to evaluate if any of these factors affected the relative RR to a given management practice, and by how much. For this purpose, climate, soil texture and duration of practice were divided into four classes ("levels") each, while three different depths of soil sampling were considered (Tab. 1, Fig. 1). A type III Wald statistics for maximum likelihood estimate of regression was chosen. Then, a t-test was used to separate means of single factors different at $p < 0.05$ [15].

Results

All practices tested influenced soil chemical quality indicators. The statistical characteristics for the response of indicators (in terms of RRs) to management practices studied are presented in Tab. 2. Both positive and negative effects were observed. A summary of the results is given in Tab. 3 and their graphical interpretation is presented in Fig. 2.

Tab. 1 Levels of the four factors considered in the linear multiple regression.

Climatic zone	**Northern** Alpine North, Boreal, Nemoral	**Western** Atlantic North, Atlantic South, Atlantic Central, Lusitanian	**Eastern** Continental, Pannonian	**Southern** Anatolian, Mediterranean Mountains, Mediterranean North, Mediterranean South
Soil texture	**Clay** clay, silty clay	**Loamy** loam, clay loam, sandy clay loam, silty clay loam	**Sandy** sand, loamy sand, sandy loam	**Silty** silt, silty loam
Sampling depth	**Low** <10 cm	**Medium** 10–30 cm	**High** >30 cm	
Duration of practice	**Low** < 5 years	**Medium** 5–10 years	**High** 11–20 years	**Very high** > 20 years

Climate zones from Metzger et al. [51], modified.

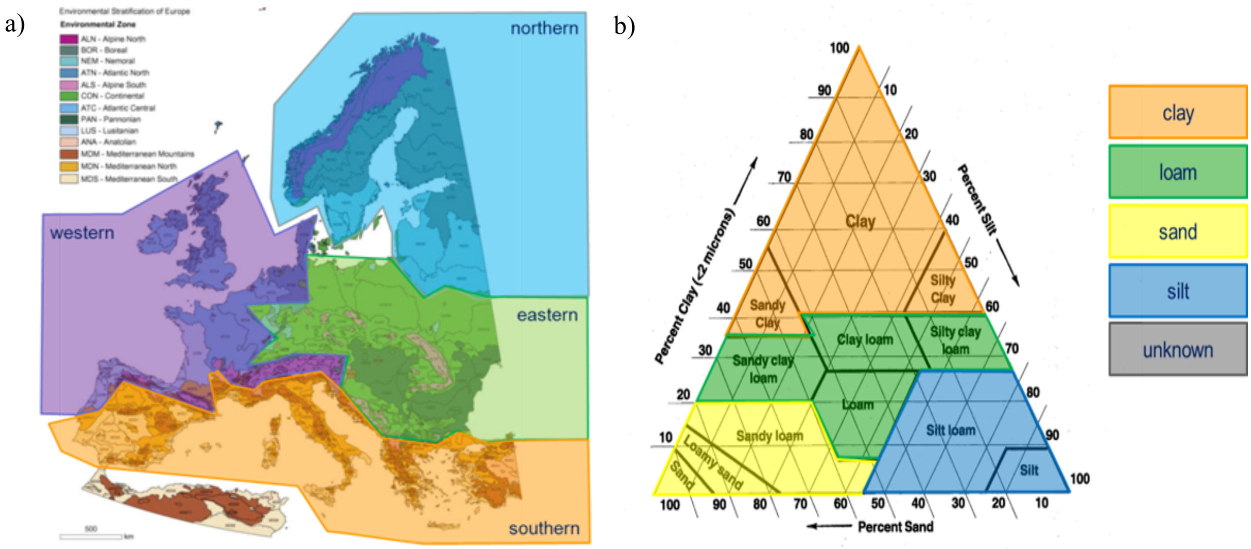

Fig. 1 Levels of the two factors considered in the linear multiple regression. **a** Climate (acronyms as in Tab. 1), from Metzger et al. [51], modified. **b** Soil texture classes.

Tab. 2 Main descriptive statistics for the response ratio (RR) of indicators to management practices.

Indicator	Count	Mean	*SD*	Min	Max	Skewness	Kurtosis	Smirnov test	*t*-test
The response to crop rotation									
RR(pH)	6	0.99	0.03	0.95	1.02	0.517	0.146	0.18	0.252
RR(N_t)	24	1.04	0.14	0.75	1.33	−0.43	0.44	0.86	0.217
RR(C:N)	6	0.96	0.033	0.91	0.99	−1.05	−0.57	0.831	0.046
RR(K_{avail})	3	0.76	0.012	0.74	0.78	−1.66	-	-	0.002
RR(P_{avail})	6	0.95	0.08	0.88	1.06	0.85	−1.73	0.292	0.216
The response to catch and cover crops (harvested)									
RR(pH)	2	0.99	0.01	0.98	0.99	-	-	-	0.295
RR(N_t)	2	0.98	0.02	0.96	0.99	-	-	-	0.330
RR(C:N)	2	0.99	0.01	0.99	1.00	-	-	-	0.293
RR(N_{tS})	8	1.04	0.04	0.99	1.11	0.22	0.04	-	0.02
RR(K_{avail})	2	0.81	0.07	0.77	0.86	-	-	-	0.155
The response to no-tillage									
RR(pH)	10	1.00	0.016	0.97	1.02	−0.19	0.31	0.139	0.526
RR(N_t)	8	1.02	0.11	0.82	1.19	−0.42	0.28	0.178	0.674
RR(N_{tS})	25	0.94	0.24	0.56	1.62	0.79	1.19	0.115	0.207
RR(C:N)	13	0.94	0.14	0.70	1.17	−0.24	−0.55	0.158	0.145
RR(N_{min})	7	1.15	0,24	0,98	1,63	1.62	1.99	0.294	0.071
RR(K_{avail})	5	0.97	0.28	0.65	1.32	−0.06	−1.99	0.252	0.826
RR(P_{avail})	30	1.30	0.40	0.64	2.20	0.88	0.11	0.178	0.000
The response to non-inversion tillage									

Tab. 2 Continued

Indicator	Count	Mean	*SD*	Min	Max	Skewness	Kurtosis	Smirnov test	*t*-test
RR(pH)	26	1.00	0.01	0.99	1.01	−0.02	−0.85	0.124	0.998
RR(N_t)	29	1.07	0.08	0.90	1.22	0.14	−0.38	0.106	0.000
RR(N_{tS})	41	1.11	0.31	0.58	1.80	0.56	−0.62	0.176	0.024
RR(C:N)	31	0.97	0.09	0.83	1.21	0.08	0.07	0.145	0.126
RR(N_{min})	1	0.87	-	0.87	0.87	-	-	-	-
RR(K_{avail})	26	1.46	0.30	1.04	2.21	0.73	0.07	0.116	0.000
RR(P_{avail})	71	1.10	0.29	0.27	1.79	0.44	0.94	0.129	0.005
The response to mineral fertilization									
RR(pH)	15	1.00	0.002	1.00	1.004	0.13	−1.35	0.613	0.171
RR(N_t)	49	1.02	0.04	0.92	1.13	−0.23	−0.22	0.572	0.002
RR(C:N)	9	0.97	0.11	0.81	1.17	0.09	−0.68	0.997	0.512
RR(N_{min})	30	1.60	0.55	0.74	2.83	0.71	−0.29	0.709	0.000
RR(K_{avail})	26	2.33	0.49	1.18	3.28	−0.15	0.22	0.919	0.000
RR(P_{avail})	37	2.64	1.01	1.35	4.85	1.08	0.19	0.116	0.000
The response to fertilization with compost									
RR(pH)	6	1.07	0.03	1.03	1.11	−0.12	−1.36	0.996	0.003
RR(N_t)	13	1.14	0.04	1.09	1.23	1.04	0.42	0.241	0.000
RR(C:N)	11	1.03	0.06	0.96	1.12	0.65	−1.12	0.760	0.106
RR(N_{min})	9	1.09	0.13	0.86	1.29	−0.39	0.04	0.994	0.065
RR(K_{avail})	4	1.04	0.05	0.98	1.10	−0.57	−0.26	0.999	0.199
The response to farmyard manure application									
RR(pH)	4	1.01	0.04	0.96	1.05	−0.81	−1.03	0.975	0.524
RR(N_t)	11	1.10	0.10	0.92	1.28	0.29	0.85	0.838	0.008
RR(C:N)	10	1.12	0.15	0.99	1.44	1.57	1.64	0.434	0.033
RR(N_{min})	3	1.48	0.11	1.41	1.61	1.67	-	-	0.017
RR(K_{avail})	1	1.28	-	1.28	1.28	-	-	-	-
The response to slurry application									
RR(pH)	1	1.05	-	1.05	1.05	-	-	-	-
RR(N_t)	4	1.13	0.06	1.09	1.21	1.14	0.16	0.927	0.017
RR(C:N)	3	1.01	0.03	0.98	1.04	−1.24	-	0.966	0.441
RR(N_{min})	3	1.25	0.05	1.19	1.29	−1.61		0.880	0.014
RR(K_{avail})	1	1.30	-	1.30	1.30	-	-	-	-
The response to residue incorporation									
RR(pH)	1	0.96		0.96	0.96	-	-	-	-
RR(N_t)	26	1.02	0.04	0.92	1.09	−0.79	0.77	0.170	0.029

Tab. 2 Continued

Indicator	Count	Mean	*SD*	Min	Max	Skewness	Kurtosis	Smirnov test	*t*-test
RR(C:N)	8	1.07	0.096	0.91	1.19	−0.38	−0.45	0.197	0.066
RR(P_{avail})	1	1.0	-	-	-	-	-	-	-

Tab. 3 Summary of main effects (RRs) of management practices on soil chemical quality indicators.

	pH	N_t	N_{tS}	C:N ratio	N_{min}	K_{avail}	P_{avail}
Monoculture (reference treatment)	1	1	1	1	1	1	1
Crop rotation	0.99	1.04	n.d.	0.96**	n.d.	0.76***	0.95
No catch/cover crops (reference treatment)	1	1	1	1	1	1	1
Catch crop / cover crops (harvested)	0.99	0.98	1.04**	0.99	n.d.	0.81	n.d.
Conventional tillage (reference treatment)	1	1	1	1	1	1	1
No-tillage	1.00	1.02	0.94	0.94	1.15*	0.97	1.30***
No-inversion tillage	1.00	1.07***	1.11**	0.97	0.87	1.46***	1.10***
No fertilizer (reference treatment)	1	1	1	1	1	1	1
Mineral fertilizer	1.00	1.02***	n.d.	0.77	1.60***	2.33***	2.64***
Mineral fertilizer (reference treatment)	1	1	1	1	1	1	1
Compost	1.07***	1.14***	n.d.	1.03	1.09*	1.04	n.d.
Farmyard manure	1.01	1.10***	n.d.	1.12**	1.48***	1.28	n.d.
Slurry	n.d.	1.13***	n.d.	1.01	1.25***	n.d.	n.d.
Residue removal (reference)	1	1	1	1	1	1	1
Residue incorporation	n.d.	1.02**	n.d.	1.07*	n.d.	n.d.	n.d.

n.d. – not enough data for statistical analysis. * $0.05 \le p < 0.1$. ** $0.02 \le p < 0.05$. *** $p < 0.02$.

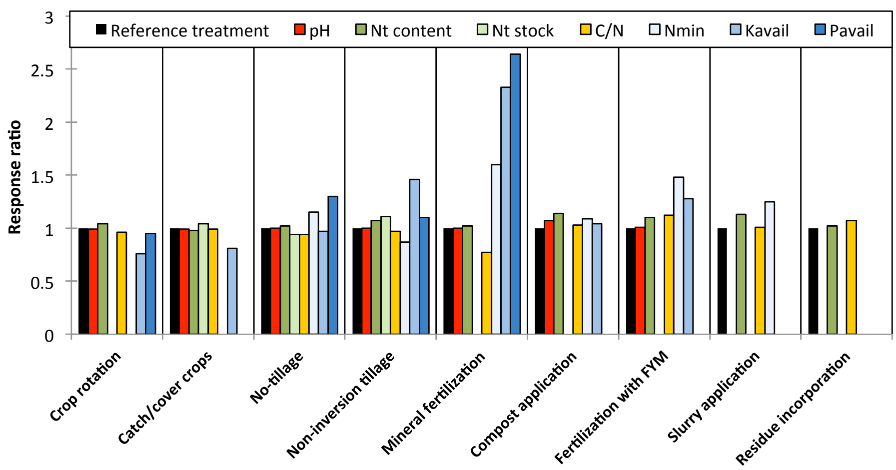

Fig. 2 Impacts of soil management practices on chemical soil quality indicators.

The effects are expressed as the mean RR of the respective soil quality indicators. An RR value of 1 means that on average there was no response of the indicator to the management practice. The highest values of N_{min}, K_{avail}, and P_{avail} RRs indicate the strongest response to mineral fertilization. Besides increase of available forms of nutrients, fertilization with famyard manure (FYM), non-inversion tillage, compost and slurry application, and crop rotation were effective for total N indicators. Compost was the only practice which significantly improved soil pH. It was effective also for N_t. Fertilization with FYM and residue incorporation increased C:N ratio.

Considering the means of all seven soil chemical quality indicators included in the analysis, based on (***i***) significance level of RRs, (***ii***) the number of indicators positively affected, and (***iii***) the size of the effects, the best practices among those tested were as follows:

- farmyard manure application,
- non-inversion tillage,
- compost application,
- mineral fertilization, and
- no-tillage.

FYM significantly increased N_t, content of available (mineral) nitrogen, and the C:N ratio (promoting accumulation of carbon over nitrogen; Tab. 2, Tab. 3). Available potassium was strongly increased, too, but this referred to one case only (hence insignificant in the meta-analysis). The response of pH to FYM was similar to the reference rate of mineral fertilization, but slightly higher RR values were found as the duration of this practice increased (Tab. 4). The increase of N_t was greater in western climatic zones (compared to northern and eastern), and on loamy (compared to clay) soils. Surprisingly, the N_t response was larger in three cases of short duration (<20 years) than in cases of >20 years duration. This can hardly be generally valid, and may be due to the unbalanced nature of the data set. It shows, however, that positive responses to FYM can be found within relatively short time frame (obviously depending on application rates, too). All data on C:N ratio referred to western and eastern climate zones, and clay and loam texture classes. While none of the covariate factors (except sampling depth) affected RR(C:N ratio) significantly, larger RR values (1.21) were found in the western than in the eastern zone (1.05), and larger values (1.16) on loam than on clay (1.02). Higher RR values were found for shallow soil layers, and longer duration (>10 years) of FYM application. A high response ratio of N_{min} was noted, but this referred to three cases only. Nevertheless, it shows that FYM can substantially contribute to accumulation of N_{min}, and therefore also to nitrate leaching losses. Effects of covariate factors on RR (N_{min}) could not be assessed as all data referred to only one class of each factor.

Non-inversion tillage compared to conventional ploughing positively influenced N total content and stock and content of available forms of K and P, all significantly (Tab. 2, Tab. 3, Tab. 5). The results are based on a considerable number of data. Responses of K_{avail} refer to only the eastern climatic zone, loamy soil, and the 10–30 cm layer of soil depth. For N_t stock and K_{avail}, highest increases were found after long (>20 and >10 years, respectively) of non-inversion tillage application. Available phosphorus was differentiated only by climatic zones, responses being stronger in the western than in the eastern zone. Effects of non-inversion tillage on this parameter were already found within 5 years.

Application of compost (relative to mineral fertilizer at the same plant available nutrient levels) significantly increased soil pH, N_t, N_{min}, and showed a tendency (not significant) to increase C:N ratio and K_{avail} (Tab. 2, Tab. 3, Tab. 6). Longer time (5–10 years) of compost application promoted the pH increase more than short time (<5 years). The positive responses of N_t and C:N ratio were not different between western and eastern climatic zones, nor between clay and loamy soils. These two parameters showed no significant effects of duration, though for C:N ratio there was a tendency of stronger responses at longer duration (>10 years). The positive effect of compost on N_{min} and K_{avail} was found in western countries, in deep (>30 cm; 10–30 cm for K_{avail}) soil layer of loamy soils and after short (<5 years) of the compost application. For all indicators it must be noted that their response to compost application will be largely determined by the composition of the compost itself.

Tab. 4 Results of the linear multiple regression for the response of chemical soil quality indicators to farmyard manure application.

Climatic zone	n	mean	Soil texture	n	mean	Sampling depth (cm)	n	mean	Duration of practice (years)	n	mean
RR of pH											
Northern	-	-	clay	-	-	<10	-	-	<5	3	1.05 b*
Western	6	1.07	loam	6	1.07	10–30	6	1.07	5–10	3	1.10 a
Eastern	-	-	sand	-	-	>30	-	-	11–20	-	-
Southern	-	-	silt	-	-	-	-	-	>20	-	-
RR of N_t content											
Northern	4	1.08 b	clay	3	1.00 b	<10	-	-	<5	2	1.26 a
Western	4	1.20 a	loam	8	1.14 a	10–30	11	1.10	5–10	-	-
Eastern	3	1.00 b	sand	-	-	>30	-	-	11–20	1	1.15 ab
Southern	-	-	silt	-	-	-	-	-	>20	8	1.05 b
RR of C:N ratio											
Northern			clay	3	1.02 a	<10	2	1.37 a	<5	1	1.02 a
Western	4	1.21 a	loam	7	1.16 a	10–30	8	1.05 b	5–10	2	1.06 a
Eastern	6	1.05 a	sand	-	-	>30	-	-	11–20	1	1.16 a
Southern	-	-	silt	-	-	-	-	-	>20	6	1.15 a
RR of N_{min}											
Northern	-	-	clay	-	-	<10	-	-	<5	3	1.48
Western	3	1.48	loam	3	1.48	10–30	-	-	5–10	-	-
Eastern	-	-	sand	-	-	>30	3	1.48	11–20	-	-
Southern	-	-	silt	-	-	-	-	-	>20	-	-

* Values marked with the same letter are not significantly different.

Mineral fertilizers (relative to no mineral fertilizer) were effective especially in increasing available phosphorus (P_{avail}), potassium (K_{avail}), and nitrogen (N_{min}), and also total N (N_t) content (Tab. 2, Tab. 3, Tab. 7). The overall increase (by 164%) of P_{avail} due to the application of P fertilizers was based on 37 cases, the increase (by 133%) of K_{avail} due to the application of K fertilizers was based on 26 cases and the increase (by 60%) of N_{min} due to the application of N fertilizers was based on 30 cases. All phosphorus data and virtually all potassium data refer to the eastern climatic zone, soil layer of 10–30 cm, loamy soil, and long-term duration (>20 years) of fertilizer application. A less pronounced response of available potassium was found in two short run (<5 years) cases, which refer to the western zone. The same pattern is seen for mineral nitrogen contents: stronger mean response for the larger data set that pertains to the eastern zone, 10–30 cm depth, and long duration (11–20 years) than for the LTEs that pertain to the western zone and to short duration (<5 years). The response of N_t to application of mineral fertilizers was very small but statistically significant.

No-tillage (relative to conventional ploughing) was ranked lower because it affected significantly only available phosphorus and N_{min} contents (Tab. 2, Tab. 3, Tab. 8). No-tillage did not clearly enhance any of the total N indicators. There were tendencies (n.s.) for no tillage to increase N_t and to decrease N_{tS} and C:N ratio. The (positive)

Tab. 5 Results of the linear multiple regression for the response of chemical soil quality indicators to non-inversion tillage.

Climatic zone	*n*	mean	Soil texture	*n*	mean	Sampling depth (cm)	*n*	mean	Duration of practice (years)	*n*	mean
RR of N_t content											
Northern	-	-	clay	3	1.15 a	<10	3	1.14 a	<5	4	1.05 a
Western	4	1.05 a*	loam	26	1.06 a	10–30	23	1.05 b	5–10	6	1.05 a
Eastern	22	1.06 a	sand	-	-	>30	3	1.15 a	11–20	19	1.07 a
Southern	3	1.15 a	silt	-	-	-	-	-	>20	-	-
RR of N_{tS}											
Northern	-	-	clay	-	-	<10	16	1.23 a	<5	-	-
Western	5	1.04 a	loam	41	1.11	10–30	25	1.04 b	5–10	-	-
Eastern	-	-	sand	-	-	>30	-	-	11–20	14	1.02 a
Southern	36	1.12 a	silt	-	-	-	-	-	>20	27	1.16 a
RR of K_{avail}											
Northern	-	-	clay	-	-	<10	1	1.29 a	<5	4	1.14 b
Western	2	1.17 a	loam	26	2.33	10–30	25	1.47 a	5–10	2	1.15 b
Eastern	24	1.49 a	sand	-	-	>30	-	-	11–20	20	1.46 a
Southern	-	-	silt	-	-	-	-	-	>20	-	-
RR of P_{avail}											
Northern	-	-	clay	4	1.25 a	<10	22	1.13 a	<5	16	1.07 a
Western	17	1.26 a	loam	45	1.07 a	10–30	43	1.06 a	5–10	15	1.01 a
Eastern	49	1.04 b	sand	4	1.00 a	>30	6	1.27 a	11–20	39	1.09 a
Southern	5	1.12 ab	silt	18	1.16 a	-	-	-	>20	1	1.10 a

* Values marked with the same letter are not significantly different.

response of P_{avail} was clear and based on a reasonable number of data. It was most pronounced in the southern zone, but also clear in the northern zone, and only weak in the eastern zone. It was expressed more on sandy soils than loamy soils, and least on silty soil (few data and no effect on silty soils). Effects were stronger in the shallow layer (<10 cm) than in the 10–30 cm layer. Responses of P_{avail} in short duration cases (<5 years) were similar to those in long-term cases (11–20 and >20 years). All N_{min} data referred to the southern zone, sandy soil, and long duration (>20 years) of the no-tillage practice. The observation that no tillage gave only a weak (an slightly negative) response of K_{avail}, while the response to non-inversion tillage was strong (and positive), is confusing. It must be noted, however, that all (5) no tillage results (for K_{avail}) refer to the southern climate zone, whereas the effects of non-inversion tillage on K_{avail} (26, mostly from one experiment) refer to the eastern climate zone. It remains difficult to judge these two practices against one another, with respect to their impact on K_{avail}.

Slurry application (relative to mineral fertilizer) increased only N_t and N_{min} significantly (Tab. 2, Tab. 3). The other indicators: RR(pH), RR(C:N ratio), RR(K_{avail}) were represented by small number of cases. Effects of covariate factors could not be assessed here.

Tab. 6 Results of the linear multiple regression for the response of chemical soil quality indicators to fertilization with compost.

Climatic zone	*n*	mean	Soil texture	*n*	mean	Sampling depth (cm)	*n*	mean	Duration of practice (years)	*n*	mean
RR of pH											
Northern	-	-	clay	-	-	<10	-	-	<5	3	1.05 b*
Western	6	1.07	loam	6	1.07	10–30	6	1.07	5–10	3	1.10 a
Eastern	-	-	sand	-	-	>30	-	-	11–20	-	-
Southern	-	-	silt	-	-	-	-	-	>20	-	-
RR of N_t content											
Northern	-	-	clay	6	1.16 a	<10	-	-	<5	3	1.17 a
Western	7	1.13 a	loam	7	1.13 a	10–30	13	1.15	5–10	3	1.11 a
Eastern	6	1.16 a	sand	-	-	>30	-	-	11–20	6	1.16 a
Southern	-	-	silt	-	-	-	-	-	>20	1	1.15 a
RR of N_{min}											
Northern	-	-	clay	-	-	<10	-	-	<5	9	1.09
Western	9	1.09	loam	9	1.09	10–30	-	-	5–10	-	-
Eastern	-	-	sand	-	-	>30	9	1.09	11–20	-	-
Southern	-	-	silt	-	-	-	-	-	>20	-	-
RR of C:N ratio											
Northern	-	-	clay	3	1.07 a	<10	-	-	<5	3	1.00 a
Western	4	1.03 a	loam	8	1.02 a	10–30	11	1.03	5–10	4	1.00 a
Eastern	7	1.03 a	sand	-	-	>30	-	-	11–20	3	1.07 a
Southern	-	-	silt	-	-	-	-	-	>20	1	1.12 a
RR of K_{avail}											
Northern	-	-	clay	-	-	<10	-	-	<5	4	1.04
Western	4	1.04	loam	4	1.04	10–30	4	1.04	5–10	-	-
Eastern	-	-	sand	-	-	>30	-	-	11–20	-	-
Southern	-	-	silt	-	-	--	-	-	>20	-	-

* Values marked with the same letter are not significantly different.

Incorporation of crop residues (versus removal) raised both N_t and C:N ratio by small, yet significant amounts (Tab. 2, Tab. 3, Tab. 9). The strongest response for N_t (RR = 1.08) was found in the southern climatic zone, but was based on two cases only, and on both clay and loamy soils. Overall, mean positive effects of incorporation on N_t were only found at sites running for more than 10 years. For C:N ratio, data were too few to assess effects of covariate factors. There was a tendency, however, for stronger increases in cases with 11–20 years duration than in cases with <5 years duration.

Crop rotation tended to increase (not significantly) N_t, but negatively affected both available potassium and C:N ratio indicators (Tab. 2, Tab. 3). In general, evaluation

Tab. 7 Results of the linear multiple regression for the response of chemical soil quality indicators to mineral fertilizer application.

Climatic zone			Soil texture			Sampling depth (cm)			Duration of practice (years)		
	n	mean		*n*	mean		*n*	mean		*n*	mean
RR of N_t content											
Northern	26	1.01 b*	clay	5	0.998 a	<10	-	-	<5	5	1.06 a
Western	5	1.06 a	loam	44	1.027 a	10–30	48	1.03 a	5–10	-	-
Eastern	18	1.03 ab	sand	-	-	>30	1	0.95 a	11–20	27	1.03 ab
Southern	-	-	silt	-	-	-	-	-	>20	17	1.01 b
RR of N_{min}											
Northern	-	-	clay	-	-	<10	-	-	<5	6	1.08 b
Western	6	1.08 b	loam	30	1.60	10–30	24	1.73 a	5–10	-	-
Eastern	24	1.73 a	sand	-	-	>30	6	1.08 b	11–20	24	1.73 a
Southern	-	-	silt	-	-	-	-	-	>20	-	-
RR of K_{avail}											
Northern	-	-	clay	-	-	<10	-	-	<5	2	1.40 b
Western	2	1.40 b	loam	26	2.33	10–30	26	2.33	5–10	-	-
Eastern	24	2.41 a	sand	-	-	>30	-	-	11–20	24	2.41 a
Southern			silt	-	-	-	-	-	>20	-	-
RR of P_{avail}											
Northern	-	-	clay	-	-	<10	-	-	<5	-	-
Western	-	-	loam	37	2.64	10–30	37	2.64	5–10	-	-
Eastern	37	2.64	sand	-	-	>30	-	-	11–20	-	-
Southern	-	-	silt	-	-	--	-	-	>20	37	2.64

* Values marked with the same letter are not significantly different.

of rotation effects on soil fertility should take into account nutrient balances (input minus offtake), which was not possible in this study.

The indicators influenced by catch and cover crops, except N_{tS}, were represented by too few data to be considered in the statistical analysis (Tab. 2). However, it was found, that the effect of catch and cover crops was significantly affected by the duration of practice. The longer time of the practice significantly increased N_{tS} comparing short time.

When the number of soil management practices was considered and the magnitude of their effect ignored, the most responsive chemical soil quality indicators were: N_t, N_{min}, P and K availability, and C:N ratio.

Discussion

The meta-analysis based on European long-term experiments data extracted from scientific publications generally confirmed the earlier results. All tested practices influenced soil chemical quality indicators. When the means of seven studied soil chemical

Tab. 8 Results of the linear multiple regression for the response of chemical soil quality indicators to no-tillage.

Climatic zone	*n*	mean	Soil texture	*n*	mean	Sampling depth (cm)	*n*	mean	Duration of practice (years)	*n*	mean
RR of N_t content											
Northern	-	-	clay	2	1.02 a	<10	1	1.19 a	<5	-	-
Western	-	-	loam	2	1.00 a	10–30	3	0.98 a	5–10	2	1.00 a
Eastern	2	1.00 a*	sand	4	1.02 a	>30	4	1.00 a	11–20	2	1.02 a
Southern	6	1.02 a	silt	-	-	-	-	-	>20	4	1.02 a
RR of N_t stock											
Northern	-	-	clay	2	1.06 a	<10	6	0.89 a	<5	1	0.96 ab
Western	5	0.99 a	loam	23	0.93 a	10–30	19	0.95 a	5–10	-	-
Eastern	-	-	sand	-	-	>30	-	-	11–20	10	1.12 a
Southern	20	0.93 a	silt	-	-	-	-	-	>20	14	0.81 b
RR of C:N ratio											
Northern	-	-	clay	-	-	<10	8	0.95 a	<5	4	1.02 a
Western	-	-	loam	13	0.94	10–30	5	0.92 a	5–10	4	0.91 a
Eastern	6	1.01 a	sand	-	-	>30	-	-	11–20	-	-
Southern	7	0.89 a	silt	-	-	-	-	-	>20	5	0.91 a
RR of N_{min}											
Northern	-	-	clay	-	-	<10	-	-	<5	-	-
Western	-	-	loam	-	-	10–30	3	1.11 a	5–10	-	-
Eastern	-	-	sand	7	1.15	>30	4	1.19 a	11–20	-	-
Southern	7	1.15	silt	-	-	-	-	-	>20	7	1.15
RR of K_{avail}											
Northern	-	-	clay	-	-	<10	5	0.97	<5	1	1.09 a
Western	-	-	loam	2	0.68 b	10–30	-	-	5–10	3	0.82 a
Eastern	-	-	sand	3	1.16 a	>30	-	-	11–20	1	1.32 a
Southern	5	0.97	silt	-	-	-	-	-	>20	-	-
RR of P_{avail}											
Northern	11	1.36 b	clay	-	-	<10	19	1.34 b	<5	14	1.45 a
Western	-	-	loam	11	1.15 b	10–30	10	1.15 b	5–10	8	0.93 b
Eastern	13	1.05 c	sand	15	1.50 a	>30	1	2.20 a	11–20	6	1.39 a
Southern	6	1.75 a	silt	4	0.99 b	-	-	-	>20	2	1.59 a

* Values marked with the same letter are not significantly different.

Tab. 9 Results of the linear multiple regression for the response of chemical soil quality indicators to residue incorporation.

Climatic zone	*n*	mean	Soil texture	*n*	mean	Sampling depth (cm)	*n*	mean	Duration of practice (years)	*n*	mean
RR of N_t content											
Northern	18	1.03 b*	clay	4	1.02 a	<10	-	-	<5	-	-
Western	6	0.98 c	loam	20	1.03 a	10–30	26	1.02	5–10	4	0.95 b
Eastern	-	-	sand	2	0.94 b	>30	-	-	11–20	11	1.04 a
Southern	2	1.08 a	silt	-	-	-	-	-	>20	11	1.03 a
RR of C:N ratio											
Northern	2	1.16 a	clay	1	0.91 a	<10	1	1.16 a	<5	-	-
Western	1	1.19 a	loam	7	1.10 a	10–30	7	1.06 a	5–10	5	1.01 b
Eastern	4	1.04 b	sand	-	-	>30	-	-	11–20	3	1.17 a
Southern	1	0.91 c	silt	-	-	-	-	-	>20	-	-

* Values marked with the same letter are not significantly different.

Tab. 10 Results of the linear multiple regression for the response of chemical soil quality indicators to catch and cover crops.

Climatic zone	*n*	mean	Soil texture	*n*	mean	Sampling depth (cm)	*n*	mean	Duration of practice (years)	*n*	mean
RR of N_t stock											
Northern		-	clay	-	-		-	-	<5	2	0.99 b
Western	4	1.04 a*	loam	7	1.04 a	0–30	8	1.04	5–10	-	-
Eastern	-	-	sand	1	1.03 a	>30	-	-	11–20	5	1.06 a
Southern	4	1.04 a	silt	-	-	-	-	-	>20	1	1.0 ab

* Values marked with the same letter are not significantly different.

quality indicators were considered in an overall evaluation, the best practices among those tested were: farmyard manure application, non-inversion tillage, compost application, mineral fertilization, and no-tillage.

Farmyard manure significantly increased N_t, content of available (mineral) nitrogen and C:N ratio. The advantage of organic fertilizers, including farmayard manure in our studies, compared to inorganic ones, is the slow and continuous release of N, and the presence of many other (than N) macro- and micronutrients. Furthermore, the percentage of N utilization in the year of application is usually less for farm manure than for fertilizer nitrogen, what is the reason for higher N and C soil contents [17]. In our study FYM strongly increased also soil available potassium (K_{avail}) content. It was showed [18], that livestock manures were a valuable source of plant available P and K. The manure additions increased the extractable K content in the topsoil and K availability was proportional to the total manure-loading rate.

The change from a ploughing to a ploughless system of shallow tillage may affect almost all soil chemical properties. In presented study non-inversion tillage compared to conventional ploughing positively influenced N total content and stock and content of available forms of K and P. The results were related to climatic zone, soil type, soil layer, and duration of the practice. It confirmed the studies of Rasmussen [19], who showed that in the Scandinavian countries of Denmark, Finland, Norway, and Sweden the best results were obtained on the heaviest clay soils, which were the most difficult for conventional tillage methods. As a result of the shallow non-inversion tillage nutrients and organic matter accumulated in topsoil and soil pH decreased in the long run. Hansen and Djurhuus [20] showed that less intensive cultivation decreased the nitrogen leaching, and spring tillage protected soil better than autumn cultivation. Stubble cultivation in spring without ploughing compared to stubble cultivation in autumn followed by ploughing on a sandy loam soil caused nitrogen losses of 35 and 76 kg ha^{-1}, respectively. Under Polish conditions of continental climate, non-inversion tillage systems also decreased soil pH in comparison to conventional tillage [21]. In the surface horizon (0–5 cm) higher contents of organic matter, total N and K available were found [22,23].

Application of compost significantly increased soil pH, N_t and N_{min}, and showed a tendency (not significant) to increase C:N ratio and K_{avail}. According to study of Epstein et al. [24] compost is an easily applied organic fertilizer, which prepares a friable seedbed with extended soil cation exchange capacity. It enabled increased soil nitrate N contents to the 15–20 cm soil depth and excess of available phosphorus during 2-year study. Soil nitrate N levels were not affected by compost applications [25]. Compost derived from animal manures is effective for maintaining or increasing soil phosphate status, without excessive accumulation of NO_3^-.

Mineral fertilizers were effective especially in increasing available phosphorus, potassium and nitrogen, and partly total N content. However, most data was related with one eastern climatic zone, loamy soil and 10–30 soil layers. Mineral fertilization is usually not effective in accumulation of organic matter. It is possible in originally poor soils or in poorly-drained clay soils, where the mineralization of plant residues is slow due to restricted aeration [26]. It was found, that mineral fertilizers, especially NH_4^+ sources, may acidify the soil. They increase also mineral nitrogen content. Higher level of nitrogen fertilization (100 versus 50 kg N/ha) may decrease the contents of total nitrogen, potassium, and organic carbon (C_{org}) in the whole soil profile and increase content of phosphorus in uppermost layer [27]. According to Koszański et al. [28] the amounts of phosphorus and potassium clearly decreased in the treatments with high N doses, and N_t and C_{org} increased. In the opinion of Panak et al. [29], however, increasing nitrogen rates do not clearly influence soil P_{avail}. Mineral P fertilization resulted in a build-up of plant-available P in the top soil [30].

No tillage practices are promoted mostly to reduce costs and labor but also because they may have positive effects on soil properties. In our study it affected significantly only available phosphorus and N_{min} contents. No tillage did not clearly enhance either of the total N indicators. The effects were related with climatic zone and soil type. However, clear results were found in the topsoil layer up to 10 cm depth. The studies of other authors confirmed that under no-tillage system (compared to conventional), nitrogen, phosphorus, potassium, and organic carbon contents increased in the surface soil layer (0–5 cm); at 5–20 cm depth, an increase of phosphorus and potassium and a decrease of total nitrogen and organic carbon were noticed [21–23,27,31]. We showed also some tendencies to increase N_t and to decrease N_{tS} and C:N ratio found. It is generally in agreement in other studies [32]. According to Oorts et al. [33] the long-term practice of no-tillage entails larger C and N stocks than conventional tillage due to better preservation of the organic matter originally present in the soil and/or less mineralization of recently added material. However, the N stocks under no-tillage system, calculated for an equivalent mass of dry soil, were only 10–15% larger than under conventional tillage. Balesdent et al. [34] indicated that no-tillage, due to physical protection of organic matter by the soil structure, contributed to the slower mineralization of organic matter. The effects depended on soil properties, regional climate, cultivation history, and cropping system. In studies by other authors [22,35] no-tillage system decreased soil pH in the plough layer. According to Stevenson [36] it can be related to an increased organic matter mineralization process, which produces nutrient elements (in particular NH_3), whose oxidation may contribute to H^+ production.

Hansen and Djurhuus [20] indicated, that no-tillage reduced leaching of nitrogen by 13 kg ha^{-1}, as compared to ploughing on a coarse sandy soil.

The other tested management practices showed smaller effect on the indicators of soil chemical quality, mainly due to not enough possible comparisons in our data base. However, based on the other literature, the expected results were as below.

Animal slurry provides a valuable source of C, N, P, and K and is a low-cost alternative to mineral fertilizers [37]. With respect to the non-amended soil, the pig slurry-amended soils had larger pH, available P and K contents, and slightly larger total N concentration [38]. Heavy dressing with slurry increased the soil pH also in contrast with mineral NPK fertilizers [39]. No considerable differences were observed between slurry and NPK-treated soils in the content of NH_4 and total N. However, uncontrolled application of slurries to soil can generate, among others, an excess of nitrates [40] and phosphorus [41].

Crop rotation has always been used in agriculture to maintain the soil fertility over the years. Changes in SOM are directly correlated to amounts of crop residue returned to the soil [42] and can be generally expected to have major impacts on other soil chemical indicators, too. In study of Aziz et al. [43] crop rotation had significant impact on total nitrogen. The corn–soybean–wheat–cowpea rotation was characterized by significantly higher total nitrogen content than continuous corn and corn–soybean. The results suggest that multiple-crop systems could be more effective for maintaining and enhancing soil quality than single-crop systems. Another study [44] emphasized the effect of total N input (as determined by the cropping system) on soil pH. The latter was lower with continuous corn than with crop rotation because of greater N input. Generally, the different nutrient balances associated with different cropping systems should be expected to have a major impact on soil fertility indicators.

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 [45]. 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 sequestration. Leguminous cover crops, in addition, fix N biologically and may improve the soil N fertility [46]. Leguminous catch crops can supplement N by fixing N_2 from the atmosphere. Forage legumes contain 3–4% N that can originate from both the soil and air [47]. When legumes are incorporated into the soil their biomas rich in nitrogen contributes to increase the content of soil organic matter. The same role, though not fixing nitrogen, play non-leguminous catch crop. These crops intercept the residual nitrogen left after the harvest of the main crop. It can be expected that green manures (not harvested) will increase the content of organic nitrogen in the soil and lower the C:N ratio.

Incorporation of crop residues is beneficial for soil fertility because it promotes accumulation of soil organic matter [48] and total N [49]. Crop residues bring to the soil some nutrients such as K, N, and Ca [50]. However, it depends on crop type. According to Rodriguez-Lizana et al. [50] cereals leave more monovalent nutrients, e.g., K, while legumes are richer in N. Uhlen [17] showed that cereal straw increased soil C and N contents and C:N ratios more than non-straw residues. Grace et al. [49] found increase of soil total N as a result of residue incorporation.

Conclusions

- Long-term use of soil management practices as crop rotation, catch/cover crops (either harvested or incorporated into the soil as green manure), no-tillage and no-inversion tillage, mineral and organic fertilization with compost, farmyard manure, or slurry, and crop residue incorporation into the soil influenced soil chemical quality indicators. Both positive and negative effects were observed.
- The effect of long-term use of soil management practices was related to climate type, soil texture, duration of practice, sampling depth.
- When the RRs values of seven soil chemical quality indicators were considered in an overall evaluation – based on their significance level, the number of indicators positively affected, and the size of the effects – the best practices among those

tested were: farmyard manure application, no-inversion tillage, compost application, mineral fertilization, and no-tillage.

- Under absence of the research on soil organic carbon, the soil management practices influenced mostly N_t and N_{min}, P and K availability, and C:N ratio.

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Wpływ wieloletniego stosowania zabiegów agrotechnicznych na wybrane właściwości chemiczne gleb

Streszczenie

Praca przedstawia wyniki ekstensywnej metaanalizy danych dotyczących wpływu zabiegów agrotechnicznych prowadzonych w zróżnicowanych warunkach glebowych i klimatycznych na wybrane właściwości chemiczne gleb. Metaanalizę wykonano na podstawie danych pochodzących z opublikowanych doświadczeń wieloletnich prowadzonych na terenie całej Europy. Analizowano następujące wskaźniki: odczyn pH gleby, zawartość N ogółem, zasób N ogółem, stosunek C:N, zawartość mineralnych form azotu (N_{min}) oraz przyswajalnych form potasu i fosforu. Spośród zabiegów agrotechnicznych uwzględniono: zmianowanie, stosowanie poplonów roślin okrywowych (zabieranych z pola) oraz przyorywanie nawozów zielonych, siew bezpośredni, uprawę uproszczoną, nawożenie mineralne, nawożenie kompostem, obornikiem, gnojowicą oraz przyorywanie resztek pożniwnych. Biorąc pod uwagę wszystkie wskaźniki reakcji RR oraz statystyczną ocenę ich istotności, a także ilość wskaźników reagujących pozytywnie i wielkość tej reakcji, za najlepsze zabiegi agrotechniczne uznano: stosowanie obornika, uproszczoną uprawę roli, nawożenie kompostem, nawożenie mineralne, siew bezpośredni.