Cropping systems diversification impacts on farmers soybean yield.

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Abstract
The increase in cropped area that occurred in the eastern Pampas of South America (Uruguay) since 2002 was largely achieved by substituting crop-pasture rotations for continuous annual cropping under no-till systems. We studied the soil properties underlying the response of soybean yield in 65 on-farm trials. Farms had three nutrient management strategies: (1) "limited by nutrient", fertilized according to "best technical means"; (2) "not limited by nutrients"; (3) "not limited by nutrient nor pH". Farms also had three different no-till cropping systems (CS): i) a mix of crop-pasture (CPR), ii) systems with high level of diversification (CC_d) and iii) soybean monocropping systems (CC_{sb}). Stochastic frontier analysis was carried out to explain and deconstruct and decompose the soybean yield gap (Y_g). The mean Yg was 1.8 Mg ha^{-1}. We decomposed it as a technical efficiency gap (0.8 Mg ha^{-1}), partly explained by farmer's cropping system improvements and choice of high agricultural land aptitude, and a resource Y_g of 1.0 Mg ha^{-1}. We identify resource Y_g components defined as soil quality and technological improvements which were explained mainly by high soil penetration resistance and water supply from R4 to R6 and the cropping systems, respectively.

Keywords
Frontier analysis; technical efficiency yield gap; resource yield gap; no tillage.

Introduction
Agricultural intensification occurred in the eastern Pampas of South America mainly by shifting cropping systems (CS) from crop-pasture rotations to a very simple continuous annual cropping system under no-till with high frequency of soybeans (Franzluebbers et al. 2014). Under low crop diversity (monocropping), CS will tend to be more susceptible to climatic variability, weed, pests and diseases problems, increasing dependency for greater inputs (Nicholls et al. 2017). Rotations with pastures, or a less drastic change towards increased frequency of maize and sorghum in the rotation, would prevent progressive soil degradation, reducing environmental pollution, and nitrogen requirements, while increasing grain yield (Ernst et al. 2020). Yield gap (Y_g) analysis can be used to investigate the relative contribution of different growth factors to actual yields (van Ittersum and Rabbinge 1997). Following Silva et al (2017), we use actual yield (Y_a) registered by farmers to estimate technical efficient yield (Y_{TEx}), yield gap (Y_g) and its components: yield gap defined by technology and Y_g attributed to resource availability.

Our study considers how much soybean yield might be constrained by CS design under no till systems and current crop management. Our hypotheses are: (1) CS design modifies efficiency and resource Y_g and (2) both, Y_g efficiency and Y_g resources are explained by changes in soil quality and technological improvements. The objectives were to: (i) quantify the efficiency and resource Y_g imposed by the CS and ii) identify factors associated with soil quality and technology determining Y_{TEx} and Y_a.

Methods
The study area is located in the southwest of Uruguay. All selected soybean fields were inside a 60 km radius around 33.06 W and 57.83 N. Soils are classified as Typic and Vertic Argiudolls. In Uruguay, soybean is mainly rainfed and under no-till, commonly sown from October 20 to December 15 and harvested March - April. The climate is meso-thermal sub-humid. Mean annual precipitation is about 1200mm with large intra – and inter – annual variations.

The research strategy included extensive on-farm trials in farmer's rainfed and irrigated soybean fields. We compare three nutrients managements: i) fertilizing following the current recommendations, ii) yield not limited by nutrients (P = 80 kg P_2O_5 ha^{-1}, K = 60 kg K_2O ha^{-1} and S = 30 kg ha^{-1}) and iii) yield not limited by nutrients nor pH (not limited by nutrients plus CaO = 260 kg ha^{-1}; MgO = 130 kg ha^{-1}). We selected 65 fields to cover a range of weather conditions, especially rainfall and distribution, and different CS under continuous no-till. The CS included: i) four-five annual crops rotating with two-four years of perennial pastures (CPR); ii) diversified continuous annual crops (CC_d) including high frequency of corn and sorghum (C4 crops) as summer crops; iii) single continuous annual crops (CC_{sb}) including high frequency of winter cover crop with summer soybeans (C3 crops) (summer C3 crop frequency > 0.8).

Y_{TEx} was estimated by stochastic frontier function (Coelli et al. 1976). Efficiency Y_g was calculated as the difference between Y_{TEx} and Y_a; resource Y_g was calculated as the difference between the average 90th percentile farmer's yields (Y_{HF}) and the mean Y_{TEx}. The 10th percentile farmer's yield was defined as the lowest yield level (Y_{LF}) and compared to Y_{HF}. The stochastic frontier function we estimated including a subset of variables defining Y_{TEx}, including nutrient management, soybean crop management (sowing date, cropping cycle length), climatic variables (radiation, temperature, water supply) and a set of soil physical and chemical proprieties describing the soil profile. Variables quantifying CS were included in the inefficiencies function. Soil capacity use and previous winter crop were included as dummy variables and soil use intensity (years of continuous cropping) and soybean frequency interaction as continuous variables. The soil subset of variables were selected after a principal component analysis, retaining only those variables with eigen values >1 and partial $R^2 > 0.05$. We assessed statistical differences ($p \leq 0.05$) between Y_{LF} versus Y_{HF} fields by Mann-Whitney U test for quantitative variables and two-way contingency tables (Chi^2) for dummy variables

Results

Cropping cycle, cumulative temperature, water supply, magnesium (7.5-15 cm) and electrical conductivity (7.5-15 cm) had a significant ($p \leq 0.05$) relation with Y_{TEx}. In the second soil layer the model captured a statistically significant ($p \leq 0.05$) negative effect of cation exchange capacity (7.5-15 cm), apparent electrical conductivity (10-20 cm) and penetration resistance (7.5-15 cm) with Y_{TEx}.

Explaining the yield gap

The mean Y_a was 3.2 Mg ha^{-1} ± 0.9 Mg ha^{-1} and mean efficiency Y_g was 0.8 Mg ha^{-1} (19%); 24% of fields had Y_g greater than 30% (Figure 1A and 1B). Inefficiencies were reduced (p<0.05) adjusting the crop management to soil capacity use classes (Soil Survey Staff, 1999). Lengthening annual cropping phase and low CS diversity increased the inefficiencies by limiting the Y_a, increasing the technical efficiency Y_g ($p \leq 0.05$). Low diversity systems are associated with soybean monocropping including both, winter fallow and annual winter grass as cover crops.

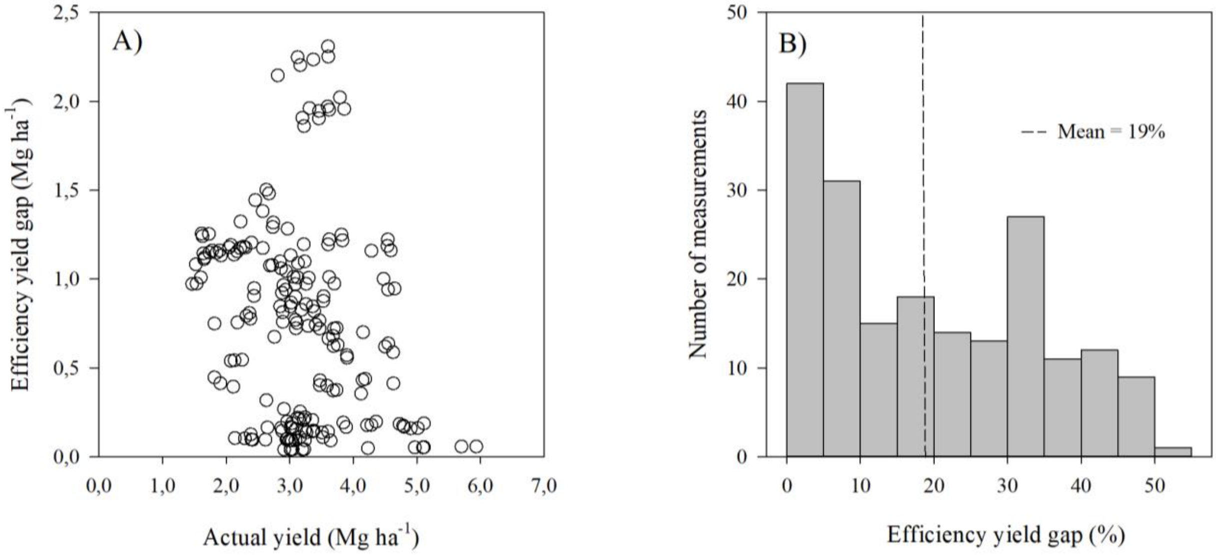

Figure 1. Efficiency Y_g for soybean in farming systems in South-eastern Pampas of South America, Uruguay: (A) illustrate the relationship between efficiency Y_g (Mg ha^{-1}) and Y_a (Mg ha^{-1}) for each soybean site*treatment analysed (n=193) and (B) the distribution of the efficiency Y_g (%).

We grouped CS in CPR, CC_d and CC_{sb}, to explain the technical efficiency Y_g (Figure 2A) and their influence on system's efficiency under irrigated and rainfed conditions (Figure 2B). CPR and CC_d had higher Y_a than CC_{sb}. While the highest efficiency under CPR is associated with a "rotation effect" described by Russelle et al. (1987), increasing years of continuous agriculture increased the technical efficiency Y_g under both CC_d and CC_{sb}. However, while increases in technical efficiency Y_g under CC_d was defined by increased Y_{TEx} rather than decreases in Y_a, under CC_{sb} they were also accompanied by a decrease in Y_a (Figure 2A).

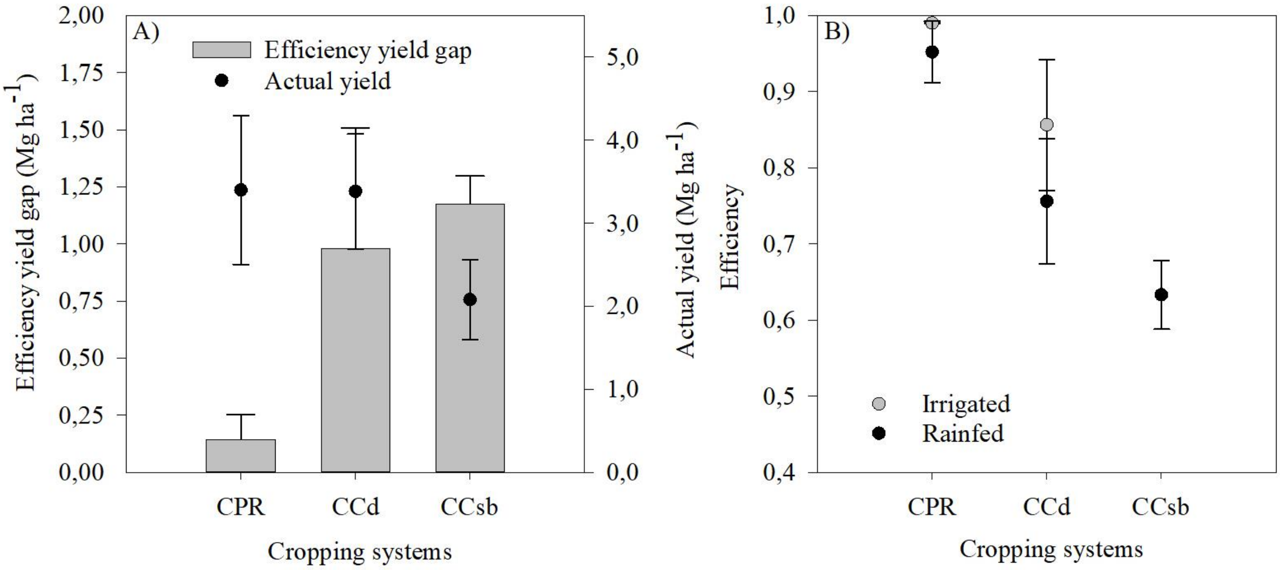

Figure 2. (A) Mean and standard deviation Y_a and efficiency Y_g when grouped by CS. (B) Rainfed and irrigated[1] systems efficiency in relation to CS.
[1]No results for yields under irrigated conditions in CC_{sb}.

Identifying resource yield gap components

The Y_{HF} was 4.9 Mg ha^{-1}, 26% lower than the potential yield estimated by Rizzo and Ernst (2020) to the studied area. The mean resource Y_g was 1.0 Mg ha^{-1}. Differences in resources assigned to soybean production can be grouped by soil quality and technology improvements. A soil quality effect on the resource Y_g was associated with subsurface soils compacted layers. Y_{LF} was related to values of penetration resistance (1423 kPa) that can limit crop development, especially under water deficit conditions. Within technology component limitations, we identify significant differences between Y_{HF} and Y_{LF} in water supply (irrigation) and CS design. Y_{HF} category included 70% of the cases under irrigated conditions and none CC_{sb} were found in Y_{HF}.

Table 2. Components of the total Y_g and the relation between resource Y_g with soil quality and technology improvements. Mann-Whitney U test was performed to compare percentiles of quantitative variables and two-way contingency tables (Chi^2) for dummy variables. Significance codes: '*' 5%.

Yield gap components	Y_{LF}	Y_{HF}
Actual yield (Mg ha^{-1})	1.8	4.9*
Technical efficient yield (Mg ha^{-1})	2.8	5.3*
Total yield gap (Mg ha^{-1})	3.1	0.5*
Efficiency yield gap (Mg ha^{-1})	1.0	0.5*
Resource yield gap (Mg ha^{-1})	2.1	0.0*
Resource yield gap components		
Soil quality		
Penetration resistance (7,5-15 cm) (kPa)	1423	1109*
Cation exchange capacity (5-15 cm) (meq 100 g^{-1})	28	25*
Technology improvements		
Total water from R4-R6 (mm)	89	173*
Irrigated systems (%)[1]	0	70*
Cropping systems[1]		
CPR (%)	5	55*
CC_d (%)	15	45*
CC_{sb} (%)	80	0*

[1]Dummy variables.

Conclusion

Our study revealed that soybean yield is susceptible to crop diversity and length of annual CS. While the "rotation effect" is associated with a high efficiency yield gap, a "C4 summer crop effect" could be associated with high technical efficient yield. When both effects are lost (soybean monocropping), a decline in actual soybean yield is observed, accompanied by an increase in technical inefficiencies. When looking into the resource yield gap, we could identify limitations such as soil quality, and technology improvements. From its analysis it was recognized that compaction, lack of water in the critical period of soybean crop and the cropping system implemented in the field, were playing an important role in shaping the resource yield gap.

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