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Outcomes from a long-term study on crop residue effects on plant yield and nitrogen use efficiency in contrasting soils

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ABSTRACT

The use of crop residues to increase crop yield and NUE is still a matter of debate since studies in different climates and soil types have led to inconclusive results and this could be partly explained by the numerous and complex factors that affect the residue-derived N cycle in field conditions. Given this complexity, long-term field experiments appear to be the more suitable tools to investigate these dynamics and develop effective management practices. In this paper, we hypothesized that residue incorporation affects crop yield and NUE, both through a direct nutritional effect given by residue decomposition and an indirect influence on soil physical and biological properties related to the input of organic carbon. We used data from a long-term field experiment started in 1970 in North-eastern Italy to evaluate the effects of crop residue incorporation on the productivity and nitrogen use efficiency of different crops (i.e., maize, winter wheat, sugarbeet, tomato and potato) in three contrasting soil types: a Fluvi–Calcaric Cambisol, a Gleyi–Vertic Chernozem and a Calcaric Arenosol. The results showed that incorporation of residues seems to have different effects depending on crop and soil type. For potato and tomato and, to a lesser extent, for sugarbeet, residues can improve crop productivity, while the effects on cereals seem to be lower. Regarding soil type, residues are proportionally more effective in sandy and sandy-loam soils, both through a direct nutritional effect and, possibly, an improvement of soil characteristics. Anyway the residue effect is relatively low, with modest increments of biomass in the most fertile soils and their effect can be compensated by N fertilization. The use of residues as organic amendment or their re-use in other processes (e.g., as a source of bioenergy) therefore has to be carefully analysed considering both the energy and C balances and the positive effects on soil productivity.

1. Introduction

World demand for nitrogen (N) fertilizers increased by 2.3 million tons annually from 2002 to 2012 (Faostat, 2012) and is expected to reach 115.9 million tons in 2016 (Fao, 2012). Given the trends in world population growth and the consequent increase in food production, it is expected that N consumption will continue to increase accordingly. The misuse of fertilizers can create serious environmental problems (Galloway et al., 2008) (i.e., eutrophication, groundwater pollution and GHGs emissions) through mechanisms such as leaching, volatilisation, surface runoff and denitrification (Van Grinsven et al., 2015). The predominant role of agriculture in N-derived pollution is underlined by the fact that fertilizers account for 63% of all anthropogenic sources of reactive nitrogen (Dobermann, 2005). The term reactive nitrogen encompasses every biologically, photochemically or radiatively active form of N that can contribute to pollution in different compartments of the biosphere (i.e., every form of nitrogen other than N_2) (Sutton, 2011). An index commonly used to detect potential excess nitrogen is the nitrogen use efficiency (NUE), which is the proportion of applied fertilizer that is effectively converted into yield by the crop. Despite the recent improvements in N use efficiency obtained by farming systems in Europe, also as a consequence of application of the Nitrates Directive, N losses from agricultural fields are still 50 kg N ha^{-1} $year^{-1}$ on average (Lassaletta et al., 2014). Reducing the production and release in the environment of reactive nitrogen is thus a primary goal that can be achieved through appropriate soil management (i.e., reducing soil acidity, using conservation tillage practices and proper water management, growing cover crops or incorporating crop residues); an optimization of N input (using organic fertilizers such as manure, controlled release fertilizers and NH_4/NO_3 inhibitors with an accu-

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rate selection of the rates and timing of application); and through the adoption of crop rotations and nitrogen efficient genotypes.

The use of crop residues to increase NUE is still a matter of debate since studies in different climates and soil types have led to inconclusive results. Malhi et al. (2011) studying two long-term (26 years) rotations in a Black Chernozem and in a Orthic Gray Luvisol in Canada, found an increase (5.2 Kg N ha^{-1}) in N uptake by seed and straw almost ubiquitous in the first type of soil while only for a reduced period in the second. On the contrary, three years of straw incorporation in a Haplic Luvisol produced no significant improvements in NUE of winter wheat (Brennan et al., 2014). In a recent meta-analysis summarizing studies on rice cultivations in China, Huang et al. (2013) found that the incorporation of rice residues allowed a 29.4% reduction of inorganic N inputs without significant decreases in yield. These apparently contrasting results could be partly explained by the numerous and complicated factors that affect the residue-derived N cycle in field conditions, such as soil pH, salinity and texture, temperature and moisture conditions, freezing and thawing cycles, wetting and drying cycles, along with macro and microorganisms (Kumar and Goh, 1999). Given this complexity, long-term field experiments appear to be the more suitable tools to investigate these dynamics and develop effective management practices (Richter et al., 2007), especially in light of increasing future demands from agricultural ecosystems (Janzen, 2009). Long-term field experiments are fundamental not only to draw up local management guidelines, but can indubitably contribute to assessing global patterns and trends (Rasmussen, 1998) by building common databases and posing multi-site questions (Janzen, 2009).

In this paper we hypothesized that residue incorporation affects NUE, both through a direct nutritional effect given by residue decomposition and an indirect influence on soil physical and biological properties related to the input of organic carbon. We used data from a long-term field experiment started in 1970 in North-eastern Italy to evaluate the effects of crop residue incorporation on the productivity and nitrogen use efficiency of different crops in three contrasting soil types. The large crop database allowed empirical models to be built that could disentangle the multiple effects of residue incorporation on crop performances.

2. Materials and methods

2.1. The experiment

The long-term experiment is located at the experimental farm of the University of Padova (Veneto region, NE Italy 45° 21′N; 11° 58′E; 6 m a.s.l.). The local climate is sub-humid, with annual rainfall of about 850 mm. In the median year, rainfall is highest in June (100 mm) and October (90 mm) and lowest in winter (50–60 mm). Temperatures increase from January (minimum average: −1.5 °C) to July (maximum average: 27.2 °C). Reference evapotranspiration (ETo) is 945 mm with a peak in July (5 mm d^{-1}). ETo exceeds rainfall from April to September. The site has a shallow water table ranging from about 0.5–1.5 m in late winter–early spring to 1–2 m in summer.

Since 1970, the experimental design has been constituted by 108 open lysimeters of 4 m^2, filled with three types of soil: sandy, sandy-loam and clay. The main physical and chemical characteristics of the soils at the beginning of the experiment are listed in Table 1. The sandy-loam soil is classified according to FAO-UNESCO as a Fluvi–Calcaric Cambisol and is native to the experimental farm. The other two soils were brought from locations in the Veneto region: the clay soil from the south-western plain, and the sandy soil from the central coastal area. The clay soil is classified as a Gleyi–Vertic Chernozem, the sandy one as Calcaric Arenosol (Fao-Unesco, 2008).

Table 1
Main physical and chemical properties of the soils at the beginning of the experiment (1970).

	Clay	Sandy-loam	Sandy
Sand (2–0.05 mm)%	40.6	57.1	98.8
Silt (0.05–0.002 mm)%	18	23.7	0
Clay (<0.002 mm)%	41.4	19.2	1.2
pH (H_2O)	7.7	7.8	8.4
SOC% [a]	1.06	0.62	0.05
Total $CaCO_3$%	6.2	30.8	22.9
P_2O_5 labile (g Kg^{-1})	5.29	1.24	1.19
P_2O_5 ass. (mg Kg^{-1}) [b]	59	23	19
K_2O exc. (mg Kg^{-1}) [c]	1.1	4.6	1.9
N tot (g Kg^{-1})	1.7	0.9	0.1

[a] Rotini method.
[b] Ferrari method.
[c] Exchangeable K_2O with 25% $NaNO_3$ pre-treatment.

Table 2
Average N contents of product and residue biomass.

	$N_{product}$	$N_{residues}$
	g kg^{-1} dm	
Maize	15	9
Potato	16	14
Sugarbeet	10	19
Tomato	26	14
Wheat	21	5

The original soil profiles were reconstructed in the lysimeters. The experimental design is a randomized block with three replicates. Until 1986/87 the trial was conducted with a maize–wheat rotation, comparing 12 treatments deriving from the factorial combination of three nitrogen doses with four methods of crop residue management (removal of all residues, burial of just wheat straw, burial of just maize stalks, and burial of both straw and stalks).

The annual doses of nitrogen were 0, 100 and 200 kg ha^{-1} for maize and 0, 80 and 160 kg ha^{-1} for wheat, splitting the distributions into 1/3 when incorporating the crop residues into the soil, 1/3 at sowing and the rest at canopy closure. The doses of P_2O_5 and K_2O were 150 and 200 kg ha^{-1} in all treatments, respectively.

The trial was modified in 1987/88, abandoning the biannual rotation and adopting a less rigid crop sequence, based on a four-year rotation of wheat, maize, tomato and sugarbeet, with the possibility of altering the crops, in particular substituting tomato with potato. The management methods of the crop residues were consequently simplified, comparing only two situations (burial of the previous crop residues–RI or their removal-RR), and the range of nitrogen doses was increased to 6 constant levels over the years (0, 50, 100, 200, 300, 400 kg ha^{-1}) in a factorial combination with the burial or removal of the crop residues. These experimental treatments were maintained until the end of the experiment in 2012.

At the end of the growing season, the fresh and dry weights of yield and aerial biomass were measured. Average N contents of product and residue biomass are given in Table 2.

2.2. Statistical analysis

The long-term trends of biomass production with and without residue incorporation were compared through a Sign test within each of the three soils considered.

The relationships between $N_{applied}$ and yield were studied with a hyperbolic model:

$$\text{Yield} = Y_0 + \frac{a \times N_{applied}}{1 + a \times N_{applied}/b} \quad (1)$$