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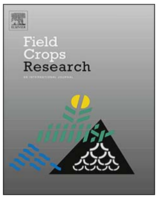

# Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield

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## ABSTRACT

When crop-pasture rotations are converted to continuous no-till annual cropping systems, the grain yield of wheat crops in the rotation stagnates or declines in response to the number of years of continuous cropping (YCC). We studied the soil properties underlining the response of wheat yield to YCC in 80 on-farm trials during three growing seasons. We determined the frontier yield and the yield gap under limited ($Y_F^-$, or best technical means) and unlimited nutrient supply ($Y_F^+$, supplemental additions of nitrogen, phosphorus, potassium and sulfur). For each field, we assessed soil quality based on soil organic carbon (SOC), phosphorus (Bray I), soil texture, field water infiltration rate (INF), and potentially mineralizable nitrogen (PMN). We also calculated a climatological index (CI) that combines temperature, radiation and precipitation during both the spike and early grain growth phases. We estimated $Y_F^-$ and $Y_F^+$ using stochastic frontier production functions with CI, YCC and soil properties as predictor variables. The $Y_F^-$ and $Y_F^+$ after a perennial pasture were 6.9 and 8.4 Mg ha$^{-1}$, with the 1.5 Mg ha$^{-1}$ yield gap attributable to nutrient supply limitations. However, while $Y_F^-$ declined by 0.12 Mg ha$^{-1}$ y$^{-1}$ from YCC = 1 to 10 ($P \le 0.05$), $Y_F^+$ stayed at roughly the same level till YCC = 5, declining thereafter by 0.17 Mg ha$^{-1}$ y$^{-1}$ ($P \le 0.05$). Reduced soil nutrient supply capacity, partially quantified as PMN and amendable with supplemental fertilization, limited $Y_F^-$ during the first five years after pasture. The subsequent $Y_F^-$ decline could not be compensated by increased nutrient supply. After 10 years, the yield gap between $Y_F^+$ for YCC = 1 and $Y_F^-$ for YCC = 10, increased to 2.6 Mg ha$^{-1}$. Up to 40% of this gap was explained by a deterioration of the soil quality that was independent of the nutrient supply; the $Y_F^+$ decline after five years of continuous cropping was best explained by INF. Thus, continuous annual cropping under no-till generated a progressive increase in the wheat yield gap associated to deterioration in soil quality that could be corrected with supplemental fertilization only in the first years after a pasture, but not thereafter, when soil physical properties seemed to degrade past a threshold that limited wheat yield and reduced nutrient use efficiency.

## 1. Introduction

The shift from crop-pasture rotations to continuous no-till annual cropping that occurred in the eastern Pampas of South America since the early 2000 s are a prime example of agricultural intensification. In this region, agricultural systems shifted from a rotation composed of a three- or four-year annual cash crop phase alternating with a three- or four-year grass-legume pasture phase, all under no-till (ROT$_{NT}$), to continuous annual cropping under no-till (CC$_{NT}$) (Franzluebbers et al., 2014; Wingeyer et al., 2015). Under ROT$_{NT}$, and in Uruguay in particular, wheat would typically be sown after a perennial pasture, a practice currently restricted to 7% of the wheat area. Most wheat is now grown after soybean (42%) or maize (13%) (DIEA, 2013). We consider CC$_{NT}$ "agricultural intensification" due to the output increase when compared with ROT$_{NT}$. However, greater outputs, and even increasing yield per unit of input (Garnett and Godfray, 2012), do not mean that a given path to agricultural intensification is sustainable if pollution is not abated or soil resources degrade severely.

Compared to tilled systems, no-till has been proposed as a strategy to mitigate soil organic carbon (SOC) depletion (Díaz-Zorita et al.,

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2002), improve biological, chemical and physical soil properties that affect productivity such as nutrient supply, soil water infiltration and water holding capacity (Munkholm et al., 2013; Boeni et al., 2014). Consequently, the shift to $CC_{NT}$ occurred under the assumption by growers, technical advisers and scientists that the continuous and diversified no-till production of annual grain crops would prevent soil degradation and sustain crops yields provided that crop residues ensure ground cover (Ernst and Siri, 2009; Kirkegaard and Ryan, 2014). However, Ernst et al. (2016) found a detrimental effect of years of continuous agriculture (YCC) under no-till on wheat yield in seasons with unfavorable weather for wheat (rainy and warm before flowering and during grain filling). These authors concluded that this reduced resilience reflected a progressive loss of soil quality, i.e. a loss of soil capacity to sustain higher biological productivity, which results in lower wheat yields and higher production risks. While the analysis did not reveal which soil properties underlie the yield reduction, the results indicate that continuous annual cropping under no-till undermines one of the pillars of ecological intensification: the maintenance or improvement of soil quality (Cassman, 1999), defined as the capacity of soils to sustain biological productivity (soil productivity function) while ensuring environmental, plant and animal health (Doran and Parkin, 1994; Blum, 2005).

To characterize the factors limiting crop growth we consider first a ceiling yield defined by the crop phenology and unlimited water and nutrient supply, second a water-limited yield as determined by the precipitation pattern and soil water storage capacity (Yw) and a nutrient limitation determined by the nutrient supply. A third limitation imposed by biotic stresses and pollutants can be accounted for (Rabbinge, 1993) but does not apply to this investigation. Yw is a relevant benchmark because it defines the nutrient demand. However, Yw is unknown when deciding the proper nutrient supply, and therefore, as stated by Fischer and Edmeades (2010), “nutrient input is adjusted taking prudent account of economics and risk”. The yield potential does not vary for two environments with the same climate but different soil properties. However, the interaction between climate and soil properties can limit crop growth. When compared to continuous cropping (CC), annual crops rotating with pastures (ROT) have higher grain yield (Franzluebbers et al., 2014). Such improved performance reflects a superior environment, where inputs are used more efficiently under ROT than under CC (de Wit, 1992).

Specifically, the higher grain yield under ROT has been partially attributed to improved soil nitrogen (N) supply under ROT and increased incidence of pests, diseases and weeds under CC (Struik and Bonciarelli, 1997; Kirkegaard and Ryan, 2014). In fact, soils under ROT have higher SOC, total N content and potentially mineralizable nitrogen (PMN), better structure and higher water infiltration than under CC (Díaz-Zorita et al., 2002; Fabrizzi et al., 2003; García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009; Boeni et al., 2014). Furthermore, even under $CC_{NT}$, total porosity of the top horizon is lower than under a pasture, with macropores oriented in parallel to the soil surface and limiting soil water infiltration (Sasal et al., 2006; Alvarez et al., 2014). This phenomenon is due to an increased platy structure in the top horizon that reduces soil water infiltration (Sasal et al., 2017).

Removing the perennial pasture phase from the rotation creates increasingly limiting conditions for crop growth that do not seem to operate additively and are difficult to neutralize. Increasing the nutrient supply and controlling for biotic stresses cannot always compensate for the grain yield loss under such conditions. Russell et al. (1987) named that portion of the yield that cannot be compensated for with synthetic chemicals the “rotation effect”. Despite decades of agricultural research, the causes of this rotation effect are not well understood (we mean rotation with a perennial pasture in this context). The rotation effect can be linked in broader terms with the concept of soil quality, which lumps the indicators of soil processes and properties that affect soil functions (Doran and Jones, 1996). Soil quality, a complex functional concept (Stocking, 2003), cannot be measured directly but may be assessed from management-induced changes in soil attributes. Conveniently, crop yield can be used as an integrator of the resultant of these indicators (Arshad and Martin, 2002; Wander et al., 2002). We argue that $CC_{NT}$ may negate the rotation effect by gradually reducing soil quality. Following Ernst et al. (2016), we also argue that the magnitude of the soil quality deterioration could increase with the lenght of the annual cropping phase.

In this study, we used the wheat phase of different rotations to test hypotheses pertaining to the impact of agricultural intensification via a lengthening of the annual cropping phase on soil properties and crop performance. Our hypotheses were: (1) Intensifying agricultural production by lengthening the annual cropping phase after pastures, even under no-till, causes a gradual, cumulative, and measurable reduction of wheat’s Yw that can be apportioned to nutrient supply and non-nutrient supply limitations; (2) this yield loss can be related to a gradual and cumulative soil quality degradation. The objectives of this study were to: (i) Quantify the effect of years of no-till continuous agriculture on rainfed wheat yield; (ii) quantify to which extent the yield loss observed under continuous agriculture can be buffered by increased application of fertilizers; iii) investigate which soil properties could explain the yield loss under no-till continuous agriculture.

## 2. Materials and methods

We pursued these objectives through a network of on-farm trials in farmers’ rainfed wheat fields during three growing seasons. In the trials, we compared two nutrient supply strategies: non-limiting supply of N, phosphorus (P), potassium (K) and sulfur (S) versus a limited nutrient supply. The latter is also considered a “best technical means” nutrient management recommendation, which follows current guidelines from local research stations (Hoffman et al., 2010). All plots were managed to ensure no impact on crop yield of weeds, diseases and pests. We selected fields spanning from one to 10 years of continuous cropping after the pasture phase and before the current wheat crop. We defined the yield of plots with non-limiting supply of N, P, K and S as yield not limited by nutrients ($Y^+$) and the yield of plots fertilized following best technical means as yield limited by nutrients ($Y^-$).

### 2.1. Study area and experimental setup

The study area is located in the northwestern part of Uruguay. All selected wheat fields were inside a 50 km radius from the Faculty of Agronomy research station in Paysandú (32.37 W; 58.04 S). Soils are classified as Typic Argiudolls & Hapludolls, and are considered prime agricultural land. In Uruguay, wheat is grown rainfed and under no-till, commonly sown from May 15 to June 30 and harvested in November and December. The climate is meso-thermal sub-humid with a mean daily temperature from May to November of 16.5 °C. Mean annual precipitation is about 1200 mm, fairly evenly distributed throughout the year, but with large intra- and inter-annual variations. Water deficits occur frequently between November and March and water surpluses between May and October.

Data were collected from 80 on-farm trials over three growing seasons: 44, 26 and 10 during 2011, 2012 and 2013, respectively. At each field, we installed two pairs of 10 × 10-m plots after wheat emergence; each pair included both nutrient supply treatments. Each field had one of the five top yielding cultivars in the trials of the National Testing Network of Wheat Cultivars for each year. The earliest and latest sowing dates in each season were less than 15 days apart. Wheat was seeded following winter fallow/soybean (YCC from 2 to 10) or pastures (YCC = 1). The pastures were a mixture of grass and legumes that were grown for three to four years. Wheat was maintained free of weeds and diseases with timely applications of herbicides and fungicides. Wheat phenology was recorded using the Zadoks scale (Zadoks et al., 1974). Crop yield was determined by hand-harvesting 10 $m^2$ per plot. Details about the fertilization treatments are provided in Table 1.