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Water and radiation productivity in different cropping sequences in the north center of Santa Fe

Productividad del agua y la radiación en diferentes secuencias de cultivos en el centro norte de Santa Fe

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Abstract

Dry matter and grain productions depend on the ability of crops to capture resources. Productivity of resourses is defined based on the amount of grain or dry matter produced per unit of available resource (solar radiation or rainfall) during the year. Our main objective was to evaluate the effect of different crop sequences on the productivity of water (WP) and radiation (RP) resources for grain production and total dry matter (DM). The trial was carried out during 2014/15 and 2015/16. Nine sequences were established, including different cultures and fertilization doses with a 25, 50 or 75 % -variable-participation of grasses.

Increases of the order of 125 and 125 % were determined in WP, and of 141 and 142 % for RP for grain and DM respectively, in the sequence b/fc-w/s respect v/s-w/s (b: barley; w: wheat; s: soybean; v: vicia; fc: fertilized corn). The results showed that the sequences of crops that included higher percentage of grasses and the adequate fertilization, increased water and radiation efficiency and productivity, achieving a greater contribution of carbon from crop residues.

Keywords

water use efficiency • radiation use efficiency • soybean • wheat • vicia • corn • barley

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Resumen

La producción de MS y grano dependen de la capacidad de los cultivos para capturar recursos. Para estudiar la eficiencia a nivel de la secuencia de cultivos se define la productividad de los recursos basada en la cantidad de granos o materia seca producidos por unidad de recurso (radiación solar o lluvias) disponible durante el año. El objetivo principal del trabajo fue evaluar el efecto de diferentes secuencias de cultivos sobre la productividad de los recursos agua (PA) y radiación (PR) para la producción de grano y materia seca total (MS). El ensayo se realizó durante las campañas 2014-15 y 2015-16, estableciendo 9 secuencias que incluyeron diferentes cultivos y niveles de fertilización, teniendo las gramíneas un 25, 50 o 75 % de participación en las mismas.

Incrementos en el orden del 125 y 125 % fueron determinados en la PA y del 141 y 142 % en la PR para la producción de grano y MS respectivamente, en la secuencia c/mf-t/s respecto a v/s-t/s. (c: cebada; t: trigo; s: soja; v: vicia; mf: maíz fertilizado). Los resultados mostraron que las secuencias de cultivos que incluyeron mayor porcentaje de gramíneas y la adecuada fertilización, aumentaron la eficiencia y productividad en el uso del agua y radiación, logrando un mayor aporte de carbono proveniente de los rastrojos al suelo.

Palabras clave

eficiencia uso del agua • eficiencia uso radiación • soja • trigo • vicia • maíz • cebada

Introduction

During the last 200 years, population growth has considerably increased the pressure on productive lands. Worldwide food demand is expected to increase by 60-100 % by 2050 (25). Plowing of agricultural soils and the low return of harvest residues to them has caused the reduction of carbon (C) in these soils (17). The absence of winter crops also reduce the capture of resources (water and radiation) which are not used to produce grains or dry matter (3). In this sense, in regions where growing season is broad and the supply of resources is favorable, a huge amount of these resources is wasted instead of being exploited by intensifying the sequences in a sustainable way.

The sustainable intensification of agriculture aims to maintain or increase the current production levels with a more intense and rational use of the resources of the environment and of lands with greater aptitude. Improvements based on sustainable intensification must be economically viable, socially acceptable and environmentally sustainable (4).

Intensive farming involving multiple crops per year could improve resource capture and productivity. Resource productivity is defined as the ratio between output (dry matter or grain yield) and annual input of Photosynthetically Active Radiation (PAR) or rainfall.

Dry Matter (DM) and grain production depend on the ability of the crop to capture resources. The efficiency of a crop sequence is defined according to the amount of grain or DM produced by resource unit, available during the year (3). This concept integrates capture and use efficiencies.

Increased radiation capture could improve the cycling of nutrients and the return of crop residues to the agricultural systems (22). This is associated with improved C balance (24) and soil aggregation (20). In similar way, the application of fertilizers increases the productivity of crops, achieving in the medium and long term a positive effect on the soil by increasing the production of crop residues (16).

The Intensification Sequence Index (ISI) depends, basically on the period of the year occupied by crops in each sequence. Besides, there is exist a negative correlation between ISI and runoff or erosion, and a positive correlation soil C content (9, 19, 23). The wheat/soybean double cropping is the more widespread sequence. This sequence occupies a great proportion of the growing season, obtaining a high and efficient capture of resources, with a value of ISI=2. On the other hand, soybean monoculture has a lower ISI value (ISI=1).

We hypothesize that the productivity of water and radiation resources can be modified according to the different participation of grasses in the sequence crop. The main objective of this work was to evaluate the effect of different crop sequences of two years on the productivity of water and radiation resources for the production of grain and dry matter.

The inclusion of winter crops for grains, allows implementing the double sequential crop, sowing a summer crop after harvesting a winter crop. Enough information for the Argentine Pampas area states that soybean monoculture causes highly negative C balances.

Other crop rotations are necessary, including such as corn with other winter alternatives other than wheat, such as vicia or barley.

Materials and Methods

The trial was carried out in the Experimental Unit of Extensive Crops, in the city of Esperanza, Santa Fe, Argentina (31º 24' 54.14''S 60º 54' 28.64''O), the soil is typic Argiudoll, Esperanza series, moderately deep and drained, with agricultural history of 8-year direct seeding and soybean predecessor.

Organic matter was determined in 2.2 % [considered medium-low (6)] and phosphorus Bray levels at 10 ppm (below the critical response levels for soybeans (10) and wheat (12)). Meteorological data (rain, radiation and temperature) were taken from the weather station located in the Facultad de Ciencias Agrarias of Esperanza.

Three criteria are proposed for the selection of agricultural sequences: 1) maintain an ISI=2 with four crops in two years; 2) soybean present in all the sequences; and 3) include alternative winter crops for wheat, both for harvest and as cover crop. The design was in randomized complete blocks with arrangement in divided plots and three repetitions.

The main plot corresponded to the crops of first occupation (winter) and the sub-plot to the rest of the crops in the sequence.

The crops were: vicia (*Vicia villosa*) -as a cover crop-; wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), soybean (*Glycine max*) and corn (*Zea mays*). Second corn had two levels of fertilization: fertilized corn (fc) [150 kg_N ha^{-1} according to the replacement dose of the N extracted by the crop to maximum yields as defined in Maddonni *et al*. (2003)] balance method, and without fertilization (c).

The grasses represented 25, 50 or 75 % of the sequence crops. In total 9 sequences were used 1) vicia/soybean-wheat/soybean (v/s-w/s); 2) vicia/soybean-wheat/soybean (v/s-w/s); 3) wheat/soybean-wheat/soybean (w/s-w/s); 4) barely/soybean-wheat/soybean (b/s-w/s); 5) wheat/corn-wheat/soybean (w/c-w/s); 6) vicia / fertilized corn-wheat/soybean (v/fc-w/s); 7) barely corn-wheat/soybean (b/c-w/s); 8) wheat /fertilized corn-wheat/soybean (w/fc-w/s); 9) barely/fertilized corn–wheat/soybean (b/fc-w/s).

A basic fertilization according to the requirements of each crop, was provided. Fertilization was performed according to diagnosis at the beginning and end of each crop of the rotation. Management practices were implemented to maximize their production in terms of nutrition, weed control, pests and diseases.

In the culture of vicia, the production of DM at the time of drying was determined. This was done with 2 l ha^{-1} of glyphosate at the beginning of flowering (20 % flowering -a flowered knot within the top five knots-).

Grain yield was determined by harvesting plants of 8 linear meters of each experimental unit. The samples were dried in an oven with forced air circulation at 65 °C until constant weight. Then, they were re-weighted to obtain total DM and threshed by hand to determine grain yield. Final weight was corrected to commercial humidity. The contribution of C in crop residues was estimated by subtracting the total aerial DM from the DM in grain, and knowing that 40 % of the DM is C (1).

The Photosynthetically Active Radiation intercepted (PARi) by crop was obtained using a radiometer LI-COR (LI-250) in each plot, PAR above (I_0) and below (I') the canopy was measured around noon (*i.e.* 1200–1400 h) on sunny days, according to methodology proposed by Gallo & Daughtry (1986). The percentage of intercepted PAR (% iP) was calculated as $100*[1-(I'/I_0)]$. The cumulative PAR intercepted by the crop (PARi) was obtained by multiplying the incident PAR by % iP during crop ontogeny.

Initial useful water stored in the profile up to 1.2 m depth, and the residual at the time of physiological maturity or at the time of drying with herbicide in the case of cover crops, was calculated by gravimetry. With the variation of soil water content (Δ h), the water balance method was used to obtain crop evapotranspiration (Etc), clearing the formula:

$$\Delta h = Etc - Pe - Per$$

where:

Pe = effective precipitation, considered as 0.8 of the total precipitation when it exceeds 20 mm (7)

Per = deep percolation (zero was assumed).

Water Productivity (WP) in different crop sequences was estimated as:

$$WP\ (g\ m^{-2}\ mm^{-1}) = WUE * Wc$$

where:

WUE = Water Use Efficiency

Wc = Water capture efficiency.

The WUE was calculated as the quotient between the sum of the yields or total DM of summer and winter crops and, the sum of the ETc of crops.

The Wc resulted from the quotient between the sum of the ETc of the crops and the rainfall from June 1, 2014 to April 20, 2016.

Radiation productivity (RP) was calculated as:

$$RP\ (g\ m^{-2}\ MJ^{-1}) = RUE*Rc$$

where:
RUE = radiation use efficiency
Rc = radiation capture efficiency.

The RUE was calculated as the quotient between the sum of the yields or total DM of the crops in the different sequences and the PARi. The Rc was the quotient between crops PARi and the photosynthetically active radiation, incident from June 1, 2014 to April 20, 2016.

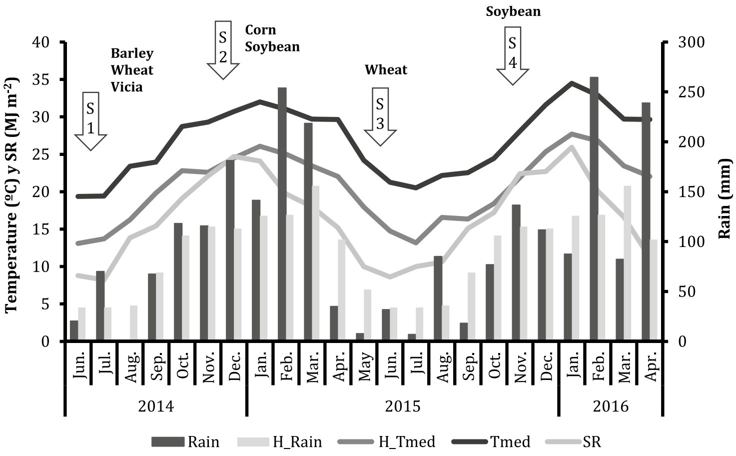
The data were evaluated by means of ANOVA for repeated measurements by sequence culture and following the structure of plots and treatments defined in the design.

When the differences between treatments for one variable were significant, the means were compared according to the LSD test (α= 0.05). InfoStat Professional version software was used (11).

Results and discussion

Meteorological conditions

During the 2014 campaign, photothermal conditions were sub optimal for the flowering period of wheat and barley crops (September 21-October 12) with temperatures higher than the historical record (figure 1). Plant growing period occurred with scarce offer of rains. The period of stem elongation was favored by the precipitations of September, followed by filling of grains with scarce precipitations and high temperatures (figure 1).



Arrow indicates date of sowing [S1: sowing winter crops –wheat, barley and vicia (cover crop)-; S2: sowing summer crops -soybean and corn-; S3: sowing winter crop –wheat-; S4: sowing summer crop–soybean-].

La flecha indica las fechas de siembra [S1: siembra cultivos de invierno -trigo, cebada y vicia (cultivo de cobertura)-; S2: siembra cultivos de verano -soja y maíz-; S3: siembra cultivo invierno –trigo-; S4: siembra cultivo verano –soja-].

Figure 1. Average temperatures (Tmed) and Historical (H_Tmed), solar radiation (SR) and monthly rains from June 2014 to April 2016 (Rain), Historical rains (H_Rain).

Figura 1. Temperaturas medias (Tmed) e históricas (H_Tmed), radiación solar (SR) y lluvias mensuales desde junio 2014 a abril 2016 (Rain) e históricas (H_Rain).

For summer crops, rainfall totaled 830 mm in the cycle (December-April), 33 % above the historical average. It should be noted that February excess rainfall had no negative effects on crops.

The 2015 wheat campaign had average temperatures around 19 °C, recommended to ensure optimum grain filling (figure 1, page 65). In the initial stages of the crop, rainfall was very scarce.

However, the period of stem elongation (September) was favored by timely and above normal rainfall during August (figure 1, page 65). For soybean cultivation, of soybean the rains in November, February and April (2015-2016) were above normal, with excesses in the month of April affecting quality grain and harvest.

Total Dry Matter and carbon contribution to the soil

The highest total DM productions were achieved with the sequences b/fc-w/s and w/fc-w/s (table 1). On average and, with respect to the lower production sequence (v/s-w/s), 4971 g m^{-2} were obtained, 93 % superior to the sequence v/s-w/s.

The rotations with 75 % of grasses and high fertilization achieved the highest productions of dry matter and contributions of crop residues C (without roots) to the soil (table 1). It is known that nitrogen fertilization, mainly in grasses, increases biomass production of crops, causing a greater accumulation of C in plant tissues and a high return to the soil (13, 14).

Table 1. Total Dry Matter (Total DM) and contribution of harvest residue carbon -without roots- (Contribution of C) in different sequences of 2 years duration crops (v= vicia, w= wheat, b= barley, s= soybean, c= corn without fertilization, fc= fertilized corn).

Tabla 1. Materia seca total (Total DM) y aporte de carbono del rastrojo -sin raíces- (Aporte de C) en diferentes secuencias de cultivos de 2 años de duración (v= vicia, t= trigo, c= cebada, s= soja, m= maíz sin fertilización, mf= maíz fertilizado).

Crop sequence	Total DM (g m^{-2})	Contribution of C (T $ha^{-1}year^{-1}$)
v/s-w/s (25)	2396 a	2.7 a
v/c-w/s (50)	2933 b	3.5 ab
w/s-w/s (50)	3139 bc	3.8 b
b/s-w/s (50)	3362 bc	4.1 b
w/c-w/s (75)	3727 cd	4.1 bc
v/fc-w/s (50)	4218 de	5.1 d
b/c-w/s (75)	4429 ef	5.4 d
w/fc-w/s (75)	4871 fg	5.7 d
b/fc-w/s (75)	5071 g	5.9 d

The percentage of grasses in the sequence is expressed in parentheses. Different letters, within the same column, indicate differences according to LSD test ($p \leq 0.05$).

El porcentaje de gramíneas en la secuencia está expresado entre paréntesis. Letras diferentes, dentro de la misma columna, indican diferencias según el test de LSD ($p \leq 0,05$).

The contributions of C to the soil were lower in the sequence v/s-w/s and v/c-w/s. However, the proper fertilization of corn in the same sequence (v/fc-w/s) allowed a 46 % increase in this variable, marking the positive and significant effect to the addition of higher doses of nitrogen. The contribution values of C ha^{-1} $year^{-1}$ of crop residues in the double crop wheat/soybean in this study, are slightly lower than those reported by Álvarez (2005) for soils of the South-eastern Pampa.

Productivity, use efficiency and capture of water

The sequences that included the highest percentage of grasses, increased the efficiency and productivity in the use of water for grain production and total DM (table 2). Increases of the order of 102, 103, 125 and 125 % were determined in WUE and WP for grain and DM in the sequence b/fc-w/s respect v/s-w/s and 64, 57, 80 and 63 % compared with the w/s-w/s, the most widespread in the region.

In double cropping w/s, the WP to produce grains (0.50 g m^{-2} mm^{-1}) was within the range reported by Caviglia *et al.* (2013) for the southeast of Buenos Aires (0.47 a 0.75 g m^{-2} mm^{-1}). However, it was lower than those of Paraná (Entre Ríos) which were in 0.84 g m^{-2} mm^{-1}. On the other hand, the WP to produce DM (1.27 g m^{-2} mm^{-1}) was lower than what was reported for two different campaigns (2.22 y 1.83 g m^{-2} mm^{-1}) in Balcarce (Buenos Aires) (5).

Table 2. Efficiency Use Water in grain and Dry Matter (WUE_g and WUE_DM), Productivity of Water in grain and in Dry Matter (WP_g and WP_DM) and efficiency of Water capture (Wc) in different sequences of crops of 2 years duration (v= vicia, w= wheat, b= barley, s= soybean, c= corn without fertilization, fc= fertilized corn).

Tabla 2. Eficiencia uso agua en grano y en materia seca (WUE_g and WUE_DM), productividad del agua en grano y en materia seca (WP_g and WP_DM) y eficiencia de captura del agua (ECA) en diferentes secuencias de cultivos de 2 años de duración (v= vicia, t= trigo, c= cebada, s= soja, m= maíz sin fertilización, mf= maíz fertilizado).

Crop sequence	WUE_g (g m^{-2} mm^{-1})	WUE_DM (g m^{-2} mm^{-1})	WP_g (g m^{-2} mm^{-1})	WP_DM (g m^{-2} mm^{-1})	Wc
v/s-w/s (25)	0.65 a	1.53 a	0.40 a	0.92 a	0.60 a
v/c-w/s (50)	0.78 ab	1.93 ab	0.47 ab	1.23 b	0.62 ab
w/s-w/s (50)	0.80 abc	1.97 ab	0.50 ab	1.27 b	0.62 abc
b/s-w/s (50)	0.84 abc	2.17 bc	0.53 b	1.30 bc	0.63 abc
v/fc-w/s (50)	1.05 abc	2.60 cd	0.67 c	1.53 cd	0.63 abc
w/c-w/s (75)	1.10 abc	2.63 cd	0.67 c	1.70 de	0.61 abc
b/c-w/s (75)	1.14 abc	2.87 d	0.70 c	1.83 ef	0.61 abc
w/fc-w/s (75)	1.20 bc	2.97 d	0.83 d	1.97 f	0.69 bc
b/fc-w/s (75)	1.31 c	3.10 d	0.90 d	2.07 f	0.69 c

The percentage of grasses in the sequence is expressed in parentheses. Different letters, within the same column, indicate differences according to LSD test ($p \leq 0.05$).

El porcentaje de gramíneas en la secuencia está expresado entre paréntesis. Letras diferentes, dentro de la misma columna, indican diferencias según el test de LSD ($p \leq 0,05$).

The values obtained from WUE_MS and the WUE_g in the sequence w/s-w/s (1.97 and 0.80 g m^{-2} mm^{-1}, respectively) were lower than those reported in Balcarce (Buenos Aires) with WUE_DM of 3.12 to 3.41 g m^{-2} $mm^{-1}$and WUE_g between 0.88 and 1.02 g m^{-2} mm^{-1}. These differences were probably given by the lower vapor pressure deficit (VPD) of the environment explored by the crops in Balcarce.

Regarding the WUE_G, it was similar to that reported by Daniels & Scott (1991), with 0.79 g m^{-2} mm^{-1}, value obtained as a general average of several sources of variation including year, irrigation and stubble management.

With respect to Wc, significant differences were achieved between the sequence v/s-w/s y v/c-w/s and b/fc-w/s, with 13.1 % in favor of the sequence with the highest % of grasses. This coincides with what was reported by Ojeda *et al.* (2018) for forage crop sequences, where the highest seasonal WP was obtained with the highest proportion of maize in the sequences, being corn a C4 species with high-WUE (26).

The values reached in the different sequences (between 0.60 and 0.69) were much lower than what was reported for the Paraná area (0.99) and, closer to the data from southeastern Buenos Aires (0.54 and 0.70) (2, 4).

The lower values of Wc and WP_g could be associated to the abundant rains registered in February 2015 and 2016 (figure 1, page 65); where rainfall exceeded the water needs of corn and soybean crops. This situation has been evaluated, explaining that 66 % of the variability of the WP_G may be due to water excess during the campaign (5).

Productivity, use efficiency and capture of radiation

Productivity and efficiency of radiation use for the production of total DM and grain, showed significant differences in favor of rotations with higher percentage of grasses[v/s-w/s (25), w/s-w/s (50), c/s-w/s (50) y v/c-w/s (50) vs. w/c-w/s (75), v/fc-w/s (50), b/c-w/s (75), w/fc-w/s (75) y b/fc-w/s (75)] (table 3, page 69).

Among the sequences with the extreme values of RUE RP and Rc (v/s-w/s vs. b/fc-w/s), increases of the order of 78.3, 80.7, 141, 142 y 34.5 % were determined for RUE_g, RUE_DM, RP_g, RP_DM and Rc, respectively, in favor of the sequence with the highest % of grasses. When comparing the most used sequence in the region (w/s-w/s) with b/cf-w/s, the achieved values were 69.8, 61.1, 105, 98.0 and 21.9 % for RUE_g, RUE_DM, RP_g, RP_DM and Rc, respectively.

In the sequence w/s-w/s, the RP_g and RUE_g was 0.20 and 0.63 g m^{-2} $MJ^{-1}$and the RP_DM and RUE_DM 0.50 and 1.57 g m^{-2} MJ^{-1} respectively; being RP_g similar to what was reported for Paraná (0.21 g m^{-2} MJ^{-1}) by Caviglia *et al*. (2004), and lower than those measured in Balcarce (0.34 g m^{-2} MJ^{-1}) as well as RUE_g and RUE_DM (0.71 and 2.07 g m^{-2} MJ^{-1} respectively) (5).

The similar response in Wc and Rc, added to the fact that water is a cumulative resource and radiation is not, reinforces the concept that increasing productivity requires radiation capture. Water can be stored in the soil, thus attenuating the imbalances between the availability of the resource and the demand. Radiation capture, however, depends on the size and structure of the canopy at a given moment, so there are no compensatory mechanisms for the recovery of radiation not intercepted by the crop.

Table 3. Radiation use efficiency in grain and dry matter (RUE_G and RUE_DM), radiation productivity in grain and dry matter (RP_G and RP_MS) and radiation capture efficiency (Rc) in different sequences of crops of 2 years of duration (v= vicia, w= wheat, b= barley, s= soybean, c= corn without fertilization, cf= corn fertilized).

Tabla 3. Eficiencia uso radiación en grano y en materia seca (RUE_G and RUE_DM), productividad de la radiación en grano y en materia seca (RP_G and RP_MS) y eficiencia de captura de la radiación (Rc) en diferentes secuencias de cultivos de 2 años de duración (v= vicia, t= trigo, c= cebada, s= soja, m= maíz sin fertilización, mf= maíz fertilizado).

Crop sequence	RUE_G ($g\ m^{-2}\ MJ^{-1}$)	RUE_DM ($g\ m^{-2}\ MJ^{-1}$)	RP_G ($g\ m^{-2}\ MJ^{-1}$)	RP_DM ($g\ m^{-2}\ MJ^{-1}$)	Rc
v/s-w/s (25)	0.60 a	1.40 a	0.17 a	0.41 a	0.29 a
w/s-w/s (50)	0.63 a	1.57 ab	0.20 a	0.50 b	0.32 ab
b/s-w/s (50)	0.70 ab	1.60 ab	0.23 a	0.53 b	0.33 abc
v/c-w/s (50)	0.77 bc	2.07 c	0.26 a	0.70 b	0.34 bcd
w/c-w/s (75)	0.90 bc	2.17 c	0.31 b	0.76 c	0.35 bcde
v/cf-w/s (50)	0.93 bc	2.27 c	0.32 b	0.79 cd	0.35 bcde
b/c-w/s (75)	0.97 c	2.37 c	0.35 b	0.87 d	0.37 cde
w/cf-w/s (75)	0.97 c	2.50 c	0.36 c	0.92 e	0.37 de
b/cf-w/s (75)	1.07 c	2.53 c	0.41 c	0.99 e	0.39 e

The percentage of grasses in the sequence is expressed in parentheses. Different letters, within the same column, indicate differences according to the LSD test ($p \leq 0.05$).

El porcentaje de gramíneas en la secuencia está expresado entre paréntesis. Letras diferentes, dentro de la misma columna, indican diferencias según el test de LSD ($p \leq 0{,}05$).

Conclusion

The sequences of crops with the same rate of intensification but with a greater percentage of grasses, increased the efficiency and productivity in the use of water and radiation for the production of grain and total DM, achieving a greater contribution of C from the crop residues to the soil. The differential response for water and radiation offer ideas for the development of strategies based on the improvement of radiation uptake to raise annual water productivity, considering different crop sequences and their strategic fertilization.

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