Shifting the production systems from crop-pasture rotation to continuous cropping decrease soil quality and attainable wheat yield

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Abstract
The increase in annually cropped area that has occurred in Uruguay since 2002 was largely achieved by converting crop-pasture rotations to continuous annual no-till cropping systems. We studied the impact of the number of years of continuous cropping after pasture (YCC) on wheat yield in 80 on farm-trials during three growing seasons comparing two nutrient managements: (1) "Limited by nutrient", fertilised with N and P according to "best technical means"; (2) "Not limited by nutrients", adding 'not limiting' amounts of N, P, K and S. We estimated the frontier yield under limiting (Y^-) and non-limiting nutrient supply (Y^+) using a stochastic frontier production function. Y^+ after perennial pasture was 8.42 vs 7.04 Mg ha^{-1} of Y^-. While Y^- was reduced 0.12 Mg ha^{-1} year^{-1} from YCC=1 to YCC=10 ($P \leq 0.05$), Y^+ was maintained at the same level till YCC=5 and then reduced by 0.18 Mg ha^{-1} year^{-1} ($P \leq 0.05$). Total yield reduction after 10 years of continuous cropping, measured as Y^+ at YCC=1 minus Y^- at YCC=10, was 2.55 Mg ha^{-1}, representing a relative yield gap of 30.4. Soil quality deterioration explained up to 40% of this yield difference. Reduced soil nutrient supply capacity, partially quantified as potentially mineralisable nitrogen (PMN), would be the soil property most limiting Y^- during a period of 4-5 years after pasture. When YCC>5, a negative effect of YCC on frontier yield could not be compensated by increased nutrient application rates. We identify reduced soil infiltration rates as a soil property that may explain Y^+ reduction after 5 YCC.

Keywords
Frontier yield, Yield gap, No tillage, Cropping system, Wheat.

Introduction

The changes in cropping systems that occurred in the eastern Pampas of South America, driven by increasing prices of soybean since 2003, are a prime example of agricultural intensification. In this region, agricultural systems shifted from a rotation composed of a three or four years annual cash crop phase alternated with a three or four years of a grass & clover 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).

Compared to tilled systems, no-till has been proposed as a strategy to mitigate soil organic carbon (SOC) depletion (Diaz Zorita et al. 1997) and improve biological, chemical and physical soil properties that affect productivity such as nutrient supply, soil water infiltration and holding capacity (Munkholm et al. 2013; Boeni et al. 2014). Consequently, this shift in cropping systems occurred under the assumption by growers, technical advisers and scientists that a diversified no-till continuous agriculture system would prevent soil degradation and sustain crop yields provided that sufficient soil cover by previous crop residues was retained (Ernst and Siri 2009; Kirkegaard and Ryan 2014). However, Ernst et al. (2016) using data from 1072 fields during four growing seasons found a negative effect on wheat yields of years of continuous agriculture (YCC) under no-till system in seasons of unfavorable weather conditions. While wheat yield reduction was 56 kg ha^{-1} per year under unfavorable weather conditions during the critical period defining wheat's sink size (Photothermal quotient<1.5), it was almost unnoticeable under favorable weather conditions during that stage (Photothermal quotient $\geq$1.5). They interpreted that this decrease 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. The analysis did not reveal which soil properties underlie the yield reduction, but it indicated than one of the pillars of ecological intensification, the maintenance or improvement of soil quality (defined as the capacity of soils to sustain biological productivity while ensuring environmental, plant and animal health (Cassman 1999), could be negatively affected by continuous no-till annual cropping.

When annual crops rotate with a 3-4 y perennial pasture phase, soils have higher SOC, total N content and potentially mineralisable 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). Total porosity of the top horizon under CC_{NT} is lower than under a pasture and macropores appear oriented in parallel to the soil surface, affecting soil water infiltration negatively (Sasal et al. 2006; Alvarez et al. 2014). This effect is related to an increased platy structure in the top horizon, a structure that reduces soil water infiltration (Sasal et al. 2016). Our hypotheses were: (1) intensifying agricultural production by lengthening the annual cropping phase after pasture, even under no-till, generates gradual and cumulative soil quality degradation; and (2), this soil quality loss in turn causes a gradual and cumulative reduction of wheat yield due to water and nutrient restrictions.

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 what extent the yield loss observed under continuous agriculture could be reduced by increased application of fertilisers; and iii) investigate which soil properties could explain the yield loss under no-till continuous agriculture.

Methods

The strategy selected to achieve these objectives was to perform extensive on-farm trials in farmers' rainfed wheat fields during three growing seasons. In those on-farm trials we compared the performance of plots supplied with two nutrient management regimes: Not limited by nutrients (N=240 kg ha^{-1}; P=90 kg ha^{-1}, K=60 kg ha^{-1} and S=20 kg ha^{-1}) () versus plots fertilised following "best technical means" (Limited by nutrient), according to current recommendations from local research stations (Hoffman et al. 2010). Both types of plots were managed to ensure no impact on crop yield of weeds, diseases and pests. We selected fields to cover a range in numbers of years of continuous cropping before the current wheat crop (YCC), from one to ten years after a pasture phase. We defined the yield of plots supplied with unlimited amounts of N, P, K and S as "yield not limited by nutrients" (Y^+) and the yield of plots fertilised following best technical means as "yield limited by nutrient" or "nutrient and water-limited yield" (Y^-).

Quantifying the effect of number of years of continuous cropping on frontier yield.

We estimated the frontier yield under limited (Y^-_F) and not limited nutrients supply (Y^+_F) using a stochastic frontier production function (SFPF) built from the 80 records obtained under "Limited by nutrient" and "Not limited by nutrients" treatments, respectively. We included as deterministic components of SFPF, weather conditions, soil texture, soil infiltration rate (INF), potentially mineralisable N (PMN) and YCC.

We estimated the effect of YCC by quantifying the yield reduction due to soil nutrient supply ($Yg^{nutrients} = Y^+_{(i)} - Y^-_{(i)}$), yield reduction due to other soil properties than nutrient supply capacity depletion ($Yg^{others} = Y^+_{(n)} - Y^+_{(n+1)}$), and yield gap total ($Yg^T = Yg^{nutrients}_{(n)} + Yg^{others}_{(n)}$).

Results

Effect on yield of fertilisation treatment and YCC

The YCC reduced both Y^+_F and Y^-_F, but the timing and magnitude of the reduction differed between yields. While Y^-_F was reduced at the same rate of 0.12 Mg ha^{-1} y^{-1} from YCC 1 to 10, Y^+_F was maintained at the same level until YCC = 5 and reduced by 0.18 Mg ha^{-1} y^{-1} from YCC 6 to 10 ($P \leq 0.05$) (Figure 1).

When wheat was sown after perennial pasture YCC=1, Y^+_F was 8.42 vs 7.04 Mg ha^{-1} of Y^-_F, representing a $Yg^{nutrients}$ of 1.47 Mg ha^{-1}. After five years of continuous cropping, $Yg^{nutrients}$ increased to 1.83 Mg ha^{-1}, while at the same time the Yg^{others} was only 0.12 Mg ha^{-1}, making Yg^T= 1.95 Mg ha^{-1} (Table 1). Total yield reduction (Yg Tot) after 10 years of continuous cropping was 2.55 Mg ha^{-1}, representing a relative total yield reduction (RYg^T) of 30.4%. Other soil properties than nutrient supply capacity depletion explained up to 40 % of this yield difference.

Highest INF and PMN were measured during the first three years after pasture (Table 2). While PMN showed a gradual reduction rate with YCC, INF was reduced quickly from YCC = 4-6 to YCC = 8-10. Soil properties that are temporarily more stable like SOC and texture were not altered by YCC.

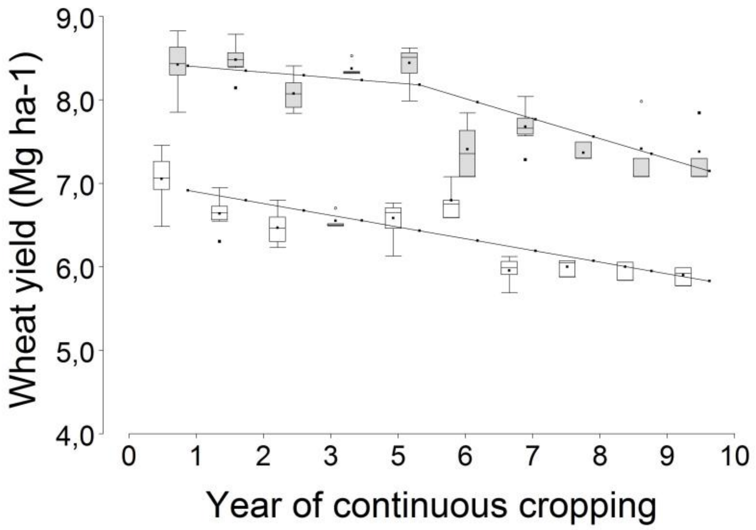

Figure 1. Boxplots of Frontier wheat yield under Not limited by nutrients (shaded boxes) ($Y^{+}F$) or Limited by nutrients (open boxes) ($Y^{-}F$) related to years of continuous cropping after a perennial pasture (YCC). Lower and upper boundaries for each box are the 25th and 75th percentiles. The line inside each box indicates the median. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. The continuous lines corresponds to adjusted functions: For YCC≤5 $Y^{+}F$ = 8.42- 0.03YCC; For YCC>5 $Y^{+}F$ = 8.42- 0.17YCC (R2 adj = 0.57); $Y^{-}F$ = 7.04- 0.12YCC (R2 adj=0.69).

Table 1. Estimated effect of YCC on total yield reduction (Yg^{T}), yield reduction due to nutrient supply ($Yg^{nutrients}$) and due to other soil properties than nutrient supply capacity depletion (Yg^{others}). The relative total yield reduction (RYg^{T}) was estimated as ($100*Yg^{T}_{(i)}/Y^{+}_{F(1)}$). The fraction of the RYg^{T} explained by nutrient supply ($FYg^{nutrients}$) and other soil properties than nutrient supply capacity depletion (FYg^{others}) were estimated as percentage of Yg^{T}.

YCC (years)	Yg^{T}	$Yg^{nutrients}$	Yg^{others}	RYg^{T}	$FYg^{nutrients}$	FYg^{others}
		Mg ha^{-1}				
1	1.47	1.47	0	17.5	100	0
5	1.95	1.83	0.36	23.2	94	6
10	2.55	1.53	1.02	30.4	60	40

Table 2. Effect of years of continuous cropping on properties of the top soil (0-20 cm): soil texture (Cl/Sd ratio), soil organic carbon content (SOC %), potentially mineralisable nitrogen (PMN, mg N-NH4 kg^{-1}), and water infiltration rate (INF, cm day^{-1}). Values correspond to mean of the first three (YCC 1_3), four to six (YCC 4_6) and eight to 10 (YCC8-10) years of continuous cropping (YCC) after a perennial pasture.

Years of continuous cropping	Cl/Sd	SOC (%)	PMN	INF
1 to 3 (n = x)	0.97	2.8	**30**	35
4 to 6 (n = y)	0.99	2.8	26	30
7 to 10 (n = z)	0.98	2.6	18	16
LSD (0.05)	0.06	0.4	10	6.3

Conclusion

Using a one farm research, we showed that agricultural intensification via a lengthening of the annual cropping phase under no-till decreased differentially both, Y^{-}_{F} and Y^{+}_{F}. While Y^{-}_{F} was reduced linearly from YCC=1 to YCC=10, Y^{+}_{F} declined slowly at first, then more steeply. The yield difference estimated within YCC when wheat was sown after pasture (YCC=1) is attributed to nutrient only, but cropping system generates a "long term Yg" explained by its effects on soil quality conservation. We quantify these two different components of the Yg , the $Yg^{nutrients}$ and Yg^{others} . The negative effect of YCC on Y^{-}_{F} not be overcome using actual NP fertilisation criteria, but it would compensated increasing nutrient applications until YCC=5. This Yg is attributed to nutrient only ($Yg^{nutrients}$ =100%). After five YCC, soil properties other than nutrients availability are limiting wheat yield, increasing the Yg^{others}. Reduced soil nutrient supply capacity, partially quantified as PMN, would be the soil property most limiting Y^{+}_{F} during a period of 4-5 years after pasture. When YCC>5, started a second phase in soil quality deterioration, where PMN continued descending, but negative effect of YCC cannot be compensated increasing nutrient fertiliser rates. We identify reduced INF as one of soil property involved during this second phase.

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