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Long-term evaluation of productivity, stability and sustainability for cropping systems in Mediterranean rainfed conditions

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ABSTRACT

Mediterranean cropping systems in rainfed conditions are generally based on rotations with a very high frequency of winter wheat and, therefore, they are at risk of declining trends for yield and soil health in the long-term. In order to quantify this risk, a long-term experiment was set-up in 1971 in central Italy, which is still running at present (2016). This experiment is based on 13 rotations, i.e. three continuous winter wheat systems with different N fertilization rates (W150, W200 and W250), five maize/winter wheat rotations with increasing wheat frequency (maize preceded by 1–5 years of wheat: i.e., WM, 2WM, 3WM, 4WM and 5WM) and five two-year rotations of winter wheat with either pea (WP), faba bean (WFB), grain sorghum (WGS), sugar beet (WSB) or sunflower (WSU). All these rotations are managed either with the removal of crop residues after harvest (REM), or with their burial into the soil at ploughing (BUR). For each rotation, all phases are simultaneously grown in each year, according to a split-plot design (with REM and BUR randomised to main plots), with three replicates in complete blocks and plots of 24.5 m^2 each. The following data are considered: (1) total and marketable biomass yields from 1983 to 2012; (2) content of Organic carbon (OC) and total nitrogen (N) in soil, as determined in 2014. Considering the 30-year period, BUR resulted in an average positive effect on yield (+3.7%), increased OC (+13.8%) and total N content (+9.4%) in soil, while the C/N ratio was not significantly affected. Wheat in two-year rotations showed a significantly higher (+19.4%) average yield level than in continuous cropping or in 2WM, 3WM, 4WM and 5WM, mainly due to a drop in yield occurring in the first (−13%) and second (−19%) year of recropping. Increasing N fertilisation level from 150 to 250 kg N ha^{-1} with continuous cropping resulted in an increase (+3.7%) in long-term average yield and in a decrease in yield stability. All rotations heavily based on wheat (continuous cropping and 5WM) produced the highest amount of buried biomass (>175 t ha^{-1} in 30 years), with the highest increase in soil OC content (>16 t ha^{-1}). All the other rotations produced a lower amount of residues and were less efficient in terms of carbon sequestration in soil, apart from WFB, which gave a high increase in soil organic carbon content (+18.9 t ha^{-1} in 30 years), in spite of a low amount of buried residues (158 t ha^{-1}).

1. Introduction

Winter wheat (*Triticum aestivum* L. and *Triticum durum* L.) is one of the major crops in Italy: according to the Italian Ministry of Agricultural Policy a total of 1,851,000 ha were grown with either durum or soft winter wheat in 2012 (https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/6161; Date of Last Access: 5/02/2016). Cropping systems based on winter wheat are particularly widespread in non-irrigated land, wherein other higher yielding spring crops (e.g. maize) may fail, due to water shortage in summer. In these conditions, the frequency of wheat within rotations becomes very high and continuous wheat cropping may often be the only profitable option.

Rotations based on a high frequency of wheat are at risk of reduced yield levels. Indeed, it has been shown that, in the short-term, wheat following wheat gives a lower yield than wheat following a different crop (Sieling et al., 2005). Several reasons have been advocated to explain such an effect: (1) increase of weed populations (Graziani et al., 2012; Blackshaw et al., 1994); (2) increase of plant pathogens and other biotic yield-limiting factors (Bennett et al., 2012); (3) lower availability of N and other nutrients (espe-

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cially for unfertilised wheat; Sieling et al., 2005; Dalal et al., 1998). These short-term effects are very important, but they are often of small practical interest for farmers, who can usually cope with such yield decreases, considering that no better alternatives to wheat are available for rainfed Mediterranean conditions. Furthermore, many of the above short-term effects may be reduced by way of careful weed and pest control, adequate genotype selection, fertilisation and management of crop residues.

Therefore, a correct selection of cropping systems should be mainly taken by carefully considering long-term effects; indeed, it is clear that no wheat-based cropping system is sustainable if it leads to a continuous downward yield trend in the long-run or to a decrease in soil 'health' over time. In this regard, reliable data from Long-Term Experiments (LTEs) should represent one of the main supporting tools for technical decision, specifically when the evolution of soil characteristics (e.g. organic matter content) is to be taken into account (Congreves et al., 2014).

A number of Long-Term Experiments (LTEs) with wheat-based cropping systems is available in literature; results are rather reassuring, in terms of the sustainability of rotations based on a high frequency of wheat. For example, Lithourgidis et al. (2006) present a 25-years long experiment with continuous wheat cropping in Greece and show that this system may be sustainable in the long run, provided that an adequate level of fertilisation and effective weed control are used all years. Procházková et al. (2003), also working with a 30-years long continuous wheat cropping, showed that the management of crop residues plays a crucial role for maintaining a high fertility level. Other studies present a list of 11–15-years long experiments in Canada, about the effects of tillage system and rotation on soil health (Congreves et al., 2015; Van Eerd et al., 2014). Although these studies do not focus on wheat in non-irrigated land and consider several other spring crops and cropping systems, they show that soil health is improved when wheat and lucerne are included in the rotations.

Although the list of literature references about LTEs in wheat is rather long (see also Congreves et al., 2014), we could not find any exhaustive studies comparing continuous wheat to other alternative rotations, which are totally relevant to Mediterranean rainfed conditions. To our knowledge, most of the published LTEs consider the effect of fertilisation and tillage (or other cropping techniques) on a small number of rotations, often including irrigated crops (Benincasa et al., 2016) or other situations that are not relevant to Mediterranean conditions (such as the winter-wheat fallow rotation, that is economically inconvenient in most parts of Italy and other developed countries).

Therefore, we present the results of a LTE started in 1971 in central Italy and still running at present (2016), which compares a wide array of rotations (13) based on wheat, with and without the incorporation of crop residues into the soil. We considered the variability of wheat yield across years and took a snapshot of soil fertility after 43 years from the beginning of the experiment, with the aims of: (1) assessing the long-term average yield level, stability and sustainability of all cropping systems; (2) comparing soil organic matter and total N content in soil, as observed with all cropping systems, in relation to the amount of buried biomass.

2. Materials e methods

2.1. Location and soil

The experiment was started in 1971, at the Experimental Farm of the Department of Agricultural, Food and Environmental Sciences (Papiano, 42.96 N, 12.38 E, 163 m a.s.l.) on plain land under rainfed conditions. The experiment is still running at present (2016).

Table 1
Main meteorological characteristics for the experimental site (Papiano, central Italy).

Month	Total rainfall (mm)	Average daily temperatures (°C)		
		T max	T avg	T min
January	63.1	9.2	4.6	0.1
February	63.9	11.5	5.8	0.3
March	63.0	15.2	8.8	2.4
April	69.2	18.3	11.7	5.1
May	73.6	23.5	16.3	8.9
June	59.4	27.8	20.1	12.3
July	37.2	31.3	22.9	14.3
August	48.0	31.1	22.9	14.7
September	81.4	26.3	19.0	11.8
October	92.8	20.8	14.5	8.4
November	105.5	14.0	9.1	4.4
December	74.3	9.6	5.6	1.6

The location is characterised by a warm temperate climate, with mild winters and no dry season (Köppen-Geiger classification: Cfa). The mean annual rainfall is 831 mm (1921–2014); the wettest month is November (105.5 mm on average) and the driest is July (37.2 mm on average). The mean air temperature is 13.2 °C, ranging from 21.6 °C in summer and 5.9 °C in winter (Table 1). Frost events take usually place from mid December to beginning of March, although damages have rarely been observed in wheat.

The soil (Fluventic Haplustept; Soil Survey Staff, 2014) is loamy (30.0% sand and 28.3% clay), with pH of 8.3, 26.7 mg kg^{-1} available P_2O_5 (Olsen method), 230 mg kg^{-1} exchangeable K_2O, 11 mg kg^{-1} total N, 6.6 g kg^{-1} organic carbon content (at the beginning of the experiment) and 1.25 t m^3 bulk density.

2.2. Experimental layout

With respect to the initial design, major changes occurred in 1983, when the experiment took its final lay-out, which has remained unchanged until now. In this manuscript, a period of 30-years was considered (1983–2012), in order to have an integer number of complete rotation cycles for most rotations (see later).

Different cropping systems based on winter wheat (*Triticum aestivum* L.) are compared, resulting from the factorial combination of two different types of management of crop residues and 13 types of crop rotation and mineral N fertilisation rates. In more detail, crop residues are cut at 50 mm height and either (i) removed by hand, or (ii) removed by hand, weighed, air-dried and, lately, incorporated into the soil at ploughing, together with 10 kg N per t of buried dry matter, in order to support the humification process. This complementary N-fertilisation practice was abandoned in 2000, as it did not bring to visible effects (Maiorana et al., 1992).

The 13 rotation/fertilisation treatment levels include (i–iii) three continuous winter wheat (W) systems, differing in N fertilization rates, i.e. 150 (W150, 'standard' rate), 200 (W200) and 250 (W250) kg ha^{-1}, split into 50% at tillering and 50% at stem extension; (iv–viii) five types of two-year rotations, wherein wheat is rotated with either pea (*Pisum sativum* L.), grain sorghum (*Sorghum bicolor* (L.) Moench), sugar beet (*Beta vulgaris* L. subsp. *saccharifera*), sunflower (*Helianthus annuus* L.) or faba bean (*Vicia faba* L. subsp. *minor*). (ix–xiii) five maize (M)–wheat (W) rotations with increasing wheat frequency, i.e. M-W, M-W-W, M-W-W-W, M-W-W-W-W, M-W-W-W-W-W. Even though this is not totally appropriate, for the sake of simplicity, we will hereby use the term 'rotation' to mean this second experimental factor with 13 levels.

For all rotations, all phases are simultaneously grown in each year, for a total of 66 plots (33 plots for each of 33 possible crop sequences by two residue management levels) in each of three blocks (198 plots in total), arranged according to a split-plot design,