Field Crops Research 186 (2016) 107–116

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Depressed attainable wheat yields under continuous annual no-till agriculture suggest declining soil productivity

Oswaldo R. Ernst[a,*], Armen R. Kemanian[b], Sebastián R. Mazzilli[a], Mónica Cadenazzi[c], Santiago Dogliotti[d]

[a] Departamento de Producción Vegetal, Facultad de Agronomía, Estación Experimental Mario Alberto Cassinoni, Universidad de la República, Ruta 3, km 363, Paysandú 60000, Uruguay

[b] Department of Plant Science, The Pennsylvania State University, 116 ASI Building, University Park, PA 16802, USA

[c] Departamento de Biometría, Estadística y Computación, Facultad de Agronomía, Estación Experimental Mario Alberto Cassinoni, Universidad de la República, Ruta 3, km 363, Paysandú 60000, Uruguay

[d] Departamento de Producción Vegetal, Facultad de Agronomía, Universidad de la República, Av. Garzón 780, 11200 Montevideo, Uruguay

ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
13 November 2015
Accepted 15 November 2015
Available online 10 December 2015

Keywords:
Attainable yield
Yield gap
No tillage
Cropping system
Wheat

ABSTRACT

The increase in annually cropped area that has occurred in the eastern Pampas of South America (Uruguay) since 2002 was largely achieved by converting crop-pasture rotations to continuous annual no-till cropping systems. We studied the impact of this intensification on the attainable wheat yield (Yatt) and the yield gap (Yg), with the latter defined as the difference between Yatt and actual yield (Ya). Our measure of agricultural intensification is the length in years of continuous cropping (YCC). We computed both Yatt and Yg from 1072 wheat yield records obtained from producers between 2009 and 2012. The database included grain yield, agro-climatic region, preceding crop, sowing date, cultivar, nitrogen (N) fertilization rate and YCC. For each field, we calculated a climatological index (CI) that combines temperature, radiation and precipitation during both the spike and grain growth phases. To estimate Yatt, we fitted a stochastic frontier production function that uses CI, cultivar, region and YCC as explanatory variables, and includes a term representing the inefficiency function. The latter quantifies management practice effects on Yg. A relative yield gap (RYg) was calculated as the ratio Yg/Yatt. We used regression trees to uncover relationships between RYg and variables integrated in the inefficiency function. The mean Yatt was 4.9 ± 0.7 Mg ha^{-1}. Its variation was a function of the cultivar and the interaction of CI and YCC. The interaction term indicated that Yatt was highest and independent of YCC when the CI was favorable for wheat growth (high CI, sunny and temperate before flowering and during grain filling as opposed to low CI, rainy and warm), but declined rapidly with YCC when CI was unfavorable for wheat growth. The average Yg and RYg were 1.5 ± 0.8 Mg ha^{-1} and 0.31 ± 0.17. The fertilizer N rate explained most of the variation in RYg. When the CI was low, YCC was the second most important variable explaining RYg. When the CI was high, the variation in RYg was best explained by the preceding winter crop. Our results indicate that under low CI, intensifying crop production with continuous annual no-till cropping can cause a measurable reduction in Yatt and Ya. The negative effect of YCC on Ya was significantly higher under weather conditions unfavorable for wheat growth, increasing the RYg. These effects could not be compensated for with the maximum N fertilization rates used by producers under low CI or with a rotation of annual crops. Our interpretation is that shifting cropping systems from a crop-pasture rotation to continuous annual no-till cropping generates a progressive limitation in soil productivity that reduces wheat yield and increases its inter annual variability.

1. Introduction

Driven by increasing grain prices, the area of grain crops in the South American Pampas has increased substantially since 2002. Following this regional trend in land use change, the annual cropped area in Uruguay increased from 400 thousand to 2 million

* Corresponding author.
E-mail addresses: oernst@fagro.edu.uy, oswaldoernst@gmail.com (O.R. Ernst).

http://dx.doi.org/10.1016/j.fcr.2015.11.005
0378-4290/

ha in 10 years, with soybean and wheat sown on 50 and 25% of the area, respectively. This large increase in cropped area was achieved by shifting the production systems from crop-pasture rotations to continuous annual cropping under no-till systems (Franzluebbers et al., 2014; Wingeyer et al., 2015).

As a consequence of this shift, wheat is currently grown mainly after full season soybean or maize (42 and 13% of the area, respectively). In turn, soybean and maize are grown after a winter fallow (73%) or in a double cropping system following barley or wheat (27%). In contrast, in the previous traditional crop-pasture rotation, wheat would be sown after perennial pastures, a practice that now happens in only 7% of the wheat area (DIEA, 2013). This expansion of no-till agriculture and shift in rotations constitutes a particular case of agricultural intensification.

Underlying this agricultural intensification are two paradigms of modern agriculture: (i) No-till has positive effects on soil quality compared to tillage-based systems (Alvarez and Steinbach, 2009; Fuentes et al., 2009), and (ii) rotating crops in the cropping sequence, even if they are annual crops, improves crop performance when compared to monocultures (Porter et al., 2003; Munkholm et al., 2013). Consequently, when producers changed their system to continuous no-till of annual crops, they expected to maintain both soil quality and grain yields, increasing the enterprise grain output with a larger share of grain crops in the rotation. Were these expectations realized? Does the yield attainable in commercial fields reflect any positive or negative effect of continuous no-till annual cropping?

One of the pillars of ecological intensification proposed by Cassman (1999) is the maintenance or improvement of soil quality, 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). The soil quality concept includes subtle and complex forms of soil degradation that would compromise future food production capacity (Cassman, 1999).

A plausible framework to analyze these questions is derived from studies showing that soil quality is better under continuous no-till compared to conventional tillage systems (Alvarez and Steinbach, 2009; Conceição et al., 2013), and that soil quality is better under no-till crop-pasture rotations than under continuous cropping. Better soil quality is attributed to higher soil organic carbon content, better soil structure, and lower soil erosion rates (Díaz-Zorita et al., 2002 in Argentina; García-Préchac et al., 2004, and Ernst and Siri-Prieto, 2009 in Uruguay; Boeni et al., 2014 in Brazil). Then, it can be posited that while a conversion from conventional tillage to no-till can improve soil quality, removing perennial pastures from no-till rotations may gradually reduce soil quality, limiting soil productivity. The mechanism would be a gradual decline in soil water and nutrient supply capacity, which would limit crop resource capture and use efficiency (Cassman, 1999; Sadras et al., 2005; Tittonell and Giller, 2013). This proposition challenges the second paradigm previously mentioned, because it would imply that to retain high productivity, it is not only important to rotate annual crops but to rotate them with perennial pastures.

A straightforward way of evaluating the effect on soil productivity of the shift from crop-pasture rotations to continuous annual cropping systems is to study the impact of the shift on attainable yield (Yatt), yield gap (Yg) and input use efficiency. Following Fischer and Edmeades, (2010), we defined Yatt as the yield achieved by a skillful producer using locally optimized agricultural best management practices and adapted cultivars, while taking into account production risks and economics. This represents the yield upper limit obtained under irrigated or rainfed conditions applying best management practices, and has also been defined as the maximum producers' yield (Lobbel et al., 2009). The Yatt has been estimated using data from individual commercial farmers' fields (Hall et al., 2013), yield contest results (Duvick and Cassman, 1999), on-farm and experimental station trials, regional yield statistics (Licker et al., 2010), and breeders' trials (Hall et al., 2013). It should be noted that irrigated and rainfed Yatt are not the same as potential and water-limited yield as defined by van Ittersum et al. (2013), which are estimated not from producers' yield records but by using crop simulation models (Lobell et al., 2009; Grassini et al., 2011; Laborte et al., 2012).

In this study, we used a stochastic frontier function to estimate Yatt. This approach was developed in economics to compare the efficiency and productivity of enterprises (Battese, 1992), and has been applied to agricultural production (Newman et al., 2010). Provided that a database from a large sample of fields and growing seasons in an agro-ecological region is available, and that the database includes skillful producers, the stochastic frontier function can estimate, in theory, the Yatt within the range of production conditions in the database.

We propose that Yatt can be used as a biological indicator of the relationship between changes in agricultural intensification and soil productivity. In particular, the rapid shift in cropping systems that occurred in Uruguay during the last decade provides an opportunity to evaluate the impact of agricultural intensification, quantified as the number of years under no-till continuous cropping systems, and crop sequence, on Yatt and Yg. To our knowledge, no previous study has used a stochastic frontier function and the concepts of Yatt and Yg to explore these relationships for a given region.

The objectives of this study were to quantify the effect of the number of years of continuous cropping (YCC) after a pasture phase in no-till rotations on wheat Yatt and Yg, and to quantify the effect of the preceding crop and nitrogen (N) application rate on wheat Yg. To accomplish these objectives, we quantified the effect of YCC on soil productivity evolution in the short term (i.e. <10 years) using wheat Yatt derived from producers' records using a stochastic frontier function; estimated Yatt considering yield defining factors for each field, including cultivar and climatic variables that depend on year, sowing date and cultivar phenology; and identified crop management variables that can control the effect of YCC on Yatt, Ya and Yg.

2. Materials and methods

2.1. Database description

Wheat in Uruguay is a rainfed crop grown in a region located in the West of the country (31–35°S; 55–58°W) (Fig. 1). Average wheat yields in the period 2009–2012 varied between 2.2 and 3.4 Mg ha^{-1} (DIEA, 2013). Wheat is commonly sown from May 15th to June 30th, but sowing dates might be delayed in rainy years. We used a database containing 1072 records obtained from wheat-producing members of the Uruguayan Federation of Regional Consortia of Agricultural Experimentation (FUCREA using its Spanish acronym) during four growing seasons (2009–2012). These years represent three different ENSO conditions. According to the International Research Institute for Climate and Society they were classified as "El Niño" (2009, rainier than the average), "Niña" (2010 and 2011, sunny and drier than the average) and "Neutral" (2012). Each record corresponds to one field in one growing season. The average field size was 61 ± 22 ha. The fields were distributed in three of the four agro-climatic regions identified for wheat production in Uruguay by Corsi (1982). These regions are differentiated by average temperatures and expected soil water excess during the wheat heading stage (Fig. 1). The soils in most agricultural fields are Typic Argiudolls.