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SOIL DEPTH, WATER AVAILABILITY AND WHEAT YIELD IN THE AUSTRAL PAMPA OF ARGENTINA

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SUMMARY

The influence of soil depth (SD) on the content of available water at sowing (AWS), in November (AWN) and crop yield (YLD) was studied in a wheat monoculture under no-till in the semi-arid region of Buenos Aires province, Argentina. The objectives were to set and rank relationships between variables such as SD, precipitation and soil water availability on YLD under zero tillage and to establish a critical SD value for less random economic returns. At 15 points selected annually in a commercial field, AWS, AWN and YLD were measured during seven years. Relative yields (RYLD) were calculated and simple regression and classification-regression tree procedures were used. Minimum and maximum absolute yields were 870 and 5900 kg ha^{-1}. Significant relationships were observed between SD and YLD in six of the seven years. A critical SD of 0.52 m was established for an RYLD value of 0.68, which corresponds to a production range between 1500 and 4000 kg grain ha^{-1}. All years showed relationship between SD and AWS ($R^2 > 0.31$, $p<0.06$), and six of them with AWN ($R^2 > 0.34$, $p<0.02$). In turn, soil water content influenced crop yield: AWS in five years ($R^2 > 0.41$, $p<0.01$), and AWN in six ($R^2 > 0.23$, $p<0.07$). Although there was a relationship between these variables and rainfall, no significant correlations could be established. Classification-regression tree selected SD as the first determinant variable for wheat RYLD, followed by rainfall during the crop cycle and rainfall in November for the shallower soils. Rainfall during crop cycle and during fallow was the determinant variable for the deeper ones. Results indicate that site-specific nutrient management is possible based on SD.

Keywords*:* Variable management, semi-arid, no till, Mollisol.

PROFUNDIDAD DE SUELO, DISPONIBILIDAD DE AGUA Y RENDIMIENTO DE TRIGO EN LA PAMPA AUSTRAL ARGENTINA

RESUMEN

Se estudió la influencia de la profundidad de suelo (SD) en los contenidos de agua disponible a la siembra (AWS) en noviembre (AWN) y rendimiento del cultivo (YLD) en un monocultivo de trigo bajo siembra directa en la región semiárida de la provincia de Buenos Aires, Argentina. El objetivo fue estudiar las relaciones entre SD y el rendimiento del trigo y determinar el umbral crítico de SD para producir trigo en dicha región. Anualmente se seleccionaron quince puntos en un lote comercial en los que se midió AWS, AWN y YLD durante 7 años. Se calcularon los rendimientos relativos (RYLD) y se utilizaron regresiones simples y árboles de clasificación-regresión. Los YLD mínimo y máximo fueron de 870 kg ha^{-1} y 5900 kg ha^{-1}. Se observaron relaciones significativas entre SD y YLD en seis de los siete años. Se estableció un umbral crítico de 0,52 m para un RYLD de 0,68; que corresponde a una producción en el rango de 1500 y 4000 kg ha^{-1}. Todos los años mostraron relaciones entre SD y AWS (R^2> 0,31, p<0,06), y en 6 años relaciones con el AWN (R^2> 0,34, p<0,02). El AWS afectó el YLD en cinco años (R^2> 0,41, p<0,01), y el AWN en seis (R^2> 0,23, p<0,07). Aun cuando los contenidos de agua disponible dependieron de las precipitaciones, no se pudieron establecer relaciones significativas entre dichas variables. Los arboles de clasificación-regresión seleccionaron a SD con la principal variable del YLD seguida por las precipitaciones durante el ciclo del cultivo y las precipitaciones en noviembre para los suelos más someros. Las precipitaciones durante el ciclo del cultivo y durante el barbecho fueron determinantes para el YLD en los suelos más profundos. Los resultados indican que el manejo especifico de nutrientes es posible basado en la SD.

Palabras Clave: manejo por ambientes, semiárido, siembra directa, molisol.

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INTRODUCTION

In the semiarid regions from Argentina the expansion of wheat/barley monocultures increased productivity at the expense of environmental stability and sustainability (Viglizzo, 1986; Viglizzo *et al.*, 1991). In this region, the variability in the occurrence of rainfall produces random crop yields. At the same time, the effective depth of the soils (SD) is affected by the presence of a petrocalcic horizon locally known as “tosca”, similar to the “caliche”, ”calcrete” or the “crôutes calcaires” in French (Giai *et al.*, 2002), which has a great variability in $CaCO_3$ content, depth, structure and degree of induration (Pazos & Mestelan, 2002). In the Buenos Aires province only, near 2,866,000 hectares with this limitation exists, (INTA, 1995) being the main limiting factor in the productivity of crops in this region.

The limited depth of soil restrains the radical exploration of the soil, water accumulation (Puricelli *et al.*, 1997, Krüger *et al.,* 2018), stubble accumulation, water use efficiency (Krüger *et al.*, 2014), availability of nutrients (Salih *et al.*, 1989; Volmer & Buffa, 2005) and response to nitrogen fertilization (Frolla *et al.*, 2016), having a negative impact on biomass production and crop yield (Calviño & Sadras, 1999; Sadras & Calviño, 2001; Calviño *et al.*, 2003). At the same time, greater emissions of greenhouse gases have been proven in these soils (Vazquez-Amabile *et al.*, 2013).

The incorporation of no-tillage system in semiarid region over the petrocalcic soils allowed yields to rise as water is used more efficiently (Hansen *et al.*, 1994; Cutforth & McConkey, 1997; Cutforth *et al.*, 2002; Buschiazzo *et al.*, 2007; Schuller *et al.*, 2007) organic matter is preserved (Bossuyt *et al.*, 2002; Balesdent *et al.*, 2000) and wind erosion is reduced (Buschiazzo *et al.*, 2007; Hevia *et al.*, 2007; Hansen *et al.*, 2012). However, the incorporation of no-till management in shallow depth soils with a wheat/barley monoculture in semi-arid regions may not be enough to achieve acceptable yields.

Interaction of the weather and soil depth determines different yields across the spatial variability of soils. Considering the extended presence of the petrocalcic horizon in the region, this relationship generates appropriate conditions for site specific management based on SD. It is of interest, in this case, the determination of critical values for the production of wheat or other winter cereals. These critical values will be useful in the definition of management units. It is postulated that even the use of deep soils would not make crop production independent of quantity and distribution of rainfall, but could improve the response to nitrogen fertilization, the probability of economically viable wheat yields, and generate a criterion for site-specific management. The objectives of this work were i) to determine and rank the effect of variables such as SD, precipitation and soil water availability at different times on wheat yields under zero tillage and ii) to establish a SD critical depth value for less random economic returns.

MATERIALS AND METHODS

The experiment was carried out in a commercial field of 66 ha in which wheat (*Triticum aestivum (L.) Thell*) is grown every year since 2010 under no-till. The field, located in the extreme western of the Austral Pampa region of Argentina (**Figure 1**), is representative of the semi-arid southwest of Buenos Aires province. Climate is temperate, continental and semiarid with a mean annual rainfall of 660 mm and mean annual temperatures of 15.2 °C. Rainfall is concentrated in fall (wheat-fallow) and spring (crop cycle) but during grain filling period available water could be lower than crop requirements (Galantini *et al.*, 2014).

The soils are an association of Argiustolls and Haplustolls (SAG y P -INTA, 1989). Later modifications of the taxonomic system place them as Petrocalcic paleustolls (Amiotti, pers. comm.). Soil texture was loamy on the surface and clay loam in the subsoil, with sequence of horizons of type: A-B-C-$2C_{km}$. Determinations made at different points of the study site did not detect significant textural differences. Characteristics of the surface horizon include: 15.9 g kg^{-1} organic carbon content (Walkley & Black, 1934), 8.6 mg kg^{-1} extractable phosphorus (Bray & Kurtz, 1945) and pH = 7.4 (soil-water dilution 1:2.5). SD in the studied field ranged between 0.1 and 1 m with a modal value of 0.5 m (Frolla *et al.*, 2015).

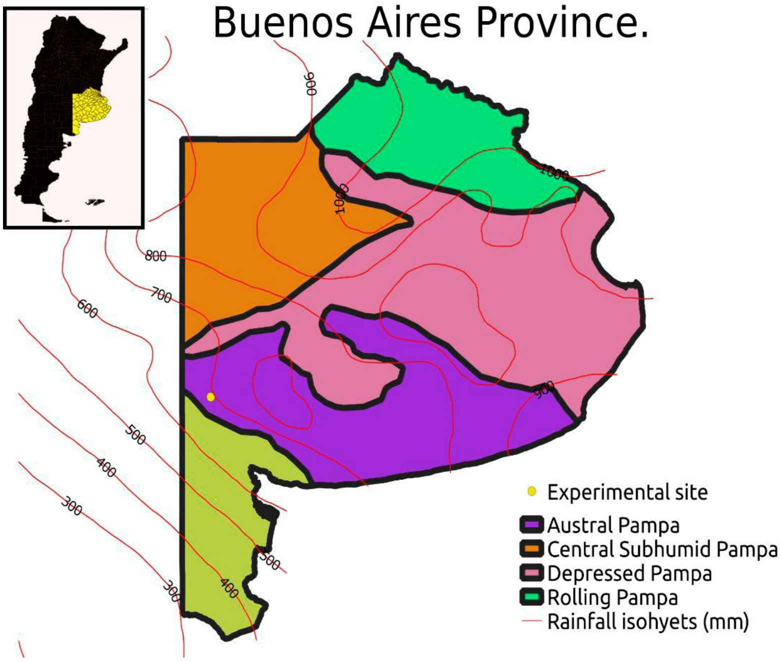

Figure 1. Location of the study site in de Buenos Aires province, Argentina. Divisions of the Pampas region adapted from Viglizzo *et al.*(2002).

Figura 1. Localización del sitio de estudio en la provincia de Buenos Aires, Argentina. División de la región Pampeana adaptada de Viglizzo *et al.* (2002).

During the 2011-2017 period, available soil water content at wheat sowing (AWS) and at crop flowering in November (AWN) and yield (YLD) were recorded in 15 geo-referenced points randomly selected annually. AWS and AWN were measured by gravimetrically (Hillel, 1998) in 0.2 m layers to the petrocalcic horizon. At the same points wheat was hand harvested (0.84 m^2 plots) and mechanically threshed. Relative yield (RYLD) was calculated as the rate of each point to maximum yield of the year. Simple regression procedures (Cate & Nelson, 1971) and classification-regression tree (Johannes & Hoddinott, 1999) were applied to analyze the relationship between variables by using Infostat® software (Di Rienzo *et al.*, 2012) and R (R Core Team, 2017). Significance levels used were α=0.05.

RESULTS AND DISCUSSION

Table 1 shows monthly rainfall distribution for each year, and average values for available historical records (2003-2017). The amount and distribution of rainfall varied between years and in relation to historical averages. In 2011, precipitation during fallow (January-May) exceeded the average while it was reduced during the crop cycle (June-November). In 2012 it was close to the average during fallow and crop cycle while in 2013 it was scarce during both periods. In 2014, rainfall was normal during fallow and excessive during the crop cycle. In 2015 it was excessive during fallow and relatively low during the cycle. In 2016 it was higher during fallow and somewhat lower than the average during crop cycle. In 2017 it was excessive during fallow

Table 1. Monthly and total annual rainfall for the period studied.

Tabla 1. Precipitación mensual y anual para el periodo estudiado.

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
							mm						
2011	293	45	100	47	61	0	16	4	0	53	112	26	757
2012	74	64	61	0	36	0	0	180	98	20	0	37	570
2013	28	71	6	106	2	0	70	0	66	39	22	2	412
2014	18	59	11	160	86	18	104	140	67	150	99	18	930
2015	127	128	118	158	40	0	35	55	15	103	34	108	921
2016	140	166	20	94	70	67	42	4	33	132	10	21	799
2017	59	131	86	330	79	73	20	48	79	25	49	24	1003
2003-2017	92	97	75	87	34	17	36	40	60	87	61	71	757

and normal during the cycle. Although there were no two similar years, there was a general trend towards more precipitation during fallow than in the crop cycle.

Figure 2 presents YLD according to SD for each year. Average yield per season ranged between 1800 and 3600 kg ha^{-1}, with an absolute maximum in 2016 (5898 kg ha^{-1}) in a deep soil, and a minimum in 2012 (871 kg ha^{-1}) in a shallow soil.

Significant relationships were observed between SD and YLD in six over seven years. Quiroga *et al.* (2012) identify different factors that, together with soil thickness, contribute to water availability and yield (climate, soil texture, porosity, consumptive use, ancestor crop fallow management). Damiano & Taboada (2000) related the variation in the available water capacity of soils in the Pampean Region with texture and depth of rooting, the latter determined by mechanical limitations in the profile or the characteristics of the crop. Díaz Zorita *et al.* (1999) observed that the dependence of wheat yields on soil water retention and total organic C contents in years with low moisture availability appears to be related to the positive influence of these soil properties on available water-holding capacity. In this

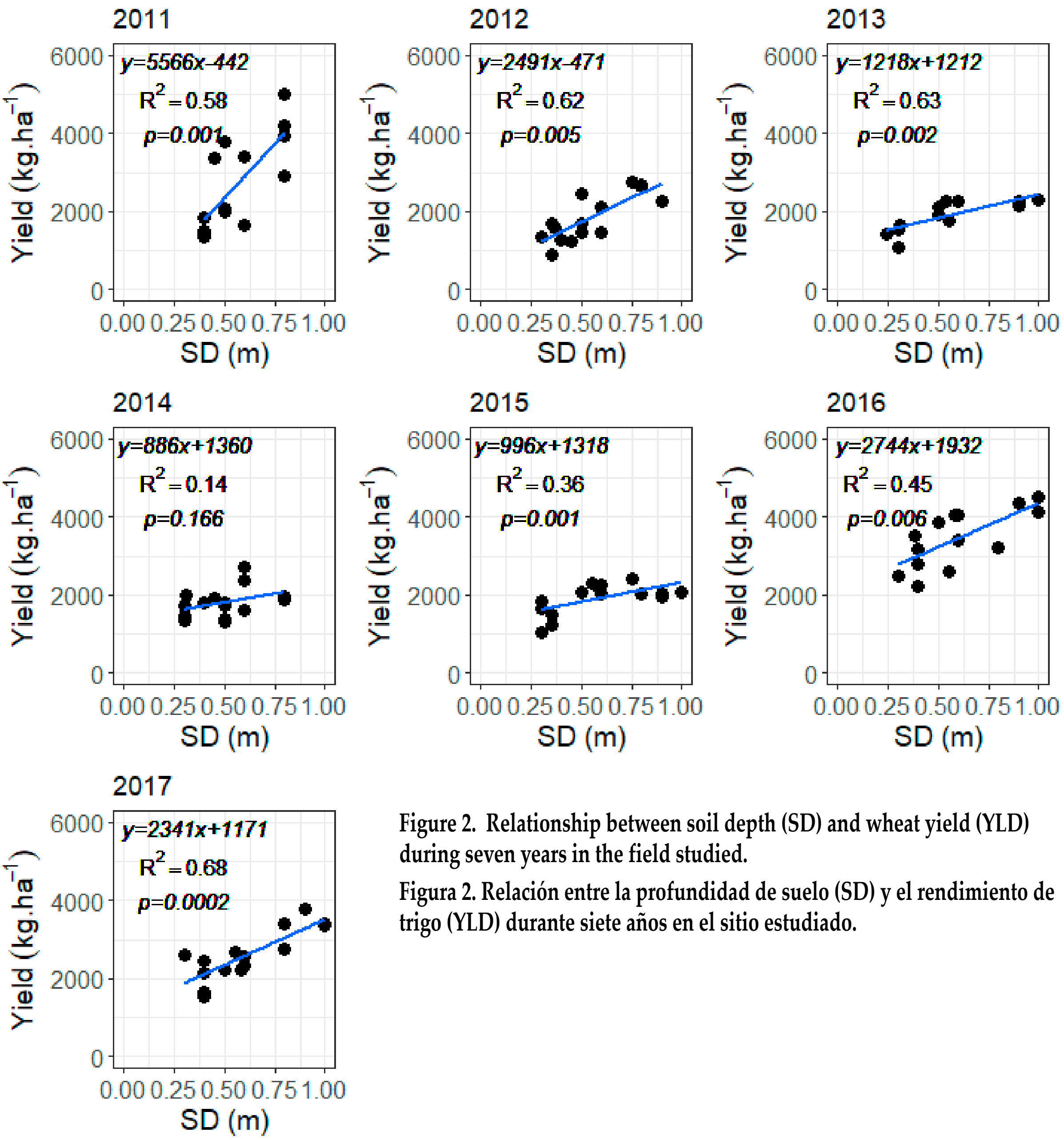

Figure 2. Relationship between soil depth (SD) and wheat yield (YLD) during seven years in the field studied.

Figura 2. Relación entre la profundidad de suelo (SD) y el rendimiento de trigo (YLD) durante siete años en el sitio estudiado.

study, since no textural differences were detected, and other factors than climate remained constant, it was reasonable to expect a close relationship between SD and YLD. However, the relationship was different each year explaining SD variation between 36 and 63% of the YLD variation.

According to Scian & Bouza (2005), several authors highlighted the dependence of yields on precipitation during fallow and the wheat cycle in the region. From **Table 1** and **Figure 2** it appears that the relative distribution of precipitation during fallow and crop cycle was an important factor in the differentiation of yields between deep and shallow soils. The greater water retention capacity of the former can increased yield in some years with low rainfall during wheat cycle (2011, 2012, 2013 and 2017). But for this to be achieved, precipitation during fallow had to be enough to complete a high proportion of this retention capacity like 2017. This did not happen in 2012 but the reloading of the profile occurred in the early stages of the wheat cycle. In 2014, excessive rainfall during crop cycle, nitrogen leaching and high incidence of fungal diseases reduced yields in deep soils and matched them with those of shallow soils. Consequently, the relationship with SD was low and not significant. In 2015 and 2016, sufficient or well-distributed rains may have increased yields in shallow soils reducing the differences with deeper ones.

Figure 3 shows a Cate & Nelson (1971) diagram representing the variation of wheat RYLD according to SD. Observations included in quadrants II and IV make up the model that determined a critical value of 0.52 m SD to obtain RYLD values greater than 0.68. Strictly speaking, this SD value sets a limit for wheat production in the studied area. It also sets a reference value to separate shallow and deep soils for site-specific management in the case of fields with complex patterns. According to the maximum yields observed in each season (**Figure 2**), a RYLD value of 0.68 corresponds to a range between 1500 and 4000 kg grain ha^{-1}. In a more humid environment and clayey soils, Puricelli *et al.* (1997) estimated the critical depth for wheat crops at 0.4 m. Bravo *et al.* (2004), in the same region observed a 54% variation in yield due to the variation of SD, the lowest yields being located in soils with a depth of less than 0.4 m. In sandy soils of the Semi-arid Pampean Region, Quiroga *et al.* (2012) related soil thicknesses less than 0.8 m with lower wheat yield and response to nitrogen fertilization than deeper soils.

Table 2 shows the results of simple linear regression analysis between the variables SD, AWS, AWN and YLD. All years showed relationship between SD and AWS (R2> 0.31, p<0.06), and six of them with AWN (R2> 0.34, p<0.02). In turn, soil water content influenced YLD: AWS in five years (R2> 0.41, p<0.01), and AWN in six (R2> 0.23, p<0. 07). Relationships between AWS and YLD of wheat and other crops has been described in similar regions (Fontana *et al.,* 2006; Quiroga & Bono, 2007). However, the initial water supply often does not explain acceptably the variation

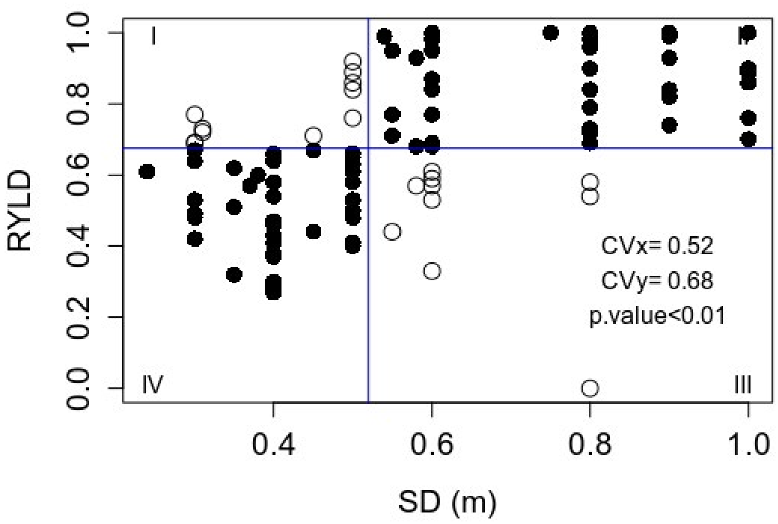

Figure 3. Relative yield of wheat (RYLD) as a function of soil depth (SD). Critical values of soil depth (CVx) and relative yield of wheat (CVy) for the set of years studied

Figura 3. Rendimiento relativo del cultivo (RYLD) en función de la profundidad de suelo (SD). Valores criticos de la profundidad de suelo (Cvx) y rendimiento relativo del trigo (Cvy) para los siete años estudiados.

Table 2. Determination coefficients (R^2) and probability values (p) for the linear relationship between different variables: soil depth (SD), available water content (at sowing, AWS and in November, AWN), and wheat yield (YLD). In each analysis independent variable is cited first.

Tabla 2. Coeficientes de determinación (R^2) y valores de probabilidad (p) para regresiones lineales entre diferentes variables: profundidad de suelo (SD), contenidos de agua (a la siembra AWS, en noviembre, AWN) y rendimiento de trigo (YLD). En cada análisis la variable independiente es citada primero.

Year	2011	2012	2013	2014	2015	2016	2017
				----- SD vs. AWS -----			
R^2	0.66	0.35	0.31	0.57	0.76	0.68	0.42
p	0.0002	0.02	0.062	0.001	0.0001	0.0002	0.0086
				----- SD vs. AWN -----			
R^2	0.02	0.55	0.49	0.82	0.78	0.34	0.34
p	0.598	0.001	0.011	0.0001	0.0001	0.023	0.023
				---------- AWS vs. YLD ----------			
R^2	0.57	0.18	0.63	0.08	0.49	0.41	0.62
p	0.011	0.115	0.002	0.301	0.004	0.01	0.0005
				---------- AWN vs. YLD ----------			
R^2	0.23	0.33	0.49	0.09	0.39	0.6	0.6
p	0.07	0.025	0.011	0.291	0.013	0.0007	0.0007

in yields. If rainfall during the cycle is low enough, AWS must be combined with rainfall during the critical period for the definition of yield (Quiroga *et al.,* 2005; Venanzi *et al.,* 2007), even if SD is greater than 0.5 m. As previously mentioned, in years with sufficient rainfall during the crop cycle, AWS has less influence on yield

Within a certain period the available soil water content (AWS or AWN) depends on the precipitation previously received, assuming that there is no significant runoff and evaporation. Verón *et al.* (2002) estimated that precipitation is the main determinant not only of the net primary productivity of crops of wheat in Argentina but also of its interannual variability, especially in soils where the water storage capacity is low and the system becomes more dependent on precipitation in the crop cycle, as those studied in this case. Different authors in the region explained the variation of wheat yields based on the rainfall received: Loewy (1987) with annual rainfall, Miranda & Junquera (1994) with september-november, Calviño & Sadras (2002) with the rain that occurred 60 days before flowering and 10 days after, Zilio *et al.* (2014) with august-november and, to a lesser extent, with october-november. The great variability in the amount and distribution of rainfall between years, together with other climatic and biotic factors, determines that these relationships are not always met or that the adjustment of the models is not acceptable. In this study, the amount of precipitation during different periods: fallow, crop cycle (June-November), vegetative stage (August and September), critical period (October and November) and annual rainfall, did not explain significantly the variation of wheat yields (data not shown). There was also no relationship between these variables and the degree of response of YLD to SD, represented by the slope of the regression lines in **Figure 2**. The limited number of years analyzed may have made it difficult to establish simple linear relationships between these variables.

The existence of collinearity prevents the use of multiple regression models to explain the relationship and the relative importance of the variables involved in the crop's water dynamics and yield. The classification-regression tree (**Figure 4**) allows the ranking of variables and the determination of critical values despite this restriction (Johannes & Hoddinott, 1999). In this case, considering SD, AWS, AWN, rainfall during the fallow (RNFf), during the cycle (RNFc) and during the month of November (RNFn) as determining variables and RYLD as a dependent variable, the model selected SD as the first variable determinant

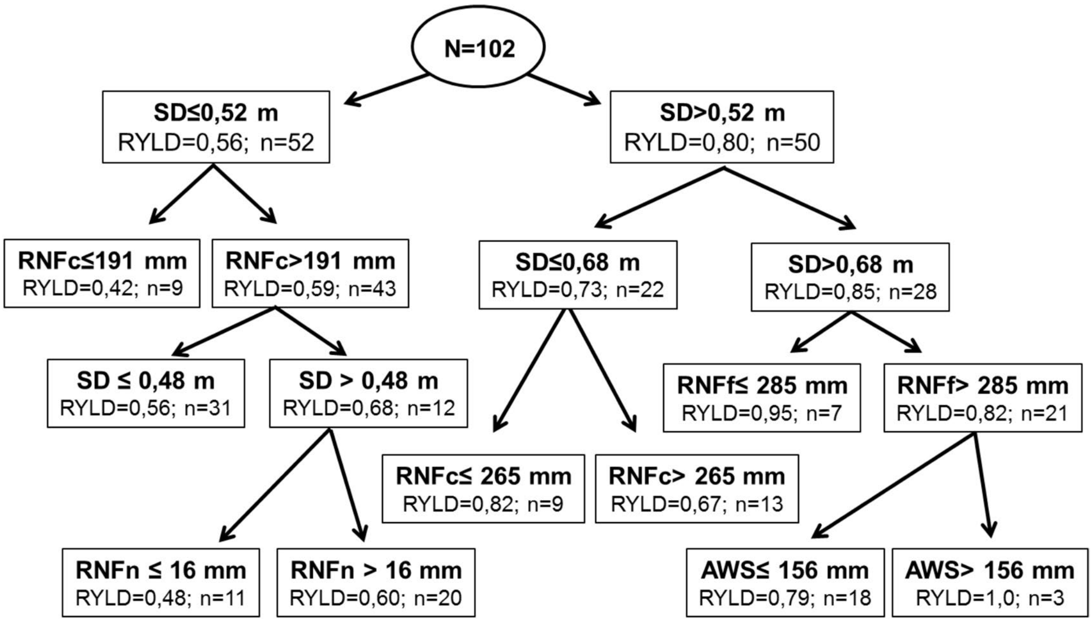

Figure 4. Classification-regression tree for the relative yield of wheat (RYLD) considering seven years, depending on the variables: effective depth (SD), available water content of the soil at sowing (AWS), available water content of the soil in November (AWN), rainfall during fallow (RNFf), during crop cycle (RNFc) and during the month of November (RNFn). N indicates the total number of cases, and those included in each group.

Figura 4. Árbol de clasificación-regresión para el rendimiento relativo de trigo (RYLD) en los 7 años analizados. Variables analizadas: profundidad de suelos (SD), agua disponible a la siembra (AWS), agua disponible en noviembre (AWN), precipitaciones durante el barbecho (RNFf), precipitaciones durante el ciclo del cultivo (RNFc) y durante el mes de noviembre (RNFn). N indica el número de casos incluido en cada grupo.

of RYLD. With a limit value of 0.52 m, SD separated two groups with average RYLD of 0.56 and 0.80 respectively. The coincidence with Cate and Nelson result is due to the fact that both procedures have the same calculation procedure.

At the second level of discrimination, SD continued to be the most important variable for deeper soils while for soils with <0.52 m SD the model selected was RNFc. At the third level, RNFf was the discriminating variable for deeper soils (> 0.68 m) and RNFc for 0.52-0.68 m SD range. On the other hand, the shallower soils that received RNFc> 191 mm were, again, separated for the SD.

Regardless of the validity of critical values and average RYLD, which should be checked in a greater number of years, the hierarchy of variables seems logical on the basis of the experience gathered throughout the study. In the shallower soils, the RNFc is important to achieve acceptable yields. An adequate rainfall distribution, with a certain volume in November, combines the relatively low water retention capacity with its frequent recharge to meet the water requirement of the crop. For this reason, in rainy cycles, the SD vs. YLD relationship usually decreases. In soils with intermediate values of SD and water retention capacity, RNFc is still important to achieve higher yields than in shallower soils. In deeper soils, RNFf allows soil water storage at levels close to field capacity, combined with low RNFc a high SD vs. YLD relationship can be achieved.

Combination of these situations determines the greater or lesser influence of SD on YLD (the slope of the regression line). Although the relationship is significant most of the years, in some of them the yield differences between shallow and deep soils are narrowed, determining a certain level of economic risk if it is intended to make a high use of inputs.

CONCLUSIONS

Soil depth, limited by the petrocalcic horizon, was significantly related to wheat yields explaining between 36 and 63% of yield variation throughout six of seven growing seasons. The relationship is based on its influence on the available water content of the soil at sowing and during the critical period for the crop (November). Due to the poor water retention capacity of the soil, both variables are combined to determine the crop yield. Although there was a relationship between rainfall and available soil water content at these times, with the available data this was not significant.

A reference depth of 0.5 m was obtained, above which an acceptable production of wheat grain is expected. On the basis of the yields observed during the study, the relative yield related to this depth (0.68) corresponds to a range between 1500 and 4000 kg grain ha^{-1} depending on climate conditions.

The classification-regression tree produced a logical ranking among the variables involved in the definition of the relative yield of wheat. Soil depth was established as first discrimination level, followed by rainfall during crop cycle and in November for the shallowest soils, and rainfall during crop cycle and fallow for the deepest ones.

The results indicate that site specific management based on soil depth is possible and advisable in this environment, provided that there are no important variations in soil texture and relief. The differences in yield observed in most years allow for the formulation of differential strategies for inputs use, mainly application levels of fertilizers and herbicides, which will contribute to the sustainability of the involved production systems.

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