

# Wheat yield as a measure of the residual fertility after 20 years of forage cropping systems with different manure management in Northern Italy

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## Abstract

After 20 years of application of different manure types, cropping systems and additional nitrogen (N) levels, their residual fertility effects were compared by measuring the yield of a following unfertilised wheat crop (Experiment 1), which was sown on exactly the same plots of the previous long-term trial. All previously applied factors caused significant differences in wheat yield. Wheat yielded more on plots that had received farmyard manure (FYM) compared to those where semi-liquid manure (SLM) was previously applied. Long-term application of a semi-intensive rotation, with three years of annual double cropping of autumn-sown Italian ryegrass and spring-sown silage maize followed by three years of mown lucerne (R6), resulted in higher wheat yield than application of just the annual double cropping of Italian ryegrass and silage maize (R1). Application of further mineral N fertilisation to previous cropping systems caused higher yield of the subsequent wheat crop. The difference in wheat yield between the R6 and R1 systems was greater with SLM (+28%) than FYM application (+11%) resulting in a significant manure × system

interaction. A companion experiment (Experiment 2) was carried out to compute the nitrogen agronomic efficiency (NAE) from the yield of wheat plots that were sown after ploughing a nearby 20-year unfertilised grassland and received four levels of mineral N fertilisation. NAE was further used to empirically estimate the productive advantage (PA) conferred by previous manure-system-mineral nitrogen combinations in the long-term trial. PA was measured as equivalent kg of mineral N to be applied to wheat to achieve the yield level recorded after any previous combination. The estimated PA values were much higher when wheat followed FYM compared to SLM application, and when it followed R6 compared to R1 system. The SLM-R1 combination had negative PA values, indicating a productive disadvantage on wheat of this preceding combination. The enhancement of residual soil fertility by long-term application of FYM compared to SLM could be attributed to greater nutrient provision during the years by FYM than by SLM. However, further fertility advantages of FYM are discussed. Despite lower nutrient supply by organic fertilisers in R6 than in R1 system, the former had higher residual fertility. The presence of lucerne in the R6 rotation likely enriched the soil in nitrogen and increased its availability for following cropping. Possible benefits of the legume on the soil suppressiveness might have been a further asset of the R6 system.

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## Introduction

The increasing concentration and intensification of the dairy cattle farming in the irrigated lowlands of Northern Italy has been paralleled by a sharp simplification of animal feeding, with spread of silage crops to maximise the production of feed energy and subsequent reduction of meadows and grain crops, and a deep modification of the management of animal excreta, with production of semi-liquid manure (SLM) instead of the traditional farmyard manure (FYM). Intensive maize (*Zea mays* L.) monoculture or short rotation cropping involving maize have drastically replaced permanent and rotational meadows that represented the main forage resource until the 1960s. The maize-Italian ryegrass (*Lolium multiflorum* Lam.) annual double crop has great yield potential under high fertilisation rates (Grignani *et al.*, 2007). Possible environmental risks of nitrogen (N) leaching associated with high fertiliser inputs can be counterbalanced in the double cropping system by the soil cover enabled in winter by the ryegrass and the high uptakes of both crops. Concerns associated with intensely managed systems also include decreased soil organic matter, degraded soil structure, increased soil erosion, and increased production costs (Karlen *et al.*, 1994; Diacono and Montemurro, 2010).

Soil fertility is defined as the ability of the soil to fulfil physical, chemical and biological needs for the plant growth, and sustainable farming systems are those that reconcile the agricultural use of soil resources with the maintenance of the different fertility

components (Diacono and Montemurro, 2010). The residual soil fertility is meant as the level of nutrients available in the soil for a crop without additional fertilisation. A build-up of residual soil fertility, as a combination of biological, chemical and physical fertility, is expected with long-term application of organic fertilisers to the soil (Nardi *et al.*, 2004; Diacono and Montemurro, 2010). Crop rotations can also affect soil fertility and, hence, crop yields (Berzsenyi *et al.*, 2000). Inclusion of legume leys in rotations increases the N supply (Riedell *et al.*, 2009) as it is expected from N-fixing species, while enhancing other biochemical and physical aspects of soil fertility (Monaci *et al.*, 2017).

Residual fertility can be assessed over one or more growth periods following the completion of a long cropping phase with organic and/or mineral fertilisation (Bhagal *et al.*, 2000; Hernández *et al.*, 2013; Suarez-Tapia *et al.*, 2018). Long-term trials are needed to investigate effects that evolve slowly, such as carbon (C) accumulation and release of nutrients, and need time to be assessed (Diacono and Montemurro, 2010). The test crop to assess the residual fertility was very often represented by a winter cereal such as wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) (Cela *et al.*, 2011; Petersen *et al.*, 2012; Hernández *et al.*, 2013; Suarez-Tapia *et al.*, 2018). Preference for a winter cereal with moderate fertilisation requirements can be suggested by the fact that the lack of any N inputs in the test year(s) may cause too poor development and non-representative yield estimates for crops with high production potential. Nonetheless, there are reports that summer crops such as maize may be better suited than winter crops to assess manure fertilisation effects (Sacco *et al.*, 2015).

The current study aimed at assessing the residual fertility effects after 20 years of application of FYM and SLM onto two alternative cropping systems with or without a legume ley. This was attained by measuring the yield of wheat sown on the previous experimental treatments and to which no N fertilisation (either organic or chemical) was applied, and estimating whether previous cropping system-manure combinations conferred any productive advantage to wheat.

## Materials and methods

### Experiment 1. Wheat crop in the test year

After 20 years of application of all combinations of two manure types, two cropping systems and three levels of additional mineral N, as detailed here below, the long-term trial was terminated in autumn 2014. In October 2015 the plots previously allocated to each system-manure-nitrogen combination were ploughed and sown with the bread wheat variety Aubuisson at 180 kg ha<sup>-1</sup> seed rate without any additional fertilisation. The experimental design was a strip-split-split-plot following the one of the previous long-term trial, with three replications and plot size of 84 m<sup>2</sup> (7×12 m). Previous manure treatments were main plots, previous cropping systems were sub-plots, and previous mineral N fertilisations were sub-sub-plots. All elementary plots of wheat were harvested by combine at maturity and the grain yield was recorded.

### Experiment 2. Assessment of nitrogen agronomic efficiency

In addition, further wheat plots (7.5 m<sup>2</sup> each, 1.5×5 m) were sown after ploughing grassland strips which were maintained for 20 years as unfertilised buffers between the replications of the

long-term trial. These plots received 0, 40, 80 or 120 kg ha<sup>-1</sup> mineral N and were sown according to a randomised complete block design with three replications. Grain yield data recorded on these plots were used to compute the nitrogen agronomic efficiency (NAE, kg/kg):

$$\text{NAE} = [(\text{yield at } N_x - \text{yield at } N_0) / \text{applied N at } N_x] \quad (1)$$

where N<sub>0</sub> is the wheat check treatment with no mineral nitrogen fertilisation, and N<sub>x</sub> is any other fertilisation level (López-Bellido and López-Bellido, 2001).

NAE was further used to estimate the productive advantage (PA) conferred by previous manure-system-mineral nitrogen combinations and measured as equivalent kg of mineral N to be applied to the wheat crop to achieve the yield level recorded after any previous combination:

$$\text{PA} = [(\text{yield MSN}_i - \text{yield } N_0) / \text{mean NAE}] \quad (2)$$

where MSN<sub>i</sub> is any *i*th previous manure-system-mineral nitrogen combination and N<sub>0</sub> is the wheat check treatment with no mineral nitrogen fertilisation in Experiment 2.

### Previous long-term trial

The trial was established in 1995 in Lodi (45°19' N, 9°28' E, 80 m a.s.l.) and described in detail by Tomasoni *et al.* (2011), who assessed the effects of cropping systems and manure management in terms of yield, nutrient balance and soil organic matter after 13 years of application.

The experiment compared two rotations, namely an annual double cropping of Italian ryegrass sown in autumn and harvested in May followed by silage maize sown immediately afterwards and harvested in September (R1), and a semi-intensive 6-year rotation with three years of the former double cropping followed by three years of lucerne (*Medicago sativa* L.) sown in spring and harvested for hay 3-4 times per year (R6). Each rotation received dairy manure in the form of both FYM, obtained from composting cattle excreta with maize stover, and SLM. Each land area unit received the amount of excreta produced by the number of adult cows that could be sustained in terms of energy by the forage produced by each crop rotation. We must emphasise, however, that the maize stover used to compost the FYM were obtained from grain maize fields other than those that received the manure in this trial and, therefore, the system cannot be considered virtuously closed. Based on the assumptions and computations reported in Tomasoni *et al.* (2011), 66 t ha<sup>-1</sup> of FYM and 100 m<sup>3</sup> ha<sup>-1</sup> of SLM were applied annually to R1, and 44 t ha<sup>-1</sup> of FYM and 66 m<sup>3</sup> ha<sup>-1</sup> of SLM to R6. Both FYM and SLM were distributed onto the soil surface immediately before ploughing at 0.3 m depth. Mean percentage values of dry matter, total N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O were 28.1%, 0.66%, 0.48% and 0.84% for FYM, and 9.2%, 0.25%, 0.18% and 0.36% for SLM. For comparison, the cattle slurry used by Grignani *et al.* (2007) in a long-term trial with organic fertilisers had 5.7% dry matter and 0.23% total N, while the FYM used in the same study had 25.7% dry matter and 0.62% total N.

Three levels of additional mineral N fertilisation were applied to each manure-system combination, namely, N<sub>0</sub> with no nitrogen application, N<sub>1</sub> with 75 kg ha<sup>-1</sup> to Italian ryegrass and 150 kg ha<sup>-1</sup> to maize (no nitrogen applied to lucerne), and N<sub>2</sub> with 150 kg ha<sup>-1</sup> to Italian ryegrass and 300 kg ha<sup>-1</sup> to maize (no nitrogen on lucerne).

## Statistical analysis

An analysis of variance (ANOVA) was performed for Experiment 1 according to the experimental design, assessing the variation for wheat grain yield in the test year of the main factors applied during the long-term trial, that is, kinds of manure, forage systems and additional mineral N fertilisation levels, as well as their first- and second-degree interactions. A second ANOVA and the least significant difference (LSD) at  $P=0.05$  compared the wheat grain yield among the mineral N fertilisation levels in Experiment 2, as well as the NAE computed from grain yield values in the same experiment. Differences in PA values - estimated from the computed NAE - among the factors tested in Experiment

1 were also assessed by ANOVA. Finally, an ANOVA and the LSD compared the wheat grain yield recorded in Experiment 1 and the estimated PA for individual manure-system-mineral nitrogen combinations applied in the preceding long-term trial.

**Table 1. Summary analysis of variance (ANOVA) of wheat grain yield from Experiment 1. Wheat sown after 20 years of applications of different manure types, forage systems and additional mineral nitrogen fertilisations, which represented the main sources of variation in the ANOVA. See Materials and methods section and Table 2 for details of these factors.**

Source of variation	DF	MS	F value	Probability
Manure type (M)	1	20.6	10.0	<0.05
Forage system (S)	1	7.80	54.3	<0.001
Mineral nitrogen (N)	2	1.44	10.0	<0.01
M × S	1	0.74	5.1	<0.05
M × N	2	0.13	0.9	0.40
S × N	2	0.19	1.4	0.28
M × S × N	2	0.10	0.4	0.64

DF, degrees of freedom; MS, mean square.

**Table 2. Mean wheat grain yield recorded in Experiment 1 after 20 years of application of different factors in the preceding long-term trial, and productive advantage estimated for the same factors based on grain yield recorded in Experiment 1 and nitrogen agronomic efficiency estimated from Experiment 2 (Table 3).**

Tested factor (from previous long-term trial)	Wheat grain yield (t ha <sup>-1</sup> )	Productive advantage (equivalent kg of mineral N)*
Manure type		
FYM	6.43 <sup>a</sup>	65.2 <sup>a</sup>
SLM	4.91 <sup>b</sup>	-0.5 <sup>b</sup>
Forage system		
R1	5.20 <sup>b</sup>	12.2 <sup>b</sup>
R6	6.13 <sup>a</sup>	52.5 <sup>a</sup>
Mineral nitrogen		
N0	5.27 <sup>b</sup>	15.5 <sup>b</sup>
N1	5.91 <sup>a</sup>	43.0 <sup>a</sup>
N2	5.82 <sup>a</sup>	38.5 <sup>a</sup>

\*See Materials and methods section for estimation Equation 2. FYM, farmyard manure; SLM, semi-liquid manure. R1, annual double cropping of Italian ryegrass and silage maize; R6, 6-year rotation with 3 years of annual double cropping and 3 years of lucerne. N0, no additional mineral nitrogen; N1, 75 kg ha<sup>-1</sup> N on Italian ryegrass and 150 kg ha<sup>-1</sup> N on maize; N2, double rates than N1. <sup>a,b</sup>For each factor and variable, mean values followed by different letters were different according to the least significant difference (LSD) at  $P=0.05$ .

**Table 3. Nitrogen agronomic efficiency computed from grain yield of wheat plots in Experiment 2 that received increasing mineral N fertilisation. Wheat plots were sown on ploughed grassland previously unfertilised for 20 years.**

Mineral N application (kg ha <sup>-1</sup> )	Grain yield (t ha <sup>-1</sup> )	NAE (kg kg <sup>-1</sup> )*
N 0	4.93 <sup>c</sup>	-
N 40	6.06 <sup>bc</sup>	28.3 <sup>a</sup>
N 80	6.46 <sup>ab</sup>	19.1 <sup>b</sup>
N 120	7.52 <sup>a</sup>	21.6 <sup>b</sup>
Mean	6.24	23.0

\*See Materials and methods section for computation Equation 1. NAE, nitrogen agronomic efficiency. <sup>a,b,c</sup>In each column, mean values followed by different letters were different according to the least significant difference (LSD) at  $P=0.05$ .

PA estimated from the recorded wheat yields in Experiment 1 and the computed NAE mean value was higher for the wheat crop following FYM than SLM long-term application, and following the R6 rotation than the R1 double cropping system (Table 2). Wheat cropped on plots not receiving any additional mineral N fertilisation in the previous 20 years (N0 treatment) obviously had lower PA than those previously supplied with additional mineral N (N1 and N2 treatments) (Table 2).

The significant manure  $\times$  system interaction of wheat yield in Experiment 1 is clearly depicted in Table 4, where the mean values of manure-system combinations are reported. The difference in following wheat yield between the previous R6 and R1 systems was larger with SLM application (5.52 vs 4.31 t ha<sup>-1</sup>, +28%) than with FYM application (6.75 vs 6.10 t ha<sup>-1</sup>, +11%), causing the significant interaction.

Even without additional mineral N application (N0 treatment), the best long-term manure-system preceding combination (FYM-R6) resulted in wheat grain yield (6.62 t ha<sup>-1</sup>) and PA (74 equivalent kg of mineral N) that significantly ( $P \leq 0.05$ ) exceeded the FYM-R1-N0 combination, as well as almost all SLM-including combinations (Table 4). The SLM-R1 preceding combination had negative PA values regardless of the mineral nitrogen application (Table 4), indicating a productive disadvantage of this combination for the following wheat crop.

## Discussion and conclusions

A residual fertility effect, assessed as the yield of the following unfertilised wheat crop, was evident from this study. Boghal *et al.* (2000) wondered whether the residual fertility observed in non-fertilised plots following a long-term experiment with mineral N fertilisation was accounted for by long-term N accumulation, or was it the effect of the previous year's residues. Suarez-Tapia *et al.* (2018) indicated that more than one test year is needed when esti-

imating residual N effects. However, Boghal *et al.* (2000) also suggested that the most recent residues were less important than the long-term ones in the soil N increase and that a build-up in the long-term soil fertility had occurred.

The current investigation clearly indicated that the residual soil fertility was enhanced by long-term application of FYM compared to SLM. This was surely an effect of the greater nutrient provision during the years with FYM compared to SLM as a result of the addition of maize stover to animal excreta in composting FYM, different gaseous N losses between FYM and SLM, and the dilution of SLM (Tomasoni *et al.*, 2011). Greater N, P and K surpluses, and higher soil organic matter were reported after repeated application of FYM than SLM across cropping systems (Tomasoni *et al.*, 2011).

However, further fertility advantages of FYM compared to more diluted forms of manure can be inferred from the literature. In their review of long-term effects of organic amendments on soil fertility, Diacono and Montemurro (2010) reported much higher soil organic C increase with FYM than with cattle slurry. In a medium-term trial (with measurements made 11 years after establishment), Grignani *et al.* (2007) found that repeated applications of organic fertilisers increased the soil organic matter in the tilled layer and that higher proportion of N and C surpluses were incorporated into the soil organic matter when FYM was used compared to the use of slurry. They also found that FYM had higher N efficiency than slurry when applied at high rates to the maize-Italian ryegrass double annual crop. From the same trial, Monaco *et al.* (2008) concluded that FYM applications caused greater increase in soil organic matter, potentially mineralisable N and soil microbial biomass than slurry, while Bertora *et al.* (2009), reporting that C and N amounts retained each year in the soil were much higher with FYM than with slurry, suggested that the production and use of FYM was the most C conservative management. The C compounds present in the bedding material mixed with excreta in the composting process for FYM have slower decomposition than those in excreta just mixed with water, thus accounting for the

**Table 4.** Mean wheat grain yield recorded in Experiment 1 for each manure-system-nitrogen combination applied in the preceding long-term trial, and productive advantage estimated for the same combinations based on grain yield recorded in Experiment 1 and nitrogen agronomic efficiency estimated from Experiment 2 (see Table 3).

Manure type	Forage system	Mineral nitrogen	Wheat grain yield (t ha <sup>-1</sup> )	Productive advantage (equivalent kg of mineral N)*	
FYM	R1	N0	5.63	31	
		N1	6.41	64	
		N2	6.27	58	
	Mean		6.10	51	
	R6	N0	6.62	74	
		N1	6.70	77	
		N2	6.93	87	
Mean		6.75	79		
SLM	R1	N0	3.70	-53	
		N1	4.68	-10	
		N2	4.54	-17	
	Mean		4.31	-27	
	R6	N0	5.15	10	
		N1	5.87	41	
		N2	5.54	26	
	Mean		5.52	26	
	LSD ( $P=0.05$ )			0.95	41

\*See *Materials and methods* section for estimation Equation 2. In italics, mean values of each manure-system combination. FYM, farmyard manure; SLM, semi-liquid manure; R1, annual double cropping of Italian ryegrass and silage maize; R6, 6-year rotation with 3 years of annual double cropping and 3 years of lucerne; N0, no additional mineral nitrogen; N1, 75 kg ha<sup>-1</sup> N on Italian ryegrass and 150 kg ha<sup>-1</sup> N on maize; N2, double rates than N1.



higher content of stabilised organic compounds in the manure than in slurry (Bertora *et al.*, 2009). Yet, the use of manure for organic matter enrichment can be controversial when FYM production requires the subtraction of crop residues from land areas other than that of its application, with a risk of improvement in the application areas at the expenses of other farmlands (Schlesinger, 1999; Tomasoni *et al.*, 2011).

Manure application provides organic C to the soil and, at the same time, protects from degradation the organic matter within stable soil aggregates promoted by the binding compounds present in the manure (Whalen and Chang, 2002; Diacono and Montemurro, 2010). In a long-term experiment with organic and mineral fertilisation, Triberti *et al.* (2016) reported that soil N content was more related to accumulated organic matter than to mineral N fertilisation. The beneficial effects exerted on soil organic C by the application of high rate of manure were still evident several years after the application was withheld. They also observed that a long crop rotation including three years of lucerne ley had the greatest increase of stable C content in the soil, implying also a build-up of stable N forms produced by the rhizobia fixation in the three years of the forage legume and made available to successive crops by microbial decomposition of legume residues (Triberti *et al.*, 2016).

Increase of soil N content when N-fixing legume species are included in crop rotations is a common finding, due directly to N fixation by legumes and indirectly to the scavenging of deep N residuals by deep-rooted legume crops, such as lucerne, which increases N availability to subsequent more shallow-rooted crops (Karlen *et al.*, 1994; Carpenter-Boggs *et al.*, 2000). Riedell *et al.* (2009) concluded that including forage legumes in extended rotations with maize would increase the sustainability of forage systems. Monaci *et al.* (2017) emphasised the role of lucerne in long rotations with annual crops in building up the soil organic C, enhancing the biological fertility and improving the soil physical conditions compared to sole annual crop rotations. Possible further benefits of the legume cultivated in rotation in terms of soil suppressiveness to soil borne diseases should not be overlooked (Mazzola, 2002).

Given these premises, it was not surprising that our results indicated that the combination of farmyard manure application and 6-year rotation including lucerne ley had the highest productive advantage (as defined in this study in terms of equivalent kg of mineral N) for the following crop. The (re)-introduction of legume meadows in the too simplified maize rotations can be suggested as a means to maintain a good fertility level in the long run in forage systems (Triberti *et al.*, 2016).

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