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Yield components, light interception and radiation use efficiency of lucerne (*Medicago sativa* L.) in response to row spacing

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ABSTRACT

Lucerne sowing is characterized by a rectangular spatial arrangement, *i.e.* greater distance between sowing rows than between plants in the row. Therefore, the reduction of row spacing generates more square spatial arrangements that can influence intraspecific competition and resource utilization, especially radiation, and thus biomass. The experiment included different row spacings (10–15–17.5–20 and 30 cm) at the same plant density in a pure lucerne crop during the first production year. Total aerial dry matter (ADM) was increased by narrow spacing (more square arrangements) up to an optimal distance (around 13 cm) (R^2 = 0.60). ADM ranged from 2292 to 1670 g DM m^{-2} for 15 and 30 cm row spacing, respectively. Plant density was the forage yield component most affected by row spacing and it increased with narrow spacing ($0.15 \geq R^2 \leq 0.5$). ADM responses to reduced row spacing were positive as revealed by both a linear increase in radiation interception (PAR_{ia}) (R^2 = 0.76) and an optimal pattern in radiation use efficiency (RUE) (R^2 = 0.45). PAR_{ia} in the first year showed an increase of 8 MJ cm^{-1} of spacing reduction. RUE values ranged from 2.0 to 1.6 g DM MJ^{-1} for 15 and 30 cm row spacing, respectively. The leaf area index (LAI) was also affected by row spacing. Additionally, seasonal variation was found for the main variables but did not interact with row spacing. In conclusion, reducing row spacing to an optimal distance is a practice that allows for more favourable spatial arrangements of a lucerne crop and has a positive impact on forage production.

1. Introduction

Row spacing is an agronomical practice that determines the spatial distribution of the plants, which affects canopy structure, light interception and radiation use efficiency and consequently, biomass production in forage cropping systems. Lucerne pastures have very limited capacity for reseeding, which means that the spatial distribution of the plants remains uniform for many years and thus determines the timing of canopy closure after every defoliation. Lucerne sowing is characterized by greater distance between rows than between plants in the row, thereby showing a markedly rectangular arrangement. It is worth noting that if the row spacing decreases at the same density, the distance between plants in the row increases, thus generating a more square spatial arrangement. This could lead to improved canopy closure and biomass accumulation at each regrowth. The effects on biomass production can be analysed through changes in forage yield components such as the number of plants per area, the number of shoots per plant and the mass per shoot (Volenec et al., 1987). Complementary, biomass production can be studied by analyzing the radiation model components: the photosynthetically active radiation (PAR) intercepted and accumulated during the crop cycle (PAR_{ia}) and the radiation use efficiency (RUE) or PAR conversion into biomass (Monteith, 1977). For this study, we performed both analyses to generate knowledge about the mechanisms involved in the biomass response to row spacing in pure lucerne crops.

Different spatial arrangements produced by changes in row spacing can affect resource competition relationships at both the intraspecific and the interspecific levels (*e.g.* affecting recruitment of weed species). Intraspecific competition has three effects: (i) density-dependent mortality, (ii) trade-offs between size and density, and (iii) population size structure alteration (Park et al., 2003). The first two effects can be inferred by changes in average forage yield components, while the distribution of plant sizes in the crop provides information about the population structure. The

Abbreviations: ADM, aerial dry matter; LAI, leaf area index; PAR, photosynthetically active radiation; PAR_{ia}, amount of photosynthetically active radiation intercepted and accumulated during crop cycle; $fPAR_i$, fraction of photosynthetically active radiation intercepted by the canopy; $fPAR_t$, fraction of photosynthetically active radiation transmitted through the canopy; RUE, radiation use efficiency.

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combination of two agronomic practices, plant density and row spacing, defines the spatial arrangement of plants. Density effects were clarified in a two-year experiment performed by Volenec et al. (1987), with a uniform distance between plants (square arrangement) for all density treatments. These authors determined that increased plant density had a positive effect on lucerne biomass production due to a higher shoot number per unit area, though the average plant size was reduced. Conversely, the focus of our work was to analyse how row spacing affected forage yield components, light interception, radiation use efficiency and biomass production at the same plant density in lucerne's first production year, where greater effects were previously found (Mattera et al., 2009).

Row spacing was studied in numerous experiments in grain and industrial crops following the radiation model. As a result, in several crops narrow spacing increased the proportion of the radiation intercepted by the canopy ($fPAR_i$), resulting in higher PAR_{ia}. This response was observed in grain crops such as corn (*Zea mays* L.) (Barbieri et al., 2000; Andrade et al., 2002; Sharratt and McWilliams, 2005), sorghum [*Sorghum bicolor* (L.) Moench] (Steiner, 1986), soybean [*Glycine max* (L.) Merr.] (Board et al., 1992; Andrade et al., 2002) and sunflower (*Helianthus annus* L.) (Zaffaroni and Schneiter, 1989). The $fPAR_i$ increase was also reported for industrial crops as sugarcane (*Saccharum* spp.) (Singels and Smit, 2009) and fiber hemp (*Cannabis sativa* L.) (van der Werf et al., 1995). The higher $fPAR_i$ was mainly explained by changes in leaves disposition; in other words, a more equidistant arrangement of the plants ensured a more uniform distribution of leaves in the canopy (Zaffaroni and Schneiter, 1989; van der Werf et al., 1995; Flenet et al., 1996; Barbieri et al., 2000; Sharratt and McWilliams, 2005). Other authors have reported that more square arrangements increased the leaf area index (LAI) (Steiner, 1986; Board and Harville, 1992; Singels and Smit, 2009) also enhancing $fPAR_i$. The effects of row spacing on biomass production are also determined by what occurs in the second component of the radiation model, the RUE. For corn, soybean, and sunflower, the positive grain yield responses were associated with increments in PAR_{ia} (Andrade et al., 2002). However, yield increases were not as proportional as the increase in PAR_{ia} suggesting a lower RUE or harvest index in narrow spacings. For corn, RUE also dropped at post-flowering, counteracting the positive effects of higher PAR_{ia} in narrow rows during the same period (Maddonni et al., 2006). The mechanisms that explain RUE reduction in narrow spacing are still under study. Maddonni et al. (2006) suggested that both light attenuation within the canopy and red/far red ratio at lower leaf stratums could have depressed photosynthesis and consequently RUE. In forage crops, the existing information reported biomass increments by row spacing reduction (for pure lucerne: Roufail, 1975; Lutz and Morley, 1982; Mattera et al., 2009; and associated with grasses: Jefferson and Kielly, 1998), but the studies were not completely detailed in terms of both forage yield and radiation model components. In crowded populations, the asymmetric competition due to light determines the death of smaller plants (Weiner et al., 1990). Self-thinning processes are common in lucerne crops (Rowe, 1988; Teixeira et al., 2007a), and unlike annual crops, changes in yield components through the years can determine size density compensation. However, in a preliminary work for a period of three years, we have found that the row spacing affected both plant size and density through the initial period (Mattera et al., 2009). We proposed the current experiment to investigate forage yield components with exhaustive detail to scrutinize these processes during the first year.

Lucerne is one of the most important forage crops due to its elevated production of high quality forage. The objectives of this work were: (i) to study the impact of row spacing on intraspecific competition by analyzing forage yield components (plant density, shoots plant^{-1} and weight shoot^{-1}) and (ii) to analyse the effects of row spacing on light interception and radiation use efficiency and its relation to aerial biomass production. The experiment included measurements at five different row spacings (10–15–17.5–20 and 30 cm) at the same plant density established by thinning, in a pure lucerne crop (cv. Monarca) during five subsequent regrowths in the first production year. To the best of our knowledge, this is the first quantitative study to deal with the yield components, light interception and radiation use efficiency of forage crops in response to row spacing. We hypothesized that the decrease of row spacing generates more square spatial arrangements which increase biomass production in lucerne crops. Specifically, we predicted that narrow spacings would increase forage yield components due to lower intraspecific competition. Although there exists a trade-off between intra-row and inter-row distances, in the case of lucerne crops, where plants are much closer in the row than between rows, the intra-row distance would limit growth first. Therefore, narrow spacing (greater intra-row distance) would delay the onset of competition. Second, narrow spacings would reach the critical LAI faster due to a plant arrangement closer to a square, increasing the time of the regrowth with optimal interception. Third, we also predicted that the spacing would not affect RUE in the range of biomass commonly explored by lucerne crops for forage production, though this could occur if a closer distribution of the plants changes light penetration through the canopy.

2. Materials and methods

2.1. Study site

The experiment was carried out from March 2009 to January 2010 on an area of flat land at the Rafaela INTA Experimental Station, Santa Fe, Argentina (31°12′S and 61°30′W). The climate of the region is subhumid humid and mesothermal, and Rafaela is characterized by annual rainfall of 957 mm with little precipitation in winter. The annual mean temperature is 19 °C, with the mean monthly lowest temperature in July (12 °C) and the maximum in January (26 °C). The soil is a "Rafaela" silt loam (USDA Soil Taxonomy: Typic Argiudoll, fine, mixed, thermic) (Mosconi et al., 1981), being the top horizon (first 20 cm) characterized by 3.4% of organic matter, 0.2% of total nitrogen, 37 mg kg^{-1} of nitrates-N, 67 mg kg^{-1} of extractable P, 9 mg kg^{-1} of sulfates-S and a pH of 6.3.

2.2. Crop establishment, experimental design and treatments

The lucerne cultivar used was Monarca SP INTA (Produsem S.A., Pergamino, Argentina) (without winter dormancy), with a thousand seed weight of 2.3 ± 0.1 g and germination power of 93 ± 1%, seeds were uncoated without treatment and inoculation. Before sowing, the seedbed was prepared by a disc harrow and a tine harrow. The experiment was hand-seeded, put in rows at a sowing depth of around 1 cm, in early autumn of 2009. Precipitation during the time of sowing was sufficient to assure a good establishment of the crop (358 mm from February to April). During the rest of the experimental period, precipitation was abundant (770 mm), exceeding lucerne evapotranspiration in every regrowth, except in October, where irrigation (≅15 mm) was done to avoid severe water stress. Weeds were hand controlled. Pesticides were applied to control insects and diseases when necessary. Degree day accumulation during each regrowth was calculated as the sum of averages of daily absolutes lowest and highest temperatures, considering a base temperature of 5 °C (Fick et al., 1988).

Rhizobia infection was expected given the previous history with lucerne in the paddock. The experimental design was a randomized complete block with five replicates. Each experimental unit consisted in a plot of 1 m × 1.5 m. Treatments were established at sowing as five row spacings: 10–15–17.5–20 and 30 cm