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Research Paper

Effects of irrigation regime on the growth and yield of irrigated soybean in temperate humid climatic conditions

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ABSTRACT

This research was conducted during two irrigation seasons (2014–2015 and 2015–2016) in Salto, Uruguay. This growing region is characterized by high annual precipitation and periods of soil water deficit of different intensities. This characterization casts much doubt to soybean growers regarding whether supplementary crop irrigation is useful for maximizing soybean yield, maintaining stable productivity and increasing profit margins. Three supplemental irrigation treatments in addition to a rainfed treatment were evaluated for their effects on soybean growth, development and yield with respect to the vegetative and reproductive stages. The results show that supplemental irrigation during the reproductive stage (R1–R8) has a positive effect on soybean growth and development, regardless of treatment. The total dry matter and leaf area index were between 8% and 40% higher in irrigation treatments compared with rainfed conditions. Actual evapotranspiration data, estimated with soil moisture sensors, showed that the crop coefficients (Kc) used in these experiments can be generalized for use in the region. During both cropping seasons, the rainfed treatment produced the lowest grain yield, with a 35% reduction in yield compared with that of the irrigated treatments. However, the water use efficiency values were inversely related to the amount of water applied. The profit margin showed that supplemental irrigation is useful in conditions during which the soybean price was greater than 350 U$D per ton, given the hypotheses considered. In the northwestern region of Uruguay, no irrigation would be the best option when the soybean price is less than U$D 350 or when rainfall is more stable during crop growth seasons.
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1. Introduction

Soybean (*Glycine Max* L.) is the sixth-most grown agricultural crop in the world (FAOSTAT, 2016). During 2006–2013, the USA, Brazil and Argentina were the main soybean-producing countries, whose soybean production equaled 70% and 80% of the total area harvest and total production in the world, respectively (FAOSTAT, 2016).

Uruguay, as the eighth soybean producer worldwide (1.2% of the total), experienced a large increase in crop area and production (288% and 373%, respectively) during the 2006–2013 period, with crop yields close to those of the main producer countries (FAOSTAT, 2016). The high soybean demand from countries such as China and the high international price achieved (MGAP, 2014), coupled with the soil and climatic conditions in Uruguay, were the main causes of the growth in Uruguay.

Irrigation significantly increases soybean yield and profit margins when the crop is growing in soils with permanent or periodic soil water deficit (Karam et al., 2005; Salassi et al., 1984). The soybean response to water deficit has been studied in many experimental trials (Dogan et al., 2007; Karam et al., 2005; Martín de Santa Olalla et al., 1994; Payero et al., 2005; Sincik et al., 2008), mainly under arid or semiarid conditions. Moderate soil water deficit for short periods of time during the vegetative stage generally do not reduce soybean yield (Lich et al., 2013; Oya et al., 2004). However, a more severe or long-term water deficit can lead to reductions in soybean yield (Lich et al., 2013). The reproductive stage shows the largest sensitivity to potential yield reduction during water deficit, while deficit during the flowering stage has a small negative effect on yield (Andrade, 1995; Foroud et al., 1993; Lich et al., 2013). However, water deficit during the pod-enlargement and seed-filling stages has a significant negative effect on the final yield and the components of yield (Andrade et al., 2002; Cox and Jolliff, 1986; Foroud et al., 1993).

Many areas of the world with a moderate humid climate in addition to the high variation in rain distribution, especially during the spring and summer, can negatively affect soybean production, as

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Table 1
Soil water content (Hv%) of soil experimental trial.

Soil Depth (m)	FC (%)	PWP (%)
0–0.10	55.60	38.15
0.10–0.20	52.40	44.00
0.20–0.30	58.90	45.60
0.30–0.40	56.90	43.20
0.40–0.50	60.90	49.60

FC: field capacity (0.01 MPa); PWP: permanent wilting point (1.5 MPa).

well as production of other agricultural systems that are based in pastures, compromising profitability and productive stability (Failde et al., 2013; Sincik et al., 2008). The use of the supplemental irrigation (Fereres and Soriano, 2007) applied during the most important stages, such as the reproductive stage, would allow growers to maximize yield, reducing the yield variability between years and increasing the profitability in temperate and humid climates, such as that of Uruguay. However, the typical rainfall season distribution of these areas, the productive costs (seeds, fertilizers, energy, etc.) and the soybean sale price reached during the harvest crop are the main reasons to decide whether growers ought to invest in irrigation system or not, under temperate humid climate conditions.

Therefore, the purpose of the present work was to evaluate the soybean response to three supplemental irrigation strategies compared with the rainfed crop (fully irrigated and two deficit irrigations during the reproductive stage), focusing on the crop growth and development, grain yield, actual evapotranspiration and water use efficiency in a clay soil under a temperate climate in Uruguay. As an additional goal, the profit margins between supplemental irrigation and rainfed soybean crops were calculated.

2. Materials and methods

2.1. Location of the experiment

The experiment was carried out during the 2014–2015 and 2015–2016 crop seasons in a 3500-m^2 plot in Salto, Uruguay (31°22′31″S, 57°42′54″W). The soil was classified as either a Vertic Argiudolls (USDA-NRCS, 2006) or a Typical Brunosol Eutrico (MGAP, 1979), composed of an A horizon (0.35 m deep) and a B horizon (0.40 m deep), with clay texture (8.8% sand, 38.6% silt and 52.6% clay) in the A horizon. The soil hydraulic characteristics (field capacity and permanent wilting point) were determined using a Richard's chamber for the soil water extraction with undisturbed samples from different depths up to 0.50 m (Table 1). It was carried out approximately one month before sowing in three representative sampling plots.

The study area has a moderate humid climate (Linderman et al., 2013) characterized by a cyclical distribution of temperatures and evaporative demand, in which summer is the hottest season with the highest ET_0 values, while winter has mild air temperature (5–8 °C) with less evaporative demand. The meteorological data during both cropping seasons were obtained using a Davis station (Davis Instruments Corp. Inc., CA, USA) located near the experiment (Table 2). The accumulated precipitation during the cropping season was 730 mm during 2014–2015 and 1174 mm during 2015–2016. The reference evapotranspiration (ET_0) was calculated according to FAO-Penman Monteith equation (Allen et al., 1998).

2.2. Crop management

The soybean cultivar used in both years was an intermediate maturity group, (cultivar 6262 IPRO, Don Mario), which average crop cycle duration is 142 days in the region, requiring from sowing around 9 days to emergence, 61 days to the beginning of bloom and 131 days to the beginning of ripening (Fassio et al., 2017). Sowing in the first experimental year occurred on November 8, 2014, whereas in the second year, it was carried out on November 24, 2015. During both seasons, the crop was planted after a ryegrass pasture, which was used as a cover crop during winter, producing 800 kg ha^{-1} of dry matter in the first cropping season and 3500 kg ha^{-1} in the second season, with the goal of avoiding erosion. Planting distance between rows was 0.40 m. A 300 kg ha^{-1} NPK (7-40-40) fertilizer were used in both cropping seasons applied at sowing date together with the seeds. Planting density was 41.2 and 28.0 plants m^{-2} in the first and second experimental years, respectively. The crop was harvested once the seedlings matured, which occurred on April 2, 2015, and April 20, 2016. The traditional cultivation techniques regarding pest and disease management of the area were used to maximize crop yield and quality.

2.3. Experimental design

Four treatments were designed to supply different water satisfaction levels of the crop according to the soybean phenological stage. During the vegetative stage, 100% of the crop water requirement (CWR) was supplied with irrigation in three of the four treatments (Fig. 1a). However, these three treatments received a different CWR percentage (100%, 75% and 50%) during the reproductive phase (R1–R8) (Fig. 1b). The diary CWR was computed according to the FAO methodology (Allen et al., 1998). The reference treatment (T1; 100–100%) provided all crop water requirements throughout the crop growth cycle, allowing maximum crop production (Table 3). The two irrigation water deficit treatments, T2 (100–75%) and T3 (100–50%), received 75% (T2) and 50% (T3) of the CWR during the reproductive stage (Table 3). Rainfed treatment (T4) was used during the entire growing season (Table 3), allowing the crop to receive only the rainfall (Fig. 1). The experimental design was a completely randomized block with 3 replicates (Fig. 1).

The treatment plot size was 12.8 m wide by 9.0 m long, providing enough surface to allow suitable crop development under a specific treatment. However, to ensure a crop water deficit and to achieve the T1, T2 and T3 treatments during the reproductive phase, it was necessary to delimit a small area that could prevent incoming rain in each plot. The rainfall-exclusion area (12.0 m^2; 3.0 m by 4.0 m), called the elemental plot (Fig. 1b), was protected by a polyethylene cover film (similar to a tunnel-like structure) fixed to the ground with flexible tubing and wires (Fig. 2). This tunnel structure was not installed on the rainfed plots. Before any rain event, the polyethylene cover was extended over the crop, after which the cover was folded (Fig. 2). In addition, the elemental plot served as a sampling area.

2.4. Irrigation management and soil water measurement

The irrigation schedule for the T1 treatment was accomplished diary using the simplified water balance method for the root zone of the crop (Allen et al., 1998; Pereira and Allen, 1999) (Eq. (1)).

$$Dr_i = ETc_i - Pe_i - I_i + DP_i + Dr_{i-1} \quad (1)$$

where, Dr: root zone depletion (mm); I: irrigation depth (mm); ETc: maximum crop evapotranspiration (mm) computed as ET_0*Kc; Pe: efective precipitation (mm); DP: deep percolation outside of root zone (mm); i: actual day; i-1: day before

The crop coefficients (Kc) used for the reference treatment were based on those in FAO-56 (Allen et al., 1998) according to the soybean phenological stage as follows: 0.4 during crop establishment, 1.15 for the reproductive stage and 0.5 before ripening. The irrigation schedule for the T2 and T3 treatments was carried out

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