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RESEARCH ARTICLE

No-till permanent meadow promotes soil carbon sequestration and nitrogen use efficiency at the expense of productivity

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Abstract The delivery of multiple ecosystem services from intensively managed cropping systems remains challenging mainly because increases in crop yields are rarely associated with greater soil carbon (C) sequestration or efficient ecosystem nitrogen (N) cycling. The sustainability of intensive cropping systems depends on trade-offs between multiple ecosystem services but experimental evidence from long-term field studies remains limited. The common expectation is that highly productive agroecosystems will be associated with lower soil C and reduced nutrient use efficiency. Here we use data spanning 30 years of a long-term field experiment established in 1985 near Lodi in Northern Italy where four arable systems (i.e., three crop rotations and a grain maize monoculture) and a no-till permanent meadow were all compared across two levels of agronomic inputs. We asked how (i) soil C stocks, (ii) fertilizer N-use efficiency, (iii) productivity, (iv) crude protein, and (v) feed units for lactation might differ across the five traditional cropping systems. We found that soil C sequestration, N-use efficiency, and crude protein production were all significantly higher in the no-till permanent meadow, which was however associated with lower dry matter yields and reduced feed units for lactation when compared with the arable systems. These findings suggest that converting arable soil into no-till permanent meadow is a win-lose solution. The most productive annual rotation (silage maize + Italian ryegrass) offers a complementary win-lose solution whereby high yields and feed units for lactation can be obtained from a smaller cropland area. The other cropping systems are less productive and provide little (or none) soil C storage benefits. Our study is one of the first to show clear trade-offs between multiple ecosystem services and to demonstrate that high fertilization rates might be only justified when the management goal is to spare land for less intensive uses such as permanent meadow.

Keywords Arable cropping systems · No-till permanent meadow · Farmyard manure · Industrial fertilizers · Dairy cattle feed

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1 Introduction

Over the last 15 years, there has been increasing evidence that agriculture is now contributing more to global GHG emissions than changes in land use mainly due to the intensive production and inefficient use of synthetic fertilizers and animal manure (FAO 2014). Soil carbon (C) sequestration is a key ecosystem service, which can significantly reduce net GHG emissions from intensively managed cropping systems (Lal 2004). Management of soil organic C is important because accumulation of organic matter in soils greatly benefits ecosystem functioning and crop growth (Powlson et al. 2011), whereas the stabilization of soil organic C over time is a fundamental element of agricultural systems sustainability. Fallowing, manuring, and crop rotation can be regarded as sustainability-enhancing practices, which have been developed by farmers (Fresco and Kroonenberg 1992) based on the knowledge that both crop type and sequence of cultivation are key factors for better exploitation of natural resources. These practices allow more soil organic C to be accrued or maintained, losses of nutrients to be minimized, and pest populations to be kept at tolerable levels. Managing croplands to increase sustainability, however, will typically lead to situations where some ecosystem services are enhanced and others are decreased (Bennett et al. 2009). In fact, intensively managed arable cropping systems are devised to fulfill basic social needs, such as food, fodder, fuel, and fiber at the cost of diminishing other ecosystem services (Powlson et al. 2011; Foley et al. 2005). For example, repeated applications of fertilizer significantly increase crop production at the expense of water quality (Carpenter et al. 1998), and through repeated soil disturbance, cropland management turns arable soils into C sources rather than sinks of C.

Thus, there is an urgent need to develop experimental research that aims to elucidate potential relationships between multiple ecosystem services, and to address which underlying mechanisms might be responsible for these relationships in order to make agricultural systems more sustainable (Bennett et al. 2009). Here we address this research gap by means of a long-term experiment where different cropping systems were compared and multiple ecosystem services were measured over 30 years. Long-term field experiments are trials based on permanent plots, which received continuous treatments over time, and were sampled periodically to assess changes over the decades (Richter et al. 2007). Such experiments are fundamental when addressing important questions which relate to the sustainable management of intensive cropping systems (Johnston 1997; Peterson et al. 2012). Additionally, because changes in soil C stocks typically occur over many decades, long-term field experiments are essential to improving our understanding of soil C dynamics (Richter and Markewitz 2001). Consequently, the value of such experiments greatly increases when soil samples are preserved in appropriate conditions and can be analyzed collectively at a later date, with new or improved chemical analysis techniques (Johnston 1997).

Long-term experiments represent unique research platforms, which contribute to addressing key societal challenges such as ways of increasing crop production in coming decades while minimizing the adverse effects on soils and the environment, and improve C and N cycling and storage across soils and agro-ecosystems (Richter et al. 2007). As N-use efficiency has substantial year-to-year variability, long-term experiments can provide a reliable quantification of N uptake and use by crop species over decades (Johnston 1997).

This study specifically addresses how soil carbon C and N stocks, efficiency use of fertilizer N, harvested dry matter, crude protein, and feed units for lactation (UFL), might change across five traditional cropping systems, which have been studied for 30 years.

Finally, because these agricultural systems were mainly conceived to produce fodder for dairy cattle and therefore maximizes feed quantity and quality (i.e., yields, feed units for lactation, and crude protein content), we question which potential trade-offs (if any) might occur in the long-term between productivity, N-use efficiency, and soil C and N sequestration.

2 Materials and methods

2.1 Site characterization and agronomic details

The long-term field experiment was undertaken in 1985, and it is still ongoing in Lodi, (45° 19′ N, 9° 30 E, 81 m a.s.l.), in the irrigated lowlands of Lombardy, Northern Italy. The experiment was conceived to evaluate the effects of five cropping systems and two levels of agronomic inputs (high vs. reduced) on dry matter yields and soil characteristics. According to van Ittersum and Rabbinge (1997), the cropping systems investigated in this study can be referred to as "production activities" defined as cultivation of crop rotations in a particular physical environment, to which are applied several complete sets of agronomic inputs, defined as "production techniques."

Details of the methodology were already presented by Tomasoni et al. (2003) who reported key findings of the influence of fodder crop rotations on the weed flora, and by Borrelli et al. (2014) who addressed yield stability for grain and silage maize over a 26-year period. In brief, the soil of the site is sandy-loam, classified as mollic Hapludalf. Soil properties within the arable layer (0–0.3 m) at the outset of the experiment in 1985 were: clay (< 0.002 mm) 9.9%, silt (0.05–0.002 mm) 24.7%, sand (2–0.05 mm) 65.4%; available soil water 97.6 mm per meter depth; bulk density 1.58 Mg m^{-3}; pH (H$_2$O) 6.5; C.E.C 11.3 (cmol$_{(+)}$ kg^{-1}).

Fig. 1 The natural competition among grasses, legumes and forbs in the no-till permanent meadow has much to offer to environmental sustainability: soil carbon and nitrogen are accrued while nitrogen applied with fertilizers is used more efficiently

The climate is sub-continental, with an average annual rainfall of about 800 mm, relatively well distributed around the year, and an average annual mean daily temperature of 12.5 °C, January being the coldest month (1.1 °C) and July the hottest (22.9 °C) (Borrelli and Tomasoni 2005).

We compared five cropping systems, a no-till permanent meadow and four arable systems. The arable systems include three crop rotations, and a grain maize monoculture. In details, the cropping systems were (i) an annual rotation (R1) of autumn-sown Italian ryegrass (*Lolium multiflorum* Lam.) + spring-sown maize (*Zea mays* L.), both for silage; (ii) a 3-year rotation (R3): grain maize (first year)—autumn-sown barley (*Hordeum vulgare* L.) + spring-sown maize, both for silage (second year)—Italian ryegrass + maize, both for silage (third year); (iii) a 6-year rotation (R6): Italian ryegrass + silage maize, both for silage (years 1, 2, and 3 of rotation)—a mixed meadow of white clover (*Trifolium repens* L.) and tall fescue (*Festuca arundinacea* Schreb), mown for hay, (years 4, 5, and 6 of rotation); (iv) a continuous grain maize monoculture (CM); (v) a no-till permanent meadow (PM), mown for hay, sown at the outset of the experiment with ladino white clover and tall fescue, and subsequently colonized by natural vegetation (grasses, legumes, and forbs) (Fig. 1). Each cropping system has been treated with two levels of agronomic inputs: (i) input A, which represents the ordinary crop management adopted by the farmers in the region when the experiment initiated (year 1985); (ii) input B, which received about 70% of the amount of synthetic and manure fertilization, and reduction of tillage. A summary of agronomic inputs applied to each cropping system is reported in Table 1. It is important to remark that the annual rotation of Italian ryegrass + maize is widely adopted by farmers in the region owing to the type of soil, which thanks to low clay content, can be easily plowed even under a relatively high soil water content. The same soil tillage schedule was adopted for Spring-sown grain and silage maize with treatments A and B: the soil was plowed to a depth of 0.30 m and refined by two subsequent rotary harrows. A reduction of depth and type of

Table 1 Annual agronomic inputs applied to individual cropping systems in terms of maize stover, industrial fertilizers and farmyard manure

Cropping system	Input	Crop residues	Soil tillage	Mineral fertilizers			Manure
				N	P$_2$O$_5$	K$_2$O	
				kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
CM	A	Buried	Traditional	250	100	100	0
CM	B	Buried	Reduced	175	70	70	0
PM	A	Removed	No-till	125	150	120	40,000
PM	B	Removed	No-till	88	105	84	28,000
R1	A	Removed	Traditional	400	200	220	40,000
R1	B	Removed	Reduced	280	140	154	28,000
R3	A	Removed	Traditional	340	167	180	26,700
R3	B	Removed	Reduced	238	117	126	18,700
R6	A	Removed	Traditional	263	175	170	26,700
R6	B	Removed	Reduced	184	123	119	18,700

tillage was adopted with input B for soil preparation of the Autumn-sown crops: under input A the soil was plowed to a depth of 0.30 m and subsequently rotary cultivated, whereas under input B the soil was rotary cultivated to a depth of 0.15 m.

Prior to the experiment initiation, the whole experimental area was cultivated with annual forage crops for at least 14 years. The dairy farm activities at the experimental station ceased in 1971. Subsequently, no alfalfa meadows were cultivated and no livestock manure was applied to the field. The species cultivated during this period were forage sorghum (*Sorghum vulgare* Pers. var. *sudanense* [Piper] Hitch), Italian ryegrass, forage rape (*Brassica napus* L.), and turnip (*Brassica rapa* L.). Therefore, no substantial residual nitrogen and carbon effects from legumes and manure were present at the beginning of the experiment. We adopted what is common practice for the maize farmers in the area, namely to apply every year three to four border irrigations of about 100 mm to the entire field experiment during the period end-June to end-August. Thus, each cropping system and input treatment received the same amount of irrigation water. Italian ryegrass was sown in mid-October to late-November and harvested at the beginning of May. The silage maize following Italian ryegrass was sown from the end of May to the beginning of June and harvested in mid-September. Grain maize was sown in the second half of April and harvested at the end of September. Barley was sown at the end of October and harvested at the end of May. The silage maize following Barley was sown at the beginning of June and harvested in the middle of September. The permanent meadow is mown for hay four to five times every year, approximately: (1) mid-May; (2) end of June, (3) early August, (4) half of September; (5) end of October.

All phases of rotations R3 and R6 (including phases of 3-year lasting meadow) were carried out each year, and in each combination of block and input level to avoid possible confounding effects of the factor year when comparing rotations. Obviously, when two crops are rotated within a year, (i.e., in the case of Italian ryegrass and maize), they will occupy the same plot thus there is no need to replicate their presence in the experiment. Overall, the trial included 72 subplots, deriving from 12 crop-phases × 3 blocks × 2 input levels. The size of the subplot is 60 m^2 (6 × 10 m).

The experimental design was a randomized complete block design with a split plot arranged in two agronomic input levels as main plots, five cropping systems as subplots, and three replications.

For a complete description of the experimental design, additional details of the management of crop residues and livestock manure across cropping systems are provided here: (i) the grain maize stover is annually returned to the soil in CM, which is a cropping system intended to produce grain for the market; on the contrary, grain maize stover was removed in R3 because it was intended to provide litter for dairy cattle in the fodder cropping system; (ii) unlike the grain maize, the silage maize, the permanent meadow, and the first year of the rotated meadow always received livestock manure. The second and the third years of the rotated meadow have not received manure. Consequently, the frequency of manure application within cropping system was as follows: never in CM, every year in R1 and PM, in two thirds of the years in R3, and also in R6, given that the meadow in rotation also received manure on its first year.

In the no-till permanent meadow, farmyard manure was spread on soil surface at the end of the winter, and mineral fertilizers distributed in the early spring. On the contrary, in the silage maize and in the first year of the rotated meadow, livestock manure was immediately buried by plowing, while the rest of industrial fertilizers (half of the N, all P, and K) were buried by rotary harrowing before sowing. Aiming to incorporate the remaining half of synthetic N fertilizer, and to control for weed species, the maize crop was rotary cultivated

between the rows during stem elongation (V3–V4 stage). Overall, the soil was plowed annually within cropping systems R1, R3, and CM. Soil was plowed for four of the 6 years within cropping system R6, while PM was permanently displaced from soil tillage.

2.2 Soil sampling and analysis

Soil samples were collected periodically from each individual plot during autumn after the harvest of grain maize, which is the latest crop being harvested in the season. Three independent soil cores were collected from each plot in the soil layer 0–0.3 m, which corresponds to the arable layer. Soil cores were collected using a soil sampler drill, model Eijkelkamp, 4 mm diameter. The three soil cores were combined to give one composite sample per plot and then sieved through a 1-mm mesh. The set of soil samples collected periodically between 1985 and 2012 was used to measure total C and N content (%) using a LECO Truspec® CHN Analyzer (LECO Corporation; Saint Joseph, Michigan, USA). While the LECO Truspec does not discriminate between organic and inorganic C content, the soil of the site had no carbonate mineral content, therefore we assumed that total C content coincided with organic C content. The Leco Truspec was also used to determine the C content of livestock manure and, therefore, the C input of individual cropping systems.

We present temporal changes in soil organic C and N content (%) and not soil C and N stocks mainly because we did not have available soil bulk density data necessary to quantify changes in C and N pools in megagrams per hectare throughout the duration of the experiment.

Soil bulk density was measured only in 1985 and 2012. We thus estimated changes in soil C and N pools taking into account differences in both soil organic carbon content and bulk density as measured in each individual plot at the outset and the end of this time interval.

When this experiment was conceived, efforts were devoted in evaluating changes of soil characteristics over time for the arable layer, i.e., the first 0.3 m depth. The IPCC also assumes a default soil depth of 0.3 m for calculation organic C stocks of mineral soils (Aalde et al. 2006)."

2.3 Crop measurements

The biomass of all crops was harvested manually from each individual plot. Fresh biomass weight was measured at each harvest date from the whole surface of the plot. For grain maize, both grain and stover weights were measured. Maize stover indicates stalk and leaves excluding grain. Subsequently, the stover was returned to the soil surface for CM. On the contrary, for R3 rotation the harvested stover was not given back to the soil because it was intended to provide litter for cattle manure applied to silage maize in rotation. A

sub-sample composed of the biomass products (i.e., grain and stover for grain maize, and whole aboveground biomass in the case of silage maize, barley, Italian ryegrass, rotated, and permanent meadow) from each plot was oven dried at 60 °C, until the dry weight was stable, to determine the dry matter content of the harvested biomass. Dried forage samples were milled and sieved for determination of the N content and crude protein (N × 6.25) using the Kjeldahl method. The N contents of the dry matter products of each individual plot enabled the calculation of N taken up by the crops and cropping systems. Because the C content of maize stover is fairly stable around 44% of dry matter regardless of N availability, we assumed such value for calculating annual C inputs in CM, which received crop residues instead of livestock manure.

Feed units for lactation of the harvested products (Unité Fourragère Lait, UFL), were estimated in accordance with Jarrige (1989). A feed unit for lactation is the amount of net energy that a ruminant can obtain during lactation from 1 kg of barley with 86% of dry matter. 1 UFL = 1700 kcal. Tables containing UFL values of diverse forages and concentrates were used to quantify the UFL produced by each cropping system.

2.4 Nitrogen use efficiency

In accordance with Cassman et al. (2002), we defined N-use efficiency of the cropping systems as the proportion of N inputs that are removed in harvested crop biomass, and incorporated into soil organic matter and inorganic N pools. N not accounted for in these sinks is considered lost from the cropping systems and thus contributing to the reactive N that cascades through the atmosphere, hydrosphere, and biosphere of the Earth. The term reactive N incorporates all biologically active, photochemically reactive, and radiatively active N compound that have negative effects on the environment (Galloway et al. 2003).

To assess N-use efficiency, we considered:

i.   annual N uptake of harvested biomass, averaged for 30 years;
ii. annual soil N accrual calculated as average increment between 1985 and 2012;
iii. N not accounted for, calculated as difference between annual N applied with fertilizers, annual N uptake and annual soil N accrual;
iv. the agronomic efficiency of applied N (AE_N), calculated as the ratio between kilograms of DM produced by all crops within cropping systems and the amount of N applied in the form of industrial and organic fertilizers; and
v.   the recovery efficiency of applied N (RE_N), calculated as the ratio of the annual N uptake with harvested biomass and the amount of N applied in the form of industrial and organic fertilizers.

2.5 Statistical analysis

The long-term experiment was based on a randomized complete block design, with a split plot arranged with two agronomic input levels (main plots) and five cropping systems (subplots) each replicated three times. In order to deal with repeated yearly measurements the PROC MIXED procedure within the SAS system was devised (Littell et al. 1996). Statistical analyses were performed with this PROC MIXED of SAS using the statement REPEATED to take into account the covariance of the experimental unit over time. The year of experiment (YOE) was a considered as fixed effect when evaluating the treatments response over time. The block factor was considered a random effect. The autoregressive model was adopted for the covariance structure. In the F test, degrees of freedom for the denominator were calculated using the Satterthwaite approximation method (Littell et al. 1996). The statistical difference between means was assessed with the instruction LSMEANS and the SMM adjustment. Regression parameters and statistics were calculated with the PROC REG of SAS (SAS Institute 2009). Comparison of the regression line slopes were evaluated with the instruction ESTIMATE of PROC MIXED of SAS.

3 Results and discussion

3.1 Soil C and N stocks

The long-term evolution of soil organic C and total N are shown in Figs. 2 a and b, respectively. As previously indicated, values are reported in percentage, rather than in megagrams per hectare because we do not have continuous soil bulk density data spanning 30 years that is necessary when calculating soil C stocks.

The organic C content of the upper soil layers (0–0.3 m) increased linearly for three of the five cropping systems over the period 1985–2012 (Fig. 2a). The slope of the regression line describing the evolution of soil organic C over time was significantly different from zero for the permanent meadow PM, with a statistical difference between input A and B that are therefore reported separately (Table 2). Conversely, for the other cropping systems, we found no difference between input A and B. Soil C accrual of PM under both inputs A and B was greater than the C accrual of R1 and R6 cropping systems. The regression slope was not significantly different from zero for both continuous maize CM and for the three-year rotation R3. Overall, our data provides evidence that soil organic C increased linearly across the 30-year experiment. Our findings agree with Fornara et al. (2016) whose study shows a linear increase in soil C stocks over 40 years of management in a manured permanent grassland in the UK. Our findings, however, do not corroborate the general assumption that rates of
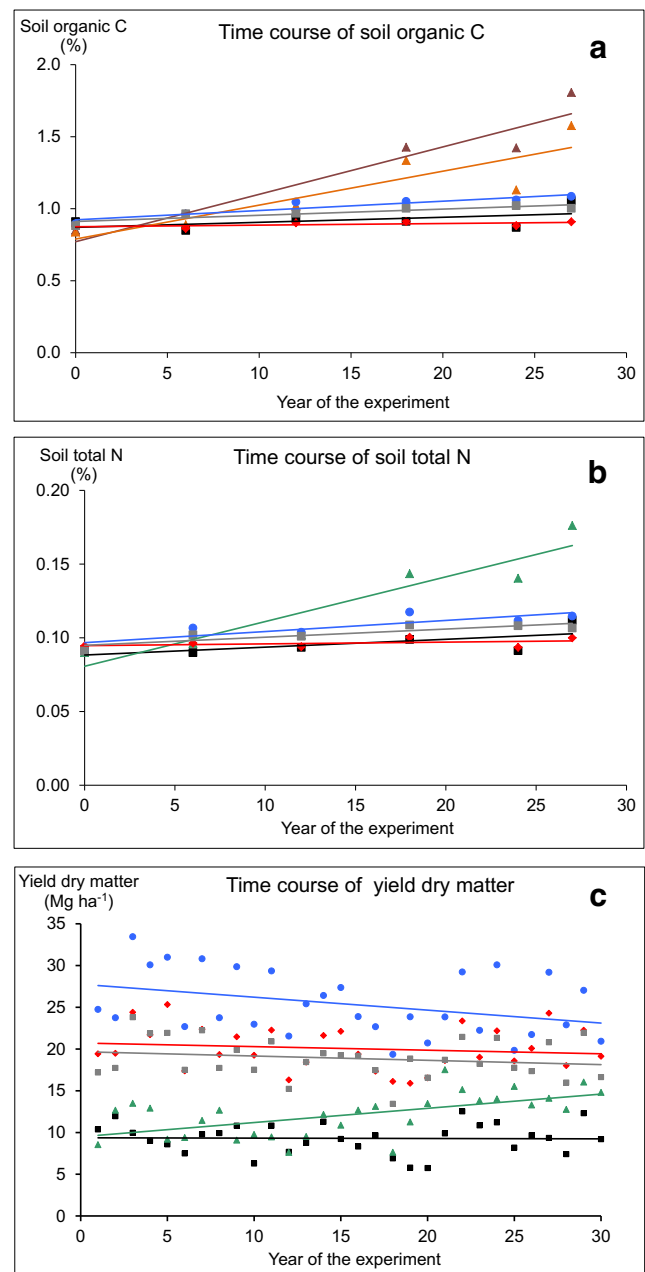
Fig. 2 Changes in soil organic C content (**a**) soil total N (**b**) within the 0–0.3 m soil-depth interval, and dry matter yield (**c**) across six different cropping systems. Treatments are indicated by colors: black = continuous grain maize (CM); brown = permanent meadow input A (PM-A); orange = permanent meadow input B (PM-B); green = permanent meadow (PM); blue = annual rotation (R1); red = 3-year rotation (R3); gray = 6-year rotation (R6). Regression values and statistical differences are reported in Table 2

increase of soil organic C follow a sigmoid curve, which tends to reach its maximum value after 20 years following significant land-use change (Lal 2004).

Based on soil bulk density values measured in 1985 and 2012, we estimated the average annual soil C and N accrual of the 27-year period reported in Table 3. We found that the average annual increase of soil organic C for PM was

Table 2 Summary of linear regression values associated with changes in soil organic C, soil total N, and yield dry matter over time for six cropping systems

Cropping systems	Intercept	$P > t$	Slope	$P > t$		R^2	RMSE	CV	n
Soil organic C (%)									
CM	0.871	< 0.0001	0.0035	0.2963	cd	0.04	0.17	18.1	36
PM-A	0.771	< 0.0001	0.0329	0.0001	a	0.61	0.27	21.3	18
PM-B	0.790	< 0.0001	0.0235	0.0008	b	0.52	0.23	20.5	18
R1	0.923	< 0.0001	0.0065	0.0038	c	0.22	0.12	11.7	36
R3	0.874	< 0.0001	0.0011	0.3938	d	0.01	0.12	14.2	108
R6	0.912	< 0.0001	0.0043	< 0.0001	c	0.11	0.11	11.7	216
Soil total N (%)									
CM	0.088	< 0.0001	0.0005	0.1246	bc	0.07	0.02	20.3	36
PM	0.081	< 0.0001	0.0030	< 0.0001	a	0.59	0.02	19.9	36
R1	0.097	< 0.0001	0.0008	0.0020	b	0.25	0.01	12.0	36
R3	0.095	< 0.0001	0.0001	0.4308	c	0.01	0.01	15.5	108
R6	0.095	< 0.0001	0.0005	< 0.0001	b	0.16	0.01	11.5	216
Yield dry matter (Mg ha^{-1})									
CM	9366	< 0.0001	− 4	0.8209	b	0.00	2169	23.3	180
PM	9495	< 0.0001	170	< 0.0001	a	0.24	2650	21.8	180
R1	27,755	< 0.0001	− 155	< 0.0001	c	0.08	4426	17.5	180
R3	20,723	< 0.0001	− 43	0.1022	b	0.01	3043	15.2	180
R6	19,686	< 0.0001	− 52	0.0240	b	0.03	2647	14.0	180

For soil total N and yield dry matter the differences between input levels were not significant. Treatments sharing common letters are not significantly different for $P > 0.05$

Treatments are: *continuous grain maize* (CM), *permanent meadow input A* (PM-A), *permanent meadow input B* (PM-B), *annual rotation* (R1), *3-year rotation* (R3), *6-year rotation* (R6)

1326 kg C ha^{-1} under input A and 1048 kg C ha^{-1} under input B. Compared to the permanent meadow (PM), annual soil C gain was 24% for CM, 21% for R1, and a mere 16% for R6 under the same input A (Table 3). Overall, all the arable cropping systems were associated with low soil organic C accrual, and we suggest therefore that the best option for increasing soil C stocks is conversion from arable cropping systems to no-till permanent meadow. It is likely that the interruption of annual soil tillage not only contributed to a decrease of organic matter mineralization, but also promoted larger rooting systems of perennial grasses, legumes, and forbs thus enhancing belowground C inputs to soils.

The reduction of agronomic inputs from A to B (implying reduced annual C inputs), was generally associated with a decrease in annual soil C gains. Compared to agronomic input A, annual soil C gains under input B were 79% for PM, 65% for R1, 48% for R6, and a mere 19% for CM. The only exception was R3, where soil C accrual was close to zero for both inputs.

Despite receiving the highest C inputs and despite all annually produced maize stover being incorporated into the soil, the continuous grain maize (CM) system showed a very low C retention coefficient (6.5% for input A and 1.8% for input B). It is important to reiterate here that CM is the only closed system in this experiment. The other cropping systems all imported C from farmyard manure, which was produced with animal feed and maize stover harvested from external areas.

Annual rotation R1 under input A only received 76% of the C received by CM under the same agronomic input; however, CM received its C inputs from maize stover whilst R1 has received C from manure (Table 3). Because the C retention coefficient of R1 resembled that of CM, our data provide no compelling evidence that C in the form of manure is any more effective than C in the form of stover in increasing soil C content. In contrast, Grignani et al. (2007), reported that animal manure was more effective than crop residues in increasing soil C stock in grain maize system. Moreover, retention coefficients calculated in our arable cropping systems were lower than those estimated by Grignani et al. (2007), who reported that 18% of C applied from manure was incorporated into arable soils.

Annual rotation R1 received the same amount of farmyard manure as permanent meadow (PM), under both inputs A or B. PM also received manure to the soil surface (being a no-till cropping system), whereas in the annual rotation R1 manure was incorporated into the arable soil layer. Despite the non-incorporation of manure, the "apparent" C retention coefficient for PM was five to six times higher than the soil C retention of rotation R1. Therefore, in the sandy-loam soils of our experiment, soil organic C accrual can be achieved more effectively with no-tillage as opposed to incorporating manure into the soil. We define it as "apparent" because it is likely that the turnover of rooting systems represents relevant

Table 3 Average values for each combination of cropping systems and agronomic input, for 30 years of experiment (1985–2015), of: (i) C inputs from stover and manure, soil C accrual and C retention coefficient; (ii) N applied in the form of industrial fertilizer and manure, N uptake with harvested products, annual soil N accrual, N not accounted for (i.e., presumed N losses), agronomic efficiency of applied N (AE_N) and recovery efficiency of applied N (RE_N); (iii) dry matter yield, feed units for lactation (UFL), and crude protein

Cropping systems	Input	Annual C input	Annual SOC accrual		C retention coeff.	Annual N applied	Annual N uptake	Annual soil N accrual		N not accounted for	AE_N	RE_N	Yield		UFL[b]		Crude protein	
		kg ha^{-1}	kg ha^{-1}		%	kg ha^{-1}					kg DM kg N^{-1}	%	kg ha^{-1}		UFL ha^{-1}		kg ha^{-1}	
CM	A	4915[a]	322	b	6.5	315	132	32	b	151	32	42	9954	h	12,144	g	828	g
CM	B	3312[a]	60	bc	1.8	254	111	27	b	116	34	44	8646	i	10,543	h	693	h
PM	A	3741	1326	a	35.4	375	336	128	a	−89	35	90	13,220	f	9315	i	2098	a
PM	B	1940	1048	a	54.0	227	264	112	a	−149	49	117	11,051	g	7463	l	1653	d
R1	A	3741	285	b	7.6	650	305	32	b	313	41	47	26,559	a	22,187	a	1905	b
R1	B	1940	185	bc	9.6	440	246	29	b	165	55	56	24,158	b	20,296	b	1540	e
R3	A	2494	−8	bc	−0.3	506	233	2	b	271	42	46	21,182	c	19,531	c	1457	e
R3	B	1293	12	c	0.9	351	195	6	b	150	54	56	18,929	d	17,321	d	1218	f
R6	A	2494	206	b	8.3	429	329	25	b	75	46	77	19,782	e	15,853	e	2055	a
R6	B	1293	98	bc	7.6	290	283	17	b	−10	62	97	17,982	e	14,342	f	1767	c

[a] Maize stover

[b] Unité Fourragère Lait (Feed Unit for Lactation), equivalent to 1700 kcal (Jarrige 1989)

C and N inputs to PM soils. These findings corroborate the main results of a permanent grassland experiment, which showed how plant species diversity can contribute to increases in total root mass and thus to greater soil C accumulation in mixed swards including grasses, legumes, and forbs (Fornara and Tilman 2008).

Tomasoni et al. (2011), working in a nearby experimental site, reported a more substantial C accumulation for rotation R1 after 11 years of experimentation. Such a result was obtained by applying 50% more farmyard manure compared to this experiment, applied twice per year: in the case of maize-Italian ryegrass double crop, where the soil is tilled prior to each sowing, farmyard manure can be incorporated twice per year.

The 3- and 6-year rotations (R3 and R6) received the minimum amount of C compared to other cropping systems, specifically 50% compared to CM input A and 39% compared to CM input B. While R3 soil C retention coefficient was close to zero, the C retention coefficient of R6 (which received manure only for 4 years out of 6, and included 3 years of rotated meadow), was very close to the soil C retention of the annual rotation R1, which received manure every year. These findings provide additional evidence that the no-till meadow plays an important role for the accrual of organic C in soils (Table 3).

Interestingly, the higher rate of soil C stock change observed in this experiment, i.e., 1326 kg C ha^{-1} of the PM with input A, is very close to the value of 1370 kg C ha^{-1} indicated for manure application in temperate climates by the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). Nevertheless, our data indicate that such value can be achieved when 40 Mg manure ha^{-1} y^{-1} is applied to PM, whereas in the case of arable rotation R1, receiving the same rate of manure application, determined a soil C accrual of only 285 kg C ha^{-1}. Indeed, Maillard and Angers (2014) indicated great variability in the magnitude of soil organic C change following manure application.

Rotation R6, which includes 3 years of meadow alternated with 3 years of arable system annual double crop of silage maize-Italian ryegrass, shows a soil C gain for input A of merely 206 kg C ha^{-1}. This result was unexpected and could be explained by the fact that intensive soil tillage associated with the 3-year phase of maize-Italian ryegrass may have canceled any soil C gain benefit resulting from the previous ley phase. This is in good agreement with Attard et al. (2016), who indicated that plowing grassland led to a rapid shift of SOC, N fluxes, and microbial activity towards the characteristics of cropland. In contrast, the restoration of grassland, in soils previously cultivated with annual crops, produced effects on soil C and N content that began to appear after 36 months. These authors attributed this time lag to the period necessary for complete establishment of grass root systems.

Our findings on R6 contrast, but do not contradict, long-term experiment data reported by Albizua et al. (2015). Working on four experimental sites in southern Sweden, these authors reported a general positive effect on SOC by the inclusion of one ley year into a 4-year crop rotation. Nevertheless, the extent of the effect of ley inclusion to SOC varied substantially across the four sites, characterized by different soil texture. This indicates that the soil type, as well as climatic conditions, influences the extent of SOC response to treatments.

Our evidence of the positive effect of no-till PM on soil C pools is consistent with previous findings, which show overwhelming positive effects of conservation agriculture on soil organic C stocks when compared with low-input, conventional, and organic systems (Autret et al. 2016). Changes in total soil N in the topsoil profile (0–0.3 m) closely resemble those observed for soil organic C (Fig. 2b). The permanent meadow (PM) was the only system that substantially increased total soil N content during the period of the experiment. Unlike soil organic C, however, no statistical difference was found between soil N content of input A and B in the PM system. The slope of the regression line describing the evolution of soil N content over time was significantly different from zero for PM, R1, and R6 systems (Table 2).

PM was associated with the highest annual soil N accrual in the topsoil profile, being, respectively, 128 kg N ha^{-1} for input A and 112 kg N ha^{-1} for input B (Table 3). Annual soil N gain was 25% for CM, 25% for R1, 20% for R6 and only 2% compared with soil N gain of PM under the same input A. Of all the cropping systems, R3 was the only one showing negligible soil N accrual.

Reduced N applications under agronomic input B led to lower soil N gains, which were 84% for CM, 88% for PM, 88% for R1, and 66% for R6 when compared with soil N gains under input A.

3.2 Fertilizer N-use efficiency

We assessed N-use efficiency of the various cropping systems over three decades. Knowing the annual rate of soil N change we were able to quantify the amount of "not accounted for" N, i.e. the amount of N not harvested with the crop and not retained in the soil. This N represents a plausible estimate of the fraction of N applied to the cropping systems that was presumably dispersed in the environment (Johnston 1997).

Considering the amount of N applied under input A, the fraction of "not accounted for" N was 50% for CM, 48% for R1, 54% for R3, and only 17% for R6 (Table 3). The arable cropping systems CM, R1 and R3 that received the high fertilization regime of input A, show unacceptable high N losses, estimated by the amount of "not accounted for" N (Table 3). In particular, 313 kg of "not accounted for" N of R1, which represent 207% of the "not accounted for" N of CM, suggest that the sustainability of intensive cropping systems such as R1 is significantly reduced.

Surprisingly, PM receiving input A had − 24% of "not accounted for" N, which implies that more N was present either in harvested biomass or accumulated in the soil compared to N applied with fertilizers. Our explanation is that the presence of N-fixing legumes in the meadow plant community substantially contributed to adding extra N to the system. Similarly, the presence of N-fixing legumes in the rotated meadow is also a likely explanation for the low amount of "not accounted for" N in rotation R6 compared to other arable systems. It is plausible that the presence of legume species in the ley phase contributed to increasing the "buffering capacity" of the soil system in relation to surplus N. In fact, Raun et al. (1999) shown that when fertilizer N was applied to cultivated alfalfa (*Medicago sativa* L.) systems, forage yields increased while soil NH4-N and NO3-N levels did not. Similar results were reported by Ceotto and Spallacci (2006), who indicated that the N-buffering capacity of legumes is the result of physiological, morphological, and ecological factors.

For input B, the amount of "not accounted for" N decreased for all cropping systems compared with input A: 46% for CM, 37% for R1, 43% for R3, − 3% for R6, and − 66% for PM. Negative values, that denote more N harvested with biomass or accumulated in the soil compared to N applied, were obtained for R6 and PM including meadow and therefore N-fixing legumes. This suggests that reliance on N-fixing legumes as a source of N tends to increase under inputs B whereas N losses tend to decrease across all cropping systems.

We estimate that the fraction of N applied which contributed to soil N stock is 10% for CM, 5% for R1, 0.4% for R3, and 6% for R6 under input A, respectively. This fraction increased to 34% for PM under the same input A. Under agronomic input B the same N fraction increased slightly for arable cropping systems, and rose to 49% for the no-till PM. Therefore, the no-till option seems to exert a marked influence on soil N stock.

Compared to all arable cropping systems, the no-till system PM is characterized by a surprisingly high recovery efficiency (RE_N) whereby the fraction of N applied that is harvested by the crop was estimated as 90% under input A and 117% under input B. These high values may relate to the presence of nitrogen-fixing legumes among plant species established in the permanent meadow, especially white clover, which is an invasive weed on our experimental site.

For the arable cropping systems, which did not include legumes among the cultivated species, the fraction of N recovered within the biomass yield was about 42–44% for CM, respectively, with input A and B, 47–57% for R1 and 46–56% for R3 for the same agronomic inputs (Table 3). Interestingly, RE_N rose from 77 to 97% for R6, a rotation in which 3 years of rotated meadow (i.e., seeded consociation of white clover-tall fescue) are alternated with 3 years of silage maize-Italian ryegrass. Also in case of arable systems, the

presence of nitrogen-fixing legumes in the rotated meadow (i.e., white clover) increased the RE_N of the cropping system. Therefore, the advantage of a 3-year break (with rotated meadow) of the continuous sequence of silage maize-Italian ryegrass was a higher recovery of N by the cropping system. As previously indicated, it is likely that the legume present in the ley phase acted as a buffer for the surplus N.

The AE_N, i.e., the amount of dry matter produced per kilogram of N applied (Table 3), tended to increase with the reduction of inputs. An increase of + 8% with input B was observed for CM, + 34% for R1, + 29% for R3, + 34% for R6 and + 38% for PM. This indicates that a 30% reduction of N supply reduced the N losses in the environment.

Overall, the values of AE_N and RE_N calculated for this experiment fall within the range reported by Cassman et al. (2002) for cereal cropping systems. In essence, the inclusion of legumes and the reduction of N input had their own contributory role in enhancing N-use efficiency of these arable and no-till cropping systems. A considerable influence of the no-till PM for increasing N-use efficiency is a core result for this experiment.

3.3 Dry matter yield, feed units for lactation, and crude protein

When observing the evolution of dry matter yields over 30 years, we found that the permanent meadow (PM) was the only system showing a steady increase, with an average yield gain of 170 kg dry matter ha^{-1} (Fig. 2c, Table 2). The regression slope of the annual rotation R1 was significantly negative, with an average annual yield decrease of − 155 kg dry matter ha^{-1}. A similar trend was observed for the 6-year rotation R6, with an annual yield decrease of 33% compared to R1. Finally, the regression slope was not significantly different from zero for both the continuous grain maize CM and 3-year rotation R3.

While changes in productivity over time are important, cropping systems characterized by different products and crop species can hardly be compared in terms of dry matter yields owing to their different nutritional value. As the cropping systems compared in this experiment were devised to feed dairy cows, more substantial comparisons can be made on feed units for lactation (Unité Fourragère Lait, UFL, and crude proteins (i.e., N × 6.25). Table 3 reports 30-year averages of dry matter yield, UFL, and crude proteins for all combinations of cropping systems and agronomic inputs.

Under nutrient input A, annual rotation (R1) was the most productive system in terms of both dry matter yield (26,559 kg ha^{-1} year^{-1}) and milk units for lactation (22,187 UFL ha^{-1} year^{-1}) but not in terms of crude protein. At the opposite extreme, permanent meadow (PM) was the highest crude protein producer (2098 kg ha^{-1} year^{-1}) albeit a mere 50% of dry matter biomass and 42% of UFL compared to

the most productive annual rotation R1. It is worth noting that crude protein produced by PM is OGM free, while for the arable cropping systems, which are based on cereal crops, imported GMO soybean is predominantly utilized to complement the diet of the cows.

This could be a strength for PM considering the willingness of some consumers to pay more for OGM free products. The other cropping systems lie in between these two extremes. The continuous grain maize CM produced just 37% of biomass and 55% of UFL compared to annual rotation R1, and only 39% of crude protein compared to PM. We stress that the widely adopted maize monoculture CM performs poorly compared to other cropping systems, especially in terms of soil C sequestration, N-use efficiency, and productivity.

The 3-year rotation R3 produced 80% of dry matter yield and 88% UFL compared to the annual rotation R1, and 69% of crude protein compared to the permanent meadow. Finally, the 6-year rotation R6 produced 74% of dry matter yield and 71% UFL compared to the annual rotation R1, compensated by 98% of the crude protein compared to permanent meadow.

We assessed whether (and to what extent) a 30% reduction of fertilizer supply with input B might influence dry matter yield, UFL, and crude protein in our systems. For the continuous maize CM, both yield and UFL under input B were 87%, while crude protein was 84% compared to input A. For the permanent meadow PM input B the yield was 84%, UFL was 80%, and crude protein was 79% compared to input A. For the annual rotation R1 input B, both yield and UFL were 91%, and crude protein was 81% compared with the input A. For the 3-year rotation R3 input B yield was 89%, and crude protein was 84% compared to input A. Finally, for the 6-year rotation R6 input B yield was 91%, UFL was 90% and crude protein was 86% compared to input A (Table 3). Therefore, a 30% reduction of industrial and organic fertilization determined a reduction in yield, UFL and crude protein, which was, however, less than the proportional reduction of fertilizer application. Nevertheless, as Loomis and Connor (1992) pointed out, fertilizers can be regarded as a substitution of energy for land, because with low fertilization more cultivated land is needed to obtain the same production target. Hence, the reduction of fertilizers applied with input B to the arable cropping systems of this experiment, is not necessarily a good bargain if one considers that more land might need to be devoted to intensive arable cropping systems.

Annual rotation R1 with input A, widely adopted by livestock farmers in the same agricultural region, provided the highest annual productivity at the expense of low annual soil C accrual, a low N retention coefficient and a low recovery of applied N. It should be emphasized, however, that this cropping system offers the indisputable advantage of land sparing: when the productivity target is met on a limited land area, the rest of the land can be devoted to less intensive management, including permanent meadow.

Overall, our findings are consistent with the view that across agricultural systems, land-use choices seldom, if ever, entail "win-win" solutions and unintended trade-offs are inevitable (Defries et al. 2004). To this end, "win-lose" solutions represent a good compromise for balancing ecosystems services and human requirements for goods.

If we refer to sustainability as land use or management, which does not undermine the natural resource base (Fresco and Kroonenberg 1992), then our findings suggest that all compared cropping systems in this study are sustainable from the SOC maintenance point of view. This is because soil organic C was maintained or increased, and the productivity level remained relatively stable within the range of large inter-annual variability across all systems. In this study, we go one step further suggesting that the challenge is not only to maintain natural resources for future generations, but also how to find the best compromise among multiple ecosystem services. Nevertheless, N losses from cropping systems must be considered in compliance with legislation requirements, in particular, the Nitrates Directive 91/676/EEC that address the excessive application of livestock effluents and the excessive use of mineral N fertilizers (Zavattaro et al. 2016). The high value of "not accounted for" N of the most productive annual rotation R1 indicates presumable high N losses in the environment.

4 Conclusion

Our study is one of the first to show clear trade-offs between multiple ecosystem services. The no-till permanent meadow is associated with substantial soil carbon sequestration, with higher N-use efficiency and higher crude protein production, but also with lower dry matter and reduced feed units for lactation when compared with the arable cropping systems. This implies that converting arable soil into no-till permanent meadow is a win-lose solution. The most productive annual rotation (silage maize-Italian ryegrass) offers a complementary win-lose solution whereby high yields and increased feed units for lactation can be obtained cultivating a smaller proportion of cropland area. The other cropping systems are less productive and provide little or no advantage for soil carbon sequestration. In conclusion, our results suggest that high fertilization rates might be justified when the main goal is to spare land for less intensive uses, such as permanent meadow.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

References

Aalde H, Gonzalez P, Gytarsky M, Krug T, Kurz WA, Lasco RD, Martino DL, McConkey BG, Ogle S, Paustian K, Raison J, Ravindranath NH, Schoene D, Smith P, Somogyi Z, Van Amstel A, Verchot L (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol 4. Agriculture, Forestry and Other Land Use, Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, p 29

Albizua A, Williams A, Hedlund K, Pascual U (2015) Crop rotations including ley and manure can promote ecosystem services in conventional farming systems. Appl Soil Ecol 95:54–61. https://doi.org/10.1016/j.apsoil.2015.06.003

Attard E, Le Roux X, Charrier X, Delfosse O, Guillaumaud N, Lemaire G, Recous S (2016) Delayed and asymmetric responses of soil C pools and N fluxes to grassland/cropland conversions. Soil Biol Biochem 97:31–39. https://doi.org/10.1016/j.soilbio.2016.02.016

Autret B, Mary B, Chenu C, Balabanec M, Girardin C, Bertrand M, Grandeaud G, Beaudoin N (2016) Alternative arable cropping systems: a key to increase soil organic carbon storage? Results from a 16 year field experiment. Agric Ecosyst Environ 232:150–164. https://doi.org/10.1016/j.agee.2016.07.008

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12:1–11. https://doi.org/10.1111/j.1461-0248.2009.01387.x

Borrelli L, Tomasoni C (2005) Nota sulle caratteristiche pedo-climatiche dell'azienda dell'Istituto Sperimentale per le Colture Foraggere di Lodi. [Pedoclimatic characteristics of the Istituto Sperimentale per le Colture Foraggere farm in Lodi]. Ann ISCF Lodi IX, pp 43–49

Borrelli L, Castelli F, Ceotto E, Cabassi G, Tomasoni C (2014) Maize grain and silage yield and yield stability in a long-term cropping system experiment in Northern Italy. Eur J Agron 55:12–19. https://doi.org/10.1016/j.eja.2013.12.006

Carpenter SR, Caraco NF, Corell DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8:559–568

Cassman KG, Dobermann AR, Walters DT (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31(2): 132–140

Ceotto E, Spallacci P (2006) Pig slurry applications to alfalfa: productivity, solar radiation utilization, N and P removal. Field Crops Res 95(2–3):135–155. https://doi.org/10.1016/j.fcr.2005.02.005

Defries RS, Foley JA, Asner GP (2004) Land-use choices: balancing human needs and ecosystem function. Front Ecol Environ 2:249–257

FAO (2014) Agriculture, forestry and other land use emissions by sources and removals by sinks: 1990–2011 analysis. FAO statistics division working paper series, 14/01, UN FAO, Rome, Italy

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Stuart Chapin F, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice C, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574. https://doi.org/10.1126/science.1111772

Fornara DA, Tilman D (2008) Plant functional composition influences rates of soil carbon and nitrogen accumulation. J Ecol 96:314–322. https://doi.org/10.1111/j.1365-2745.2007.01345.x

Fornara DA, Wasson EA, Christie P, Watson CJ (2016) Long-term nutrient fertilization and the carbon balance of permanent grassland: any evidence for sustainable intensification? Biogeosciences 13:4975–4984. https://doi.org/10.5194/bg-13-4975-2016

Fresco LO, Kroonenberg SB (1992) Time and spatial scales in ecological sustainability. Land Use Policy 9(3):155–168. https://doi.org/10.1016/0264-8377(92)90040-4

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, Cosby BJ (2003) The nitrogen cascade. Bioscience 53(4):341–356. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Grignani C, Zavattaro L, Sacco D, Monaco S (2007) Production, nitrogen and carbon balance of maize-based forage systems. Eur J Agron 26: 442–453. https://doi.org/10.1016/j.eja.2007.01.005

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories. IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/

Jarrige R (1989) Ruminant nutrition, recommended allowances and feed tables. John Libbey Eurotext, Montrougue

Johnston AE (1997) The value of long-term field experiments in agricultural, ecological, and environmental research. Adv Agron 59:291–333

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 13:1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Littell RC, Milliken GA, Stroup WW, Wolfinger RD (1996) SAS system for mixed models. SAS Institute Inc., Cary

Loomis RS, Connor DJ (1992) Crop ecology: productivity and management in agricultural systems. Cambridge University Press, Cambridge

Maillard E, Angers D (2014) Animal manure application and soil organic carbon stocks: a meta-analysis. Glob Chang Biol 20:666–679. https://doi.org/10.1111/gcb.12438

Peterson GA, Lyon DJ, Fenster CR (2012) Valuing long-term field experiments: quantifying the scientific contribution of a long-term tillage. Soil Sci Soc Am J 76(3):757–765. https://doi.org/10.2136/sssaj2011.0413

Powlson DS, Gregory PJ, Whalley WR, Quinton JN, Hopkins DW, Whitmore AP, Hirsch PR, Goulding KWT (2011) Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36:572–587. https://doi.org/10.1016/j.foodpol.2010.11.025

Raun WR, Johnson GV, Phillips SB, Thomason WE, Dennis JL, Cossey DA (1999) Alfalfa yield response to nitrogen applied after each cutting. SSSAJ 63(5):1237–1243. https://doi.org/10.2136/sssaj1999.6351237x

Richter DD, Hofmockel M, Callaham MA, Powlson DS, Smith P (2007) Long-term soil experiments: keys to managing Earth's rapidly changing ecosystems. Soil Sci Soc Am J 71:266–279. https://doi.org/10.2136/sssaj2006.0181

Richter DD, Markewitz D (2001) Understanding soil change. Cambridge, UK, pp 272. ISBN 0521771714

SAS Institute (2009) SAS/STAT 9.2 User's guide, 2nd edn. Cary, NC, USA

Tomasoni C, Borrelli L, Ceotto E (2011) Effect of integrated forage rotation and manure management on yield, nutrient balance and soil organic matter. Ital J Agron 6-10:55–60. https://doi.org/10.4081/ija.2011.e10

Tomasoni C, Borrelli L, Pecetti L (2003) Influence of fodder crop rotations on the potential weed flora in the irrigated lowlands of Lombardy, Italy. Eur J Agron 19:439–451. https://doi.org/10.1016/S1161-0301(02)00137-5

Van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Res:197–208. https://doi.org/10.1016/S0378-4290(97)00037-3

Zavattaro L, Assandri D, Grignani C (2016) Achieving legislation requirements with different nitrogen fertilization strategies: results from a long term experiment. Eur J Agron 77:199–208. https://doi.org/10.1016/j.eja.2016.02.004