ABSTRACT

Winter crop production in eastern Argentina and western Uruguay has been limited to wheat (Triticum aestivum L.) and barley (Hordeum vulgare L.), forming a double annual cropping system with soybean [Glycine max (L.) Merr.] and maize (Zea mays L.) during summer seasons. Currently, double annual cropping system covers less than 30% of the area. Past studies suggest that the rapeseed (Brassica napus L.)/wheat yield ratio ranges from 40 to 60%, and the inclusion of rapeseed in the system could improve grain yield of the following crops. The objectives of this study were to: (i) quantify the rapeseed/wheat yield ratio under different cropping systems; (ii) quantify the differential yield of summer crops compared with wheat and rapeseed while keeping a similar harvest date for winter crops and planting date for summer crops, respectively; and (iii) assess the economic result of the evaluated cropping systems. Rapeseed and wheat crops were sown in a long-term rotation trial where different cropping systems were evaluated. Experiments were conducted for two seasons (2014 and 2015) and in each summer season after the winter crop harvest, soybean (2014–2015) and maize (2015–2016) were sown. No yield differences were detected for wheat and rapeseed as a result of the previous cropping systems, and the rapeseed/wheat yield ratio was about 55%. Higher summer crop yields were obtained after rapeseed compared with wheat (11 and 17% for soybean and maize, respectively). Producers may be able to enhance both production levels and profitability by adopting a more diverse cropping sequence.

Abbreviations: ALUR, Alcohols from Uruguay; ANCAP, National Administration of Fuels Alcohol and Portland; CC-NT,c, continuous cropping rotation with no-till including C3 summer crops; CC-NT,c, continuous cropping rotation with no-till including C4 summer crops; CC-NT,soybean in summer season and fallow during winter season; COPAGRAN, National Agricultural Cooperative; CP-CT, crop–pasture rotation with conventional tillage; CP-NT, crop–pasture rotation with no-till; CT, conventional tillage; CUSA, Uruguayan Chamber of Agricultural Services; GP, gross product; GM, gross margin; NT, no-till.
et al., 2013; Kirkegaard and Ryan, 2014). Under this scenario, rape-
seed (Brassica napus L.) represents a possible economic alternative for
use in rotation with winter cover crops.

A global analysis by Rondonini et al. (2012) suggests that the
relationship between rapeseed and wheat yield ratio ranges between
40 and 60%. Analyzing the ratio of rapeseed/wheat yields for
particular countries, a great variability in the indicator was found,
particularly when wheat yield was less than 2000 kg ha⁻¹. Under such
conditions, the ratio was lower than when wheat yield was greater
than 4000 kg ha⁻¹. According to this information, it seems unlikely
to obtain a rapeseed yield lower than 40% of the wheat yield, and in
environments that are limiting for wheat, rapeseed yield may reach 90
to 100% of the wheat yield.

Production systems face problems such as increased frequency
of extreme weather events (Wollenweber et al., 2003). In the study
region, an important risk is the increase in probability of waterlogging
conditions during the winter season (de San Cledonio et al., 2014).
Ernst et al. (2016) reported wheat yield depletion in response to a
continuous no-till annual cropping system, mainly under unfavorable
weather conditions for wheat growth. Reduced nutrient supply and
deteriorated soil physical properties are considered as yield limiting
factors (Ernst et al., 2018). Limited research comparing these effects
on wheat and rapeseed simultaneously is available, but according to
physiological response, wheat would be less affected than rapeseed
under such conditions (Ashraf and Mehmood, 1990; Xu et al.,
2015; de San Cledonio et al., 2014, 2018; Wollmer et al., 2018).
Under commercial production conditions, yield losses associated
with waterlogging depend on climatic conditions, crop (wheat or
rapeseed) (Ploschuk et al., 2018), cultivar (Setter and Waters,
2003; Zhang et al., 2007; Cheng et al., 2010), crop stage (de San
Cledonio et al., 2014; Marti et al., 2015), and soil quality (Munkholm
et al., 2013; Sasal et al., 2017; Ernst et al., 2018).

Long-term cropping system experiments provide an
opportunity to compare the impact of variation in soil properties
induced by cropping systems on wheat and rapeseed. The objectives
of this study were to: (i) quantify the rapeseed/wheat yield ratio
under different cropping systems; (ii) quantify differential yield of
summer crops compared with wheat and rapeseed while keeping a
similar harvest date for winter crops and planting date of summer
crops, respectively, under commercial N and P fertilization rate; and
(iii) assess the economic result of the evaluated cropping systems.

Several authors reported increased wheat yield when legumes
or rapeseed are included as a “break crop” in wheat monocropping
systems (Kirkegaard et al., 2008; Angus et al., 2015). Distinctive features of our analyses are: (i) double annual cropping system, which
demonstrates that wheat and rapeseed can affect summer crop yield
differentially; (ii) the quantification of residual effects of the winter
crop on the following summer crop yield, removing differences
attributed to the harvest date of the winter crop and the planting
date of the summer crop; (iii) it applies to wheat vs. rapeseed yield comparisons, which reduce the effect of foliar diseases, as opposed to
wheat–wheat vs. rapeseed–wheat comparisons; and (iv) data from a
long-term experiment including different cropping systems were used
to estimate soil quality effects on crop yield within the same soil type.

**MATERIALS AND METHODS**

**Experimental Design and Field Evaluation**

The experiment was located in northwestern Uruguay, 10 km
south of Paysandú (32°23’8.12” S/58°3’47.61” W; 61 m above
sea level), within the Northern Campos region of the Rio de la
Plata grasslands (Soriano, 1992). The long-term trial was started
in 1993 at the Dr. M.A. Cassinoni Experimental Station. During
21 yr of continuous experimentation, the following treatments
were evaluated in a randomized complete block design with three
replications: (i) continuous cropping rotation with no-till (NT)
including C4 summer crops (CC-NTC4); (ii) crop–pasture rotation
with conventional tillage (CT) (CP-CT); (iii) continuous cropping
rotation in NT with soybean in the summer season and fallow during
the winter season (CC-NTS); (iv) crop–pasture rotation with NT
(CP-NT); and (v) continuous cropping rotation with NT including
C3 summer crops (CC-NTC3). Each of these major plots represents
different levels of soil conservation. The details of the experiment
can be found in Salvo et al. (2010, 2014).

During the 2014 winter season, blocks were split in two double
annual crop sequences under no-till: wheat–soybean vs. rapeseed–
soybean followed by rapeseed–maize vs. wheat–maize during the
following growing season (2015). Plots that had rapeseed during
2014 were sowed with wheat in 2015 and vice versa. The last presence
of a previous wheat crop was during the 2011 winter season. The main
management details of each crop are presented in Table 1. The sowing
date and varieties of wheat and rapeseed were selected to make the
harvest date as similar as possible, so that the next summer crop was
sowed immediately after harvesting the winter crops each year. We
selected varieties widely used by producers. All crops were adequately
managed to minimize the effect of pests, weeds, and diseases on the
crop yields.

At harvest maturity of each crop, 4 linear meters (2 rows) were
harvested to estimate grain yield. Each sample was threshed and the
grain weight was adjusted for grain humidity to obtain yield with
commercial humidity (8% for rapeseed and 14% for the rest of the
crops). For rapeseed, seed oil concentration (%) was determined by
Soxhlet extraction (method 1.122 from IUPAC, 1992) and the
results were expressed on a dry basis.

### Table 1. Main management practices applied to crops.

<table>
<thead>
<tr>
<th>Activities</th>
<th>Rapeseed</th>
<th>Wheat</th>
<th>Soybean</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivar</td>
<td>Rivette</td>
<td>Fuste</td>
<td>A 5019</td>
<td>DOW S10</td>
</tr>
<tr>
<td>Cultivar</td>
<td>Rivette</td>
<td>Fuste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row distance, m</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>P, kg P₂O₅ ha⁻¹</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>N applied, kg ha⁻¹</td>
<td>103</td>
<td>115</td>
<td>103</td>
<td>115</td>
</tr>
</tbody>
</table>

1. P₂O₅ and N applied correspond to the average amount applied by producers when soybean and maize are seeded under a double annual crop production system in the region.
Economic Evaluation of Crop Sequences

The cost of each crop was estimated using the record of management practices applied to each crop (Table 1 and Supplemental Tables S2–S5). Each agrochemical and/or fertilizer used, as well as each grain produced, was assigned a price per season. For labor (fertilization, sowing, etc.), it was assumed that in all cases the services of machinery were hired and prices were obtained from the Uruguayan Chamber of Agricultural Services (CUSA using its Spanish acronym) (www.cusa.com.uy). In cases where the price of labor was associated with the price of gas oil, this was obtained from the records published by the National Administration of Fuels Alcohol and Portland (ANCAP using its Spanish acronym) (https://www.ancap.com.uy).

Agrochemical prices were calculated using a database provided by the National Agricultural Cooperative (COPAGRAN using its Spanish acronym) since there are no official government reports or organizations that publish this information. Grain prices were calculated using the publication from the Mercantile Chamber of Products of the Uruguay (http://www.camaramercantil.com.uy). In the computation, average grain prices of March, April, May, and June were used for summer crops, whereas the average grain prices for November, December, and January were used for wheat. Rapeseed prices were obtained using referenced prices from the main local buyer, Alcohols from Uruguay (ALUR using its Spanish acronym). The price of rapeseed was adjusted according to the oil content of grains, taking 42% as a base and increasing 1% of the price for each point above that value or decreasing the price in the same proportion.

To estimate the transportation cost of the grain produced, it was assumed that wheat, soybean, and maize were delivered for export in the Nueva Palmira, Uruguay port (196 km from the experimental site), and that rapeseed production was delivered to the local biodiesel production plant, located in Montevideo (362 km from the experimental site). The calculation of gross margin did not include other selling costs, land rent, taxes, and the structural costs that a company would face to produce the crops (personnel, technical advice, mobility, etc.)

Data Analysis

The effect of previous soil management on wheat and rapeseed yield and rapeseed seed oil concentration was analyzed for each crop-year separately, using an analysis of variance with three complete blocks and five soil managements (five treatments). The rapeseed/wheat yield ratio was estimated for each year. Data analysis was accomplished using Infostat 2016/p (Balzarini et al., 2008). Regression analysis was also performed to assess the relationship between relative (to wheat yield) rapeseed yield and wheat yield using 2014 and 2015 data. For summer crops (soybean and maize), an analysis of variance was performed based on a split plot design, where the main plot was the previous management of the soil, and the previous winter crop the subplot (wheat or rapeseed); the interaction between these variables was also evaluated. If a significant difference of the “cropping system” on wheat and rapeseed yield and “cropping system × previous winter crop interaction” on summer crop yield factors were observed, a priori Fisher’s least significant difference was used for mean separation ($P < 0.05$).

RESULTS

Climate Characterization

During the 2014 winter season, rainfall was 40% and average temperature was 0.7°C above the long-term average for the site. This generated an unsuitable environment for winter crops during the yield concretion period (Fig. 1). In contrast, during the 2015 winter season, rainfall was in line with the expected amount for the period (~600 mm) and temperatures were lower than average (1.5°C lower than expected) during the critical period for yield determination (September, October, and November), making it a year with higher yield potential for winter crops than average (Fig. 2).

Summer growing season runs from November to April of the next year. During the summer season in which the summer crop was soybean (2014–2015), weather conditions were favorable, with high levels of rainfall during the months of December and January. Although rainfall was below the average in the following months (February–April), previous rainfalls and temperatures were in line with the expected, and hence less water stress (Fig. 1). During the next summer season, where maize was grown (2015–2016), weather conditions were also favorable. Rainfall was 18% higher than the average and temperatures showed no major deviations (Fig. 1). In summary and according to the expected behavior of the crops in the region, weather conditions were very favorable for summer crops

![Fig. 1. Monthly precipitation and average monthly temperature for the experimental period in relation to the average expected (2002–2013).](image-url)
during both years of evaluation. However, it was unfavorable for winter crops during the first year of evaluation and very favorable during the second year of evaluation.

**Relation between Wheat and Rapeseed Yield**

Despite differences in soil quality previously reported for the experimental site, it was not possible to detect differences in wheat and rapeseed grain yields and rapeseed seed oil concentration based on previous soil management (Fig. 2; Supplemental Table S1). The average wheat yield was 4709 and 6066 kg ha\(^{-1}\) for the 2014 and 2015 seasons, respectively, whereas the average for rapeseed was 2707 kg ha\(^{-1}\) (43% seed oil concentration) and 3129 kg ha\(^{-1}\) (46% seed oil concentration) in the 2014 and 2015 seasons, respectively. Yield differences between years were in line with the climatic conditions of each season (Fig. 1).

The average rapeseed yield represented 59 and 51% of wheat average yield for the 2014 and 2015 seasons, respectively. We detected
a weak negative but significant ($P$ value = 0.002) relationship between relative (to wheat yield) rapeseed yield and wheat yield for the 2014 and 2015 winter seasons. It indicates that under low wheat yield, relative rapeseed yields exceeded the average observed in the study (Fig. 3).

**Summer Crop Yields following Rapeseed or Wheat Winter Crops**

Both summer crops, soybean (2014) and maize (2015), achieved a significantly higher yield when they were sowed after rapeseed than after wheat. The increase was 11% ($P$ value = 0.04) in soybean and 17% ($P$ value = 0.01) in maize (Fig. 4; Supplemental Table S1). Neither of the summer crops showed a response to the previous cropping system ($P$ value = 0.341 for soybean and $P$ value = 0.960 for maize) or the interaction between cropping system and previous winter crop (rapeseed or wheat) ($P$ value = 0.543 for soybean and $P$ value = 0.738 for maize).

**Gross Margin of the Crops and Crop Sequences**

The gross margin (GM) of the rapeseed crop was greater than the wheat crop in both years by an average of US$ 395 ha$^{-1}$ (Fig. 5; Supplemental Tables S2 and S3). These differences were mainly explained by differences in gross product (GP) (on average, GP was $374 greater for rapeseed) as both crops had similar production costs. Gross product has two components: wheat to rapeseed yield and grain price ratio (Table 2). Under normal condition, price ratio is more favorable (2.5) that yield ratio (1.8).

The production costs of summer crops (soybean and maize) were independent of previous winter crop, and both summer crops had higher yields when they followed rapeseed than wheat (Fig. 4). Therefore, the gross margin was higher when the previous crop was rapeseed than wheat, resulting in higher margins for the double crop rapeseed/summer crop. Despite the gross margin advantage for summer crops after rapeseed, the benefits of previous sowing date was not experimentally exploited and higher cost of grain transportation were applied to rapeseed with respect to wheat.

**DISCUSSION**

Although rapeseed is not a new crop in the region, its sowing area has increased recently (Oil World, 2018) due to economic and political incentives directed toward soil conservation and the production of biofuels. Current agricultural systems are dominated by soybean as a summer crop (Paruelo et al., 2006; Baeza et al., 2014; Pinto et al., 2017), whereas wheat and barley have been the main economic alternatives as winter crops (DIEA, 2017). Regionally, 89% of the agricultural area remains as fallow during the winter season (Pinto et al., 2017), but locally it is mainly occupied by cover crops (DIEA, 2017). Therefore, there are two options to increase the rapeseed sown area: (i) occupy the area that is not currently being sown with a winter cash crop (fallow or cover crop); and (ii) as a break cash crop. Considering this second option, rapeseed would be included in crop sequences that already have two crops per year, but alternating during the winter season with gramineous crops (mainly wheat) to reduce wheat and barley disease problems (Carignano et al., 2008; Mazzilli et al., 2016). Our results support the second option, which confirmed that the rapeseed/wheat yield ratio in the region is approximately 55% (Rondanini et al., 2012) (Fig. 3). This was particularly good, considering that rapeseed cultivar could not utilize the good environmental conditions in 2015 (http://www.inia.org.uy/convenio_inase_inia/ resultados/index_00.htm). The rapeseed cv. Rivette is the most widely used cultivar in commercial farms. It is a very old cultivar whose yield rarely exceeds 4000 kg ha$^{-1}$ in cultivar trials. Conversely, the wheat cultivar used was a new, high-yield potential cultivar whose yields in trials of cultivars reached as high as 7800 kg ha$^{-1}$, so under good environmental conditions, the wheat cultivar can differentiate from rapeseed. During the 2 yr evaluated, the rapeseed price (without oil

<table>
<thead>
<tr>
<th>Crop</th>
<th>Units</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>US$ kg$^{-1}$</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>0.50</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Rapeseed/wheat</td>
<td>Proportion</td>
<td>2.20</td>
<td>2.72</td>
</tr>
</tbody>
</table>
Concerning wheat, the economic advantage of including rapeseed was magnified by improving the following summer crop yields (Fig. 2). The positive effect was quantified even though the early harvest advantage of rapeseed in relation to wheat under commercial conditions was not experimentally exploited. Therefore, summer crop yield increase after rapeseed cannot be associated only with early sowing dates, which is particularly favorable for soybean crops in the region (Caviglia et al., 2004; Andrade et al., 2015; Andrade and Satorre, 2015). Although our results are strongly demonstrating the agronomic and economic advantages of including rapeseed in the cropping systems, we cannot fully elucidate which process is determining the increased yield quantified on the followed summer crop. Positive effects have been linked to increased nutrient availability for the next crop (Sarker et al., 2018), its “biofumigant” effects (Kirkegaard and Sarwar, 1999), and improved soil structure, which reduces soil penetration resistance (Chan and Heenan, 1996). These sets of direct residual effects are confused with the beneficial effects expected due to rapeseed’s shorter cycle to harvest, which offer the possibility of sowing a summer crop earlier compared with wheat, with less stubble and faster decomposition rate (Caviglia et al., 2004; Andrade et al., 2015). Although some negative effects of rapeseed have been quantified on the following cash crops, especially when the following crop is a gramineous (Owen et al., 2010; Koide and Peoples, 2012; Schillinger and Paulitz, 2018), we remark that both yield of soybean and maize were improved when rapeseed was the previous winter crop rather than wheat.

Our work had two different aspects from other research in this area: (i) we analyzed the advantage of including rapeseed in a crop sequence with “corrected defects” (no monocultures and crop management that reduce differential effect of crop diseases or weeds), as comparisons are mainly between the advantages of wheat/wheat monoculture in relation to rapeseed/wheat rotation; and (ii) we evaluated the residual effect of winter crops on summer crops, irrespective of “sowing date effect.” Acknowledging the differences of the work performed, full double crop season with rapeseed as winter crops achieved 40 to 80% higher gross margins (2014 and 2015, respectively) than double crop seasons with wheat as the winter crop. However, this difference cannot be extrapolated to a system that replaces wheat with rapeseed, since a continuous rapeseed cropping exposed the crop to diseases (Harker et al., 2015; Hegewald et al., 2018). Therefore, our results are useful when the rapeseed crop is integrated into the cash crop winter options, as rapeseed cannot be competitive but complementary to the other possible sequences.

Finally, despite differences in soil quality between quantified treatments in the experimental site (Ernst et al., 2009; Salvo et al., 2010, 2014), and climatic conditions favorable to waterlogging damage (at least for the 2014 winter season) (Fig. 1), we did not detect a differential behavior of both wheat and rapeseed in response to previous long-term soil management. For the summer season, environmental climatic conditions, which may have reduced the soil quality influence on grain yields, did not seem to be a limiting factor. In turn, crops were managed as actual fertilization recommendation and therefore at that fertilization rate, no differences were observed that could be potentially detected when the fertilization levels increase (Ernst et al., 2016, 2018).

Our results suggest that the following topics should be elucidated to sustain intercalated inclusion of rapeseed as a winter crop alternative in double annual cropping systems: (i) What is the optimal frequency of rapeseed included as a break crop of fungi diseases of wheat or barley? (ii) Can increased yield of maize be attributed to low N fertilization rate used in the experiment? Differences in amount and quality of rapeseed stubble compared with wheat stubble could be amplifying differences under these low-input systems.

CONCLUSIONS

Results confirmed that the rapeseed/wheat yield ratio is on average about 55% within the study region. Following actual fertilization rates, this ratio was stable under different production conditions (soil quality and weather). The rapeseed crop was a better previous winter crop for summer crops (soybean and maize) than wheat at the same summer crop sowing date. Although winter crop production costs were similar (wheat vs. rapeseed), the rapeseed/wheat grain price ratio was 2.5 during the analyzed period. Systems that included rapeseed obtained higher income than systems that included wheat. Under current economic and production conditions, producers need to adopt a more diverse cropping sequence, particularly by rotating wheat and rapeseed during the winter season to enhance both production levels and profitability.

SUPPLEMENTAL MATERIAL

The supplementary information contains a table of analysis of variance for yield and oil results and agronomic management, production cost, and gross margin for each of the crops analyzed.

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