USE OF A CROP MODEL TO EVALUATE SOIL IMPEDANCE AND ROOT CLUMPING EFFECTS ON SOIL WATER EXTRACTION IN THREE ARGENTINE SOILS

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ABSTRACT. *Argentina is the third largest producer of grain soybean in the world and the largest producer of soybean meal and soybean oil exports. Soybean is grown mostly in the Pampas of central–eastern Argentina. Argillic soils (typic and vertic argiudolls) and typic pelluderts are present in approximately 50% of the soils used for soybean production. Those soils have swelling and cracking behavior that may result in root clumping, and thus the root system's ability to extract water may be restricted due to limited proliferation into the surrounding soil. The CROPGRO–Soybean model's root growth and root water uptake routines were modified to improve its ability to simulate root growth and water uptake in soils where root penetration is restricted or roots are clumped together. Two empirical soil parameters, referred to as a soil impedance factor and a root clumping factor, were incorporated into this "revised" model. Data sets from a vertic argiudoll (Oliveros, Santa Fe), a typic argiudoll (Balcarce, Buenos Aires), and an enthic hapludoll (Manfredi, Córdoba) were used to evaluate the ability of the model to predict soil water extraction by soybean crops. An adaptive simulated annealing technique was used to estimate the soil impedance and root clumping factors. The revised CROPGRO–Soybean model was able to predict soil water extraction for three Argentine soils with different soil textures. The effectiveness of the model was expressed by low percent errors of estimation, ranging from 3.5% to 7.0% among different sites. The incorporation of soil impedance and root clumping factors allowed us to assess the effects of the argillic horizons in restricting root depth growth and root proliferation and thus in decreasing the potential root water uptake rates. The argillic horizons had more significant effects on root clumping than on restrictions of root depth growth. The clumping of roots caused by the presence of cracking horizons also reduced the rate of water uptake below those layers. Critical clay content thresholds as predictors of soil impedance and root clumping were found, providing a method for predicting soil impedance and root clumping factors for argillic soils.*

Keywords. *Crop simulation, Root growth, Root water uptake, Soil impedance, Soil water.*

Argentina is the third largest producer of grain soybean in the world and the largest producer of soybean meal and soybean oil exports (USDA, 2001). Soybean is grown mostly in the Pampas of central–eastern Argentina, under a range of mean temperatures from 18°C to 23°C over the growing season and annual rainfall from 600 to 1000 mm (Hall et al., 1992). This area covers 520,000 km^2 (INTA–PNUD, 1990), and 60% of its soils (31 million ha) are suitable for soybean production (Gorgas, personal communication). Most soils of the Pampas were formed from loess parent material. Since they were developed under favorable water conditions (mainly in the eastern and southeastern region), they are underlain by an argillic subsurface horizon formed by clay movements caused by illuviation and clay formation in situ (Vargas Gil, 1973). Within this group of argillic soils, typic argiudolls are the predominant soils, followed by vertic argiudolls. Typic pelluderts are also present in the northeastern region (INTA–PNUD, 1990). Arguidolls and pelluderts soils are known for their swelling and cracking characteristics.

Dardanelli et al. (2000), using a soil database for Argentina (INTA–PNUD, 1990; Gorgas et al., 1993), estimated that swelling and cracking behavior is present in approximately 50% (16 millions ha) of the soils that are used for soybean production. Typic argiudolls, vertic argiudolls, and pelluderts represent 75%, 12%, and 13% of these soils, respectively. The presence of swelling and cracking behavior, however, may result in root clumping. Under such conditions, roots may grow freely through macropores, cracks, or fissures to deeper soil depths, but their ability to extract water and nutrients may be restricted due to limited proliferation into the surrounding soil (Passioura, 1983, 1988, 1991; Tardieu, 1994; Tardieu et al., 1992). As a result of this non–uniform root distribution, plants often exhibit symptoms of water deficit even though the soil has a

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considerable quantity of available soil water (Amato and Ritchie, 1995). Even though clumping soils offer some limitations for plant growth, these soils are very productive when water is available at the right time and amount.

Water deficiency prevents the demand of water by plants from being fulfilled during critical stages of development. The Pampas region usually experiences water deficiencies and high rainfall variation coefficients, which increase the risks for crop production (Hall et al., 1992). In addition, significant runoff losses have been observed for some soils in the region due to soil surface crusting (Dardanelli et al., 1992). The combination of restricted surface infiltration, variable rainfall distribution, and soil–induced restrictions (such as soil impedance and clumping that may prevent soil water extraction by the rooting system) can create very complex water availability scenarios.

Unpredictable and intermittent periods of water deficit occur almost every year (Collino et al., 2000) in the Pampas. A crop growth model that is capable of accurately predicting soil water dynamics could be a powerful tool for forecasting yields, assessing risks, and defining management strategies.

Several crop models with different degrees of complexity have been developed to simulate soybean growth and soil water balance (Acock and Trent, 1991, Sinclair, 1986; Robertson and Carberry, 1998; Boote et al., 1997). CROPGRO–Soybean (Jones et al., 1989; Hoogenboom et al., 1994; Boote et al., 1998) is a functional crop model that simulates growth, development, and yield of soybean under different climate, soil, and management conditions. Many researchers have used it for various purposes (Wilkerson et al., 1983; Swaney et al., 1983a, 1983b; Coleman et al., 1987; Forston et al., 1989; Curry et al., 1995; Jones et al., 1991; Hoogenboom et al., 1992; Boote et al., 1989, 1996; Piper et al., 1996; Paz et al., 1997). However, few attempts have been made to evaluate the root growth and water extraction components of this model. Moreover, the soil water component of this model was structured for deep, well–drained soils, and it does not have mechanisms for restricting root growth and water uptake under widely varying soil conditions.

Recently, Calmon et al. (1999a) modified CROPGRO–Soybean's root growth and root water uptake routines, thus improving its ability to simulate root growth and water uptake in soils where root penetration is restricted or roots are clumped together. Two empirical soil parameters, referred to as a soil impedance factor ($\gamma_{I,L}$) and a root clumping factor ($\gamma_{c,L}$) were incorporated into this "revised" model. The $\gamma_{I,L}$ parameter influences the ability of roots to penetrate and grow in soil layers with high physical impedance or chemical constraints. The $\gamma_{c,L}$ parameter limits root water uptake in soil layers where roots are not uniformly distributed as a result of root clumping or a presence of isolated roots. The clumps may be so widely spaced in those layers that roots extract only a small fraction of the available water (Passioura, 1991). Thus, soil water content in those layers may be considerably higher than in soil layers that are fully explored by roots. The values of those two factors vary from 0.0 (no root growth and/or no soil water uptake) to 1.0 (no restriction).

A robust crop model such as the revised CROPGRO–Soybean model can be very useful in assessing the effects of root clumping and soil impedance on root water uptake and root depth progression. However, the application of this model for predicting soil structure effects on the water balance requires the incorporation of new parameters that must be derived from soil properties currently available, or easily collected in the field. In this sense, Connolly (1998) stated that the simulation capacity of crop models is much less of a limitation than parameterization and understanding how to apply them.

The objectives of this study were:

- To evaluate the ability of the revised CROPGRO–Soybean model to predict soil water extraction for three Argentine soils with different soil texture characteristics.
- To propose procedures for predicting the soil impedance and root clumping parameters from widely available soil properties.

Materials And Methods

Description of the Model

The soil water balance component of the revised CROPGRO model (Calmon et al., 1999a) used in this study was originally derived from the CERES models (Ritchie, 1985; Jones and Kiniry, 1986; Ritchie and Godwin, 1989a, 1989b; Ritchie et al., 1990; Jones and Ritchie, 1990). In the revised model, modifications were made to the root growth and root water uptake routines; no other changes were made to the original CROPGRO–Soybean model. Two empirical soil characteristics, referred to as a soil impedance factor ($\gamma_{I,L}$) and a root clumping factor ($\gamma_{c,L}$), were incorporated into the revised model.

Soil Impedance Factor ($\gamma_{I,L}$)

The $\gamma_{I,L}$ factor was incorporated to influence the ability of roots to grow and proliferate in a soil layer. This factor, which varies from 0.0 to 1.0, is defined as the relative ability of roots to penetrate and explore soil layers, thereby affecting downward root growth and root proliferation. A value of 0.0 for a given soil layer indicates no penetration or proliferation of roots. A value of 1.0 means no soil impedance restrictions, and root depth growth and root proliferation progress at a predefined maximum rate of root depth extension per thermal time, if there is no water or soil stress. A value less than 1.0 is assigned to any soil layer that restricts root growth and root proliferation, such as a layer with high mechanical impedance. It is assumed that the root length–to–weight ratio varies in proportion to $\gamma_{I,L}$, and it is averaged over the depth of soil layers that contain roots.

Rate of root depth increase is assumed to occur at a genetically determined rate per physiological day (or thermal time unit) under ideal soil conditions. If the soil is too wet or too dry, or if the soil temperature is not optimum, then $\gamma_{I,L}$ is less than 1.0 and the rate of depth increase is reduced. It is assumed that roots grow preferentially in a vertical direction and that soils have cracks and other structural characteristics that reduce the effective impedance for downward root growth relative to horizontal proliferation. More details are presented in Calmon et al. (1999a).

Root Clumping Factor ($\gamma_{c,L}$)

In the original CROPGRO–Soybean model, the soil–limited root water uptake rate was calculated using the radial flow to single roots (Ritchie, 1985), assuming uniform root length density in each layer. This approach is limited because it does not account for clumping of roots or restrictive soil layers.

The model was modified so that potential root water uptake from each soil layer is computed by multiplying the maximum fraction of water that can be taken up by roots from a soil layer per day, with the clumping factor ($\gamma_{c,L}$). This factor affects the rate of root water uptake in situations where roots do not grow and proliferate uniformly in the soil layer, thereby accounting for increased resistance of water flow from the bulk soil to the roots. This approach is similar to the "time constant" concept used by other authors for root water extraction (Monteith, 1986; Monteith et al., 1989; Passioura, 1991). Potential root water uptake (μ_L) from each soil layer is computed multiplying the maximum rate of water uptake by $\gamma_{c,L}$. Uptake is affected by the available water, the depth of the soil layer, a root length density function, and a water excess function:

$$\mu_L = \gamma_{c,L}\,\alpha_{w,L}\,(\theta_L - \theta_{LL,L})[1.0 - \exp(-8.0\rho_L)]\sigma_{w,L}\,Z_L \quad (1)$$

where

$\alpha_{w,L}$ = maximum fraction of water that roots in layer L can take up (per day)
θ_L = actual soil water content in layer L ($cm^3\ cm^{-3}$)
$\theta_{LL,L}$ = soil water content at the lower limit of layer L ($cm^3\ cm^{-3}$)
ρ_Λ = root length density in layer L (cm root cm^{-3} soil)
$\sigma_{w,L}$ = soil water excess factor for a layer (1.0 = no stress; 0.0 = maximum stress)
Z_L = thickness of layer L.

The $\sigma_{w,L}$ was calculated as:

$$\sigma_{w,L} = 1.0 - \exp[-100(\theta_{SAT,L} - \theta_L)] \quad (2)$$

where $\theta_{SAT,L}$ is the soil water content at saturation in the layer ($cm^3\ cm^{-3}$). It is assumed that the maximum proportion of water that can be extracted in a day ($\alpha_{w,L}$) from layers with uniform roots that have reached a critical threshold value is 0.10 d^{-1} (Ritchie and Dardanelli, 2000). Total root water uptake potential is computed from the sum of potential water uptake from each layer with roots. At the end of the day, actual plant transpiration is the minimum of two potential rates, the climatic demand and potential root water uptake.

Experimental Data Sets

Data sets from Oliveros, Santa Fe (Andriani, 2000), Balcarce, Buenos Aires (Andriani et al., 1991; Dardanelli et al., 1991), and Manfredi, Córdoba (Dardanelli et al., 1997), were used in this study. The Oliveros experiment was conducted in 1997–1998 at the Oliveros INTA Experimental Station, Argentina (32° 33′ S; 60° 50′ W), the Balcarce experiment was conducted in 1986–1987 at the Balcarce INTA Experimental Station, Argentina (37° 45′ S; 58° 15′ W), and the Manfredi experiment was conducted in 1992–1993 at the Manfredi INTA Experimental Station, Argentina (31° 49′ S; 63° 48′ W).

Oliveros, Santa Fe, Experiment

On 30 December 1997, the experimental area was seeded at 3 cm depth with six soybean varieties. Plant population was 35 plants m^{-2}. Only plots planted with the RA 702 variety (maturity group VII) were used in this study, and these plots were under imposed water stress from the R2 stage until physiological maturity (R7). Rainfall was excluded for 50 days (from 55 to 105 days after sowing), but due to low rainfall prior to this period, the supply–limited period started earlier, at 42 days after sowing. Physiological maturity was reached on 15 April 1998.

The soil was a silt loam vertic argiudoll (fine, illitic clay, thermic) with 2.1% organic matter in the first 20 cm depth. An argillic horizon was present at 30 to 70 cm depth, with clay content greater than 38%. More details can be found in table 1.

Soil water content measurements were made at planting and 11 times during the growing season at about 20 cm depth intervals, using the gravimetric procedure in the upper 30 cm and the neutron probe technique from this depth to 200 cm depth. Daily weather measurements (maximum and minimum air temperature, relative sunshine fraction for solar radiation estimates, wind velocity, and relative humidity) were recorded at a site located 100 m from the plot area. Daily precipitation was measured at the experimental area.

Balcarce, Buenos Aires, Experiment

On 10 November 1986, the experimental area was seeded at 3 cm depth with the indeterminate soybean cultivar Asgrow 3127 (maturity group III). Plant population was 33 plants m^{-2}. Two water stress periods were imposed on the plots, one from R1 to R4 and the other from R4 to R6.5 (Fehr and Caviness, 1977). Rainfall was excluded during 68 continuous days (33 to 101 days after sowing), although a 60 mm irrigation depth was applied at 78 days after sowing to increase soil water content on the upper 60 cm of the soil profile. Physiological maturity was reached on 25 April 1987.

The soil was a loamy typic argiudoll (fine, illitic clay, thermic) with 5.2% to 5.5% organic matter in the upper 25 cm depth and a petrocalcic subsurface horizon at 200 cm depth. An argillic horizon was observed at 37 to 85 cm depth, with

Table 1. Selected soils properties for the Oliveros, Balcarce, and Manfredi experiments: clay (C) silt (SI), sand (S) content, organic matter (OM) percent, and bulk density (BD).

Site	Horizon	Depth (cm)	C (%)	SI (%)	S (%)	OM (%)	BD ($g\ cm^{-3}$)
Oliveros,	A	0–20	21.4	75.0	3.6	2.1	1.36
Santa Fe	B1	20–30	28.5	67.5	4.0	1.4	1.39
	B21	30–45	40.5	58.0	1.5	1.2	1.40
	B22t	45–70	38.5	59.0	2.5	1.1	1.40
	B23	7090	30.5	68.0	1.5	0.7	1.35
	B3	90–115	25.5	69.5	5.0	0.5	1.33
	C1	115–140	22.0	70.0	8.0	0.3	1.26
	CCa	140–200	23.0	69.5	7.5	0.2	1.28
Balcarce,	Ap	0–11	26.1	40.7	33.2	5.5	1.17
Buenos	A12	11–25	25.8	39.4	34.8	5.2	1.20
Aires	B1	25–37	26.5	34.2	39.3	2.1	1.28
	B21	37–51	35.4	28.8	35.9	1.3	1.33
	B22t	51–85	35.8	26.5	37.7	0.6	1.40
	B3	85–100	24.0	30.6	45.4	0.3	1.32
	C	100–200	19.0	31.0	50.0	0.4	1.24
Manfredi,	A	0–23	16.7	68.7	16.5	2.0	1.23
Córdoba	AC	23–53	12.2	71.1	16.0	1.0	1.22
	C	53–225	10.2	71.9	15.8	0.4	1.20

clay content greater than 35%. More details can be found in table 1.

Soil water content in the upper 40 cm was measured weekly from planting at 10 cm depth intervals using the gravimetric procedure, and the neutron probe technique was used to measure water content from 40 to 200 cm depth at 20 cm intervals. Weather measurements (maximum and minimum air temperature, solar radiation, wind velocity, and relative humidity) were recorded at a site approximately 1000 m from the experimental area. Daily precipitation was measured at the experimental field.

Manfredi, Córdoba, Experiment

On 24 November 1992, the experimental area was seeded at 4 cm depth with three soybean varieties. Plant population was 38 plants m^{-2}. Only data from the plots planted with the RA 702 variety (maturity group VII) and the Asgrow 3127 variety (maturity group III) were used in this study. Rainfall was excluded during 50 consecutive days (from 45 to 95 days after sowing), but low rainfall prior to this drought–induced period extended the water supply–limited period from 37 days after sowing (prior to flowering for the RA 702 and Asgrow 3127 varieties) until the end of the experiment. Physiological maturity for the RA 702 variety was reached on 23 March 1993.

The soil was a silt loam enthic haplustoll (fine, illitic clay, thermic) with 2.0% organic matter in the first 23 cm depth, and there were no physical constraints to root development throughout the entire soil profile. More details can be found in table 1.

Soil water content was measured at planting in each plot and weekly during the season. The gravimetric technique was used for the upper 10 cm, and the neutron probe technique was used from 10 to 230 cm depth at 20 cm intervals. Daily weather measurements (maximum and minimum air temperature, relative sunshine fraction for solar radiation estimations, wind velocity, and relative humidity) were recorded at a site approximately 500 m from the experimental plot area. Daily precipitation was measured at the experimental area.

Parameter Estimation

The ASA WATER optimization program, which uses the adaptive simulated annealing (ASA) technique (Ingber, 1993, 1996), was used to estimate the soil impedance ($\gamma_{I,L}$) and root clumping ($\gamma_{c,L}$) factors . These parameters were estimated by minimizing the sum of squares of errors between measured and predicted soil water content over time, at different soil depths. The program automatically runs the CROPGRO–Soybean model along with ASA parameter search routines. More details are described in Calmon et al. (1999b).

The following assumptions are necessary before the ASA WATER optimization program can be used to estimate the $\gamma_{I,L}$ and $\gamma_{c,L}$ parameters:

- The soil water content at the drained upper limit (DUL) and lower limit (LL) at each soil depth needs to be accurately estimated from field experiment or laboratory data.
- At least for part of the growing season, the potential transpiration (demand) should be greater than the supply of water by roots (supply), and the roots should be completely developed for each particular soil layer condition. Thus, the plants are growing solely on stored water, and the water extraction front velocity corresponds closely to the root growth front. The program cannot be used to find the best fit during periods of precipitation and irrigation events, because during these periods the soil water content tends to fluctuate at the shallower depths, and soil water at deeper layers is not extracted at potential rates.
- The crop characteristics (e.g., genetic coefficients) and all other model inputs are known.
- Due to uncertainties in soil water measurements and the inherent instability observed at the surface soil layers, it is assumed that there was no restriction to root penetration and/or root water uptake in the first 15 cm of soil. Thus, $\gamma_{I,L}$ and $\gamma_{c,L}$ for the first two layers (0 to 15 cm and 15 to 30 cm) were set to 1.0.

All the experiments included in this study had a long period of water stress and therefore could be used to estimate $\gamma_{I,L}$ and $\gamma_{c,L}$. The DUL and the LL for each soil layer were obtained from previous field experiments, from soil water data measured during the growing season, from laboratory measurements at –1.5 MPa (when the LL was not achieved during the season), or by extrapolating the LL from values found at shallower depths, if the soil properties were similar for the deeper soils. The volumetric water content at saturation (SAT) was determined in the laboratory. The LL, DUL, and SAT values used in this study are given in table 2.

The predetermined maximum rate of root extension (RFAC2) was set at 4.5 cm d^{-1} for the whole crop growing period to match the root depth increase predicted by the model to the extraction front velocity estimated from water content measurements at Balcarce (Dardanelli et al., 1991) and Manfredi (Dardanelli et al., 1997) for the same experiments.

The $\gamma_{I,L}$ and $\gamma_{c,L}$ parameters for the Asgrow 3127 and RA 702 varieties were compared at Manfredi in order to eliminate any possible genotype effect on the estimation of these parameters. Because the growing season duration was different for these varieties, the pooled $\gamma_{I,L}$ and $\gamma_{c,L}$ values of the soil layers in which fully roots exploration could be assumed were used.

Parameter Prediction

Correlations between $\gamma_{I,L}$ and $\gamma_{c,L}$ parameters and clay content were higher than with bulk density parameters (data not shown). Therefore, we used regression splines with a single break point in the generalized linear model to estimate $\gamma_{I,L}$ and $\gamma_{c,L}$ as dependent variables and clay content as the predictor variable (Stasinopoulos and Rigby, 1992). Deviations between profile–measured and simulation data sets were used to assess differences between break points for the $\gamma_{I,L}$ and $\gamma_{c,L}$ models.

Results and Discussion

The pooled values of $\gamma_{I,L}$ and $\gamma_{c,L}$ obtained at Manfredi, for the layers from 30 to 105 cm depth, were not different for the two varieties used in the experiments. The $\gamma_{I,L}$ values were 0.870 ±0.018 and 0.880 ±0.011, and the $\gamma_{c,L}$ values were 0.836 ±0.018 and 0.840 ±0.017 for Asgrow 3127 and RA 702, respectively. Therefore, no genotype effect was ob– served on soil impedance and clumping of roots. At

Table 2. Measured and estimated volumetric soil water content at the lower limit (LL), drained upper limit (DUL), and saturation (SAT) for the Oliveros, Balcarce, and Manfredi experiments for replications 1, 2, and 3.

Site	Depth (cm)[a]	Replication 1		Replication 2		Replication 3		SAT
		LL	DUL	LL	DUL	LL	DUL	
Oliveros	5	0.170	0.408	0.170	0.408	0.170	0.408	0.521
	15	0.170	0.408	0.170	0.408	0.170	0.408	0.521
	30	0.205	0.411	0.175	0.411	0.200	0.411	0.531
	45	0.330	0.475	0.330	0.475	0.330	0.492	0.554
	60	0.335	0.482	0.335	0.493	0.335	0.482	0.568
	75	0.347	0.468	0.340	0.468	0.330	0.498	0.568
	90	0.270	0.417	0.270	0.417	0.285	0.417	0.521
	105	0.227	0.376	0.227	0.376	0.227	0.376	0.508
	120	0.210	0.376	0.214	0.376	0.214	0.340	0.508
	135	0.190	0.322	0.189	0.322	0.189	0.332	0.452
	150	0.180	0.328	0.180	0.328	0.180	0.328	0.458
	165	0.178	0.328	0.178	0.328	0.178	0.328	0.458
	180	0.180	0.334	0.180	0.334	0.180	0.334	0.464
	195	0.184	0.334	0.184	0.334	0.184	0.334	0.464
Balcarce	5	0.160	0.340	0.160	0.380	0.160	0.340	0.441
	15	0.160	0.340	0.160	0.380	0.160	0.340	0.441
	30	0.142	0.320	0.142	0.320	0.142	0.320	0.453
	45	0.175	0.333	0.175	0.333	0.180	0.333	0.488
	60	0.227	0.365	0.227	0.365	0.225	0.360	0.528
	75	0.240	0.380	0.240	0.380	0.245	0.385	0.528
	90	0.235	0.375	0.215	0.335	0.215	0.328	0.528
	105	0.225	0.351	0.195	0.311	0.181	0.290	0.508
	120	0.194	0.327	0.160	0.280	0.140	0.280	0.498
	135	0.171	0.301	0.145	0.270	0.120	0.260	0.468
	150	0.175	0.306	0.130	0.260	0.120	0.260	0.468
	165	0.176	0.306	0.130	0.260	0.130	0.260	0.468
	180	0.174	0.304	0.130	0.260	0.145	0.270	0.468
	195	0.165	0.295	0.130	0.260	0.142	0.270	0.468
Manfredi, MG III	5	0.140	0.341	0.140	0.341	0.140	0.341	0.558
	15	0.122	0.341	0.125	0.341	0.123	0.341	0.558
	30	0.137	0.307	0.137	0.307	0.137	0.307	0.538
	45	0.132	0.284	0.132	0.284	0.132	0.284	0.491
	60	0.128	0.274	0.128	0.274	0.125	0.274	0.449
	75	0.126	0.271	0.124	0.271	0.123	0.271	0.445
	90	0.124	0.271	0.124	0.271	0.122	0.271	0.445
	105	0.122	0.268	0.124	0.268	0.122	0.268	0.445
	120	0.123	0.265	0.124	0.265	0.122	0.265	0.445
	135	0.122	0.265	0.124	0.265	0.122	0.265	0.445
	150	0.120	0.265	0.120	0.265	0.120	0.265	0.445
	165	0.117	0.265	0.120	0.265	0.120	0.265	0.445
Manfredi, MG VII	5	0.140	0.341	0.140	0.341	0.140	0.341	0.558
	15	0.123	0.341	0.122	0.341	0.124	0.341	0.558
	30	0.137	0.307	0.137	0.307	0.140	0.307	0.538
	45	0.132	0.284	0.132	0.284	0.134	0.284	0.491
	60	0.131	0.274	0.128	0.274	0.129	0.274	0.449
	75	0.127	0.271	0.126	0.271	0.126	0.271	0.445
	90	0.124	0.271	0.124	0.271	0.124	0.271	0.445
	105	0.122	0.268	0.122	0.268	0.122	0.268	0.445
	120	0.123	0.265	0.123	0.265	0.123	0.265	0.445
	135	0.123	0.265	0.122	0.265	0.125	0.265	0.445
	150	0.120	0.265	0.120	0.265	0.120	0.265	0.445
	165	0.117	0.265	0.117	0.265	0.117	0.265	0.445
	180	0.118	0.265	0.117	0.265	0.116	0.265	0.445
	195	0.118	0.265	0.117	0.265	0.116	0.265	0.445
	210	0.118	0.265	0.115	0.265	0.116	0.265	0.445
	225	0.118	0.265	0.115	0.265	0.116	0.265	0.445

[a] The depth of the soil layers was based on the default soil layer depth used to run the model.

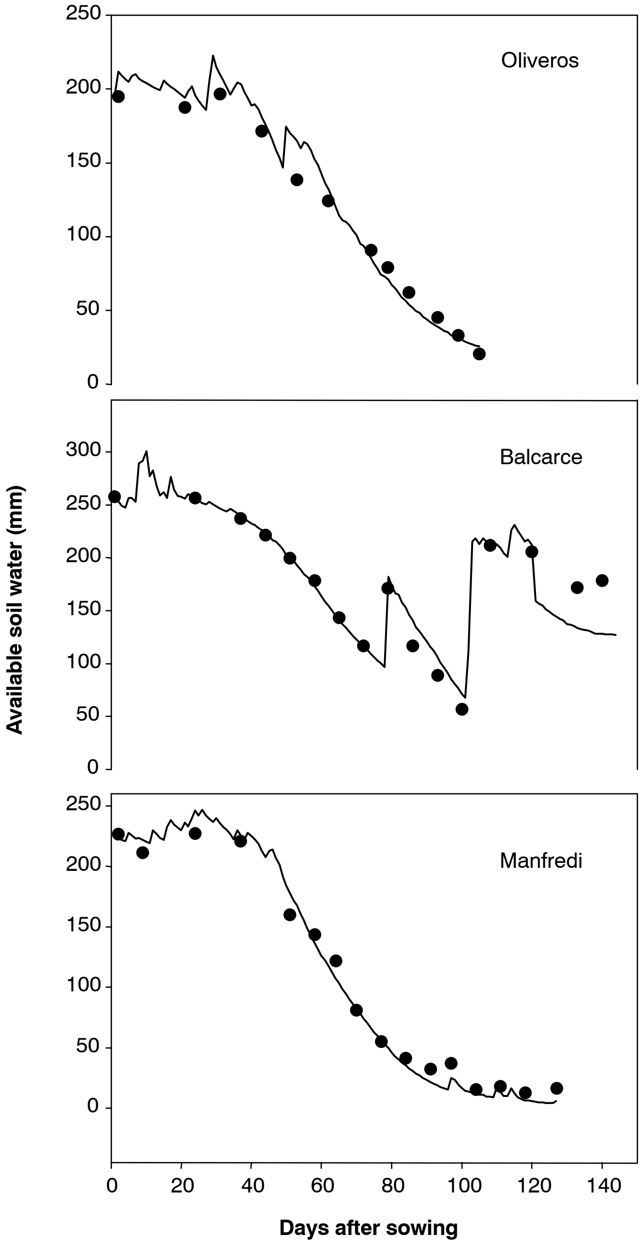

Figure 1. Predicted (lines) and measured (circles) available soil water content above the lower limit (LL, mm) in selected plots for the RA 702 variety at Oliveros, the Asgrow 3127 variety at Balcarce, and the RA 702 variety at Manfredi. Soil depths considered were 195, 195, and 225 cm for Oliveros, Balcarce, and Manfredi, respectively.

Manfredi, the RA 702 experiment was used for further analysis because it was better adapted to its environmental conditions than the other experiments.

The total available soil water in the entire soil profile decreased from 63%, 93%, and 66% at the beginning of the drought–imposed period to 6%, 20%, and 4% at the end for the Oliveros, Balcarce, and Manfredi experiments, respectively. The model was successful in simulating these wide ranges of available water dynamics (fig. 1). Likewise, soil water contents over time at different depths were also well predicted by the model (figs. 2 and 3). At Balcarce, irrigation applied at 78 days after sowing did not increase the water content below 60 cm.

The absolute percent error, with the exception of the 15–30 cm depth soil layer, ranged from 3.5% to 7% among the different sites (table 3), which were close to the 4.5% to 11% range reported for experiments carried out in the U.S. using the revised model and lower than the 6% to 19% range obtained with the current model (Calmon et al., 1999a). The highest errors observed at Balcarce can probably be attributed to the irrigation applied during the drought–imposed period. The higher percent error and RMSE measured at the 15–30 cm depth layer can be attributed to errors in soil water measurements or the inability of the model to simulate rapid changes in soil water contents at shallower depths (Calmon et al., 1999b).

The presence of the argillic horizon affected the downward root growth at Oliveros and the uniformity of root proliferation in the soil at Oliveros and Balcarce, as expressed by significant decreases in the $\gamma_{I,L}$ and $\gamma_{c,L}$ parameters (fig. 4). The minimum $\gamma_{I,L}$ averaged value (0.66) was observed at Oliveros at the 30–60 cm depth, which corresponds to the soil horizons with higher clay content (B21 and B22t, with clay content varying from 38.5% to 40.5%; table 1). That $\gamma_{I,L}$ value shows that the downward root growth was only reduced by 4% because the model uses an exponential equation to translate the soil impedance effects on root depth growth and root proliferation. It is assumed that the soils usually have cracks and other soil structural characteristics that can also reduce the effective soil impedance (Calmon et al., 1999a).

The impedance effect detected in this experiment at Oliveros agrees with the previous results obtained by Andriani (2000). In that study, soybean was sown during several years at similar dates in vertic argiudoll soils (similar to the soil at the Oliveros site) and in hapludolls (where there were no rooting depth constraints), and rooting depth was measured at different times during the growing season. The observed data are shown in figure 5. The corresponding fitted lines indicate that at 80 days after sowing, the rooting depth was 18 cm shallower in vertic argiudolls than in hapludolls. In agreement with those observed data, simulated rooting depth by the model at Oliveros (using $\gamma_{I,L}$ values obtained by parameter optimization) resulted in a 15 cm reduction in depth 80 days after sowing when compared to the simulated value obtained when no impedance effects were considered ($\gamma_{I,L} = 1$).

The presence of the argillic horizons had a much greater effect on root uniformity than on rooting depth (fig. 4). The minimal $\gamma_{c,L}$ values estimated by the model were 0.35 and 0.18 for Balcarce and Oliveros, respectively. These lower values corresponded to the 45–60 cm depth at Oliveros and the 60–90 cm depth at Balcarce and matched very closely to the B22t horizon at both sites (table 1). The minimal $\gamma_{c,L}$ values estimated in this study were lower than the $\gamma_{c,L} = 0.5$ reported by Calmon et al. (1999b) for a sandy silt loam and silty clay loam soils. These lower values indicated a high degree of root clumping. Presence of clumped roots bypassing the argillic horizon through the continuous vertical fissures that were created by clay shrinkage was observed at Oliveros (Andriani, 2000).

Shrinking and swelling is more common in soils dominated by 2:1 expanding clays, such as smectite or montmorillonite clay minerals. The main clay mineralogy composition of the Argentine Pampas argiudoll soils is illite, followed by smectite (Scoppa, 1976). However, the amount of smectite is significantly higher in the argillic horizons when compared to the A and C soil horizons (Scoppa, 1976, Scoppa and

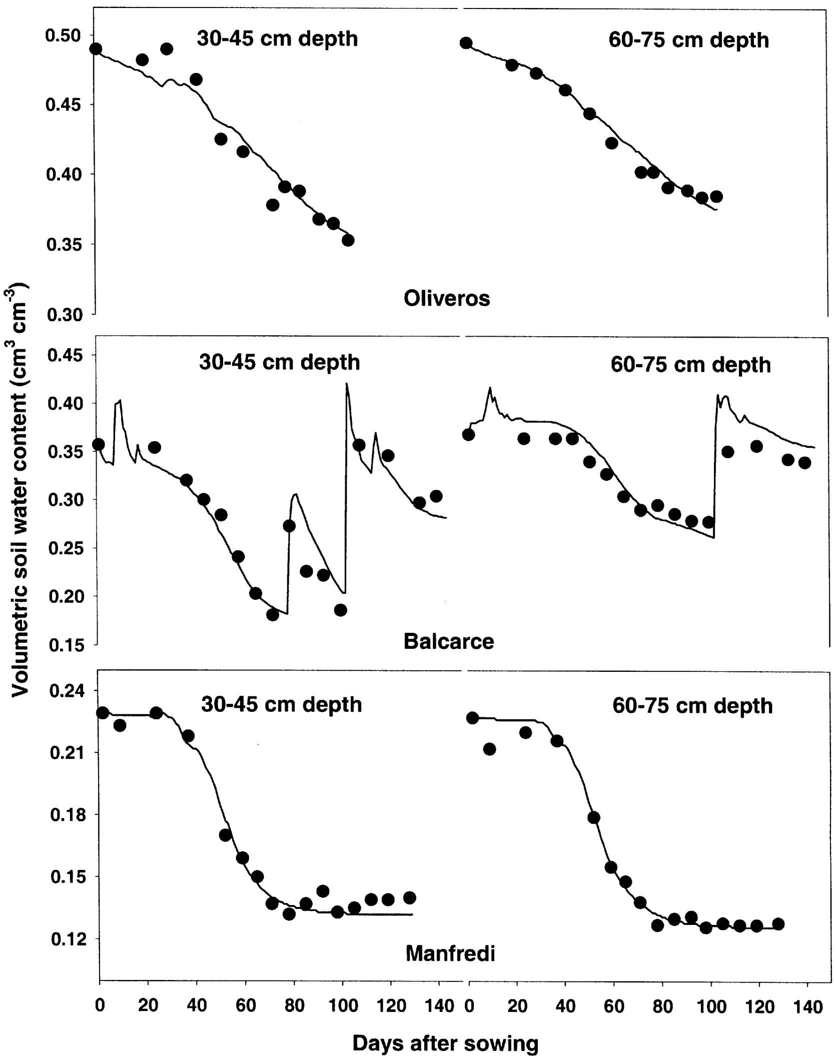

Figure 2. Predicted (lines) and measured (circles) volumetric soil water content at the 30–45 cm depth and the 60–75 cm depth at Oliveros, Balcarce, and Manfredi.

Pazos, 1981), allowing the soils to shrink and form cracks during drying periods. The mineralogical composition of the argillic horizon at Oliveros was 55% illite, 35% irregular interstratified illite–smectite, and 10% kaolonite. The lower minimum $\gamma_{c,L}$ value found for the vertic argiudoll at Oliveros site could be attributed to the higher proportion of expandable clay that is expected in this type of soil when compared to the typic argiudolls. Scoppa (1976) compared the mineralogical clay of argillic soil horizons in the Pampas region and found higher smectite proportion in vertic argiudolls than in typic argiudolls.

Figure 6 shows that in the soil layers that have the minimum $\gamma_{c,L}$ values, the LL was not reached at the Oliveros and Balcarce experiments. The water depletion occurred at those experiments at lower rates when compared with layers at similar depths at Manfredi. Tardieu (1988b) found that root water depletion in corn was half as rapid when roots were clumped. In this study, based on the minimum $\gamma_{c,L}$ values found, root water depletion was 5 times slower and 3 times slower at Oliveros and Balcarce, respectively. Passioura (1988) stated that in addition to the clumping effects per se, the roots growing in large pores might face another impediment to extracting water from the soil. The intimate contact between root and soil, which is created when the root creates its own pore, is missing when the root is growing in a large pre–existing soil pore. Moreover, channels for the flow of liquid water are sparse, and much of the flow may occur as vapor.

At the shallower depths, $\gamma_{c,L}$ values remained significantly lower than values in the soil without any constraint and with a uniform root distribution (at Manfredi, fig. 4). This behavior indicates that clumping of roots caused by the presence of cracking horizons also reduced the rate of water uptake below those layers, suggesting that root length density and/or root distribution are not completely recovered. Tardieu (1988a) reported that the root density in corn was not only reduced at the compacted soil depths, where the roots penetrated through the cracks, but also at the lower soil layers, where the soil structure was not limiting for root proliferation. The soil structure of this compacted soil also had an indirect effect in the lower well–structured layers, where a clustered spatial pattern was observed. The reduction in root density and the presence of clustered roots in subsequent soil layers was described by Tardieu (1994) as a "shadow effect" of cracking layers. This "shadow effect" also resulted in lower rates of root water uptake (Tardieu, 1988b).

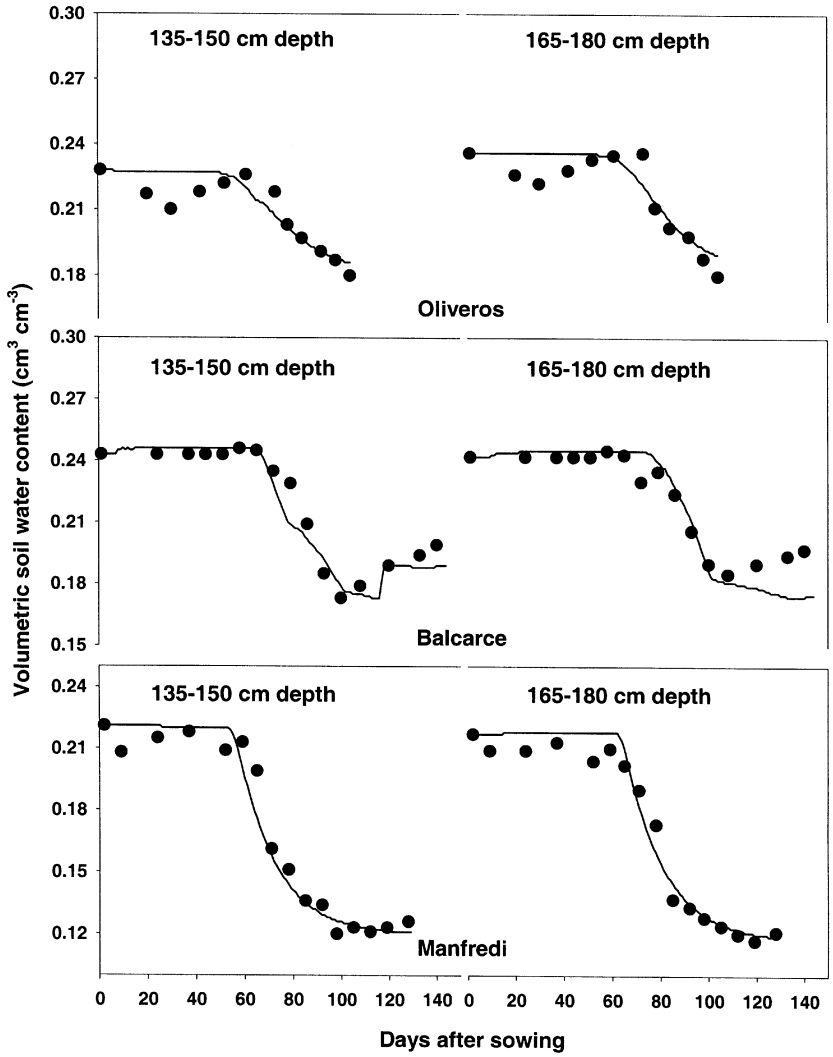

Figure 3. Predicted (lines) and measured (circles) volumetric soil water content at the 135–150 cm depth and the 165–180 cm depth at Oliveros, Balcarce, and Manfredi.

Table 3. Average values of root mean square error (RMSE) and mean absolute percent error (MAPE) of predicted and measured volumetric water content for the Oliveros, Balcarce, and Manfredi experiments.

	Oliveros		Balcarce		Manfredi	
Depth (cm)	RMSE (cm cm^{-3})	MAPE (%)	RMSE (cm cm^{-3})	MAPE (%)	RMSE (cm cm^{-3})	MAPE (%)
15–30	0.032	12.2	0.041	14.2	0.012	5.0
30–45	0.010	2.0	0.020	6.2	0.008	4.2
45–60	0.009	1.7	0.021	5.5	0.005	2.2
60–75	0.011	2.3	0.019	4.9	0.005	2.0
75–90	0.014	3.3	0.013	3.5	0.006	3.0
90–105	0.007	2.5	0.013	4.0	0.005	2.6
105–120	0.008	3.0	0.020	5.8	0.007	2.9
120–135	0.007	2.8	0.030	11.1	0.008	3.3
135–150	0.008	2.5	0.024	8.3	0.008	3.8
150–165	0.008	3.0	0.021	7.3	0.008	3.5
165–180	0.006	3.2	0.017	6.6	0.007	3.3
180–195	0.013	5.0	0.020	7.3	0.007	3.5
195–210	—	—	—	—	0.008	4.1

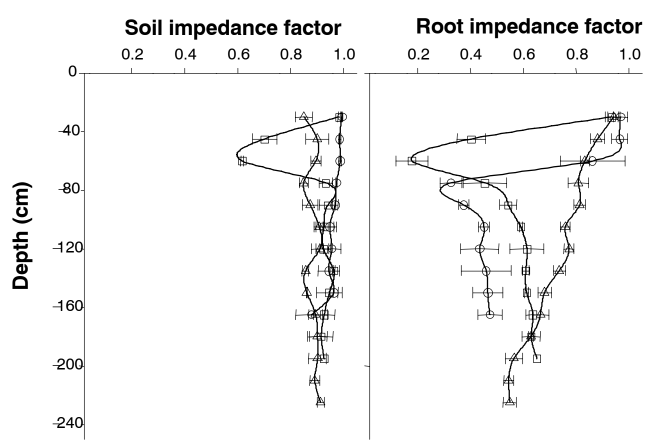

Figure 4. Mean values over depth of soil impedance factor and root clumping factor for a vertic argiudoll at Oliveros (squares), a typic argiudoll at Balcarce (circles), and an enthic haplustoll at Manfredi (triangles). Bars indicate mean standard errors.

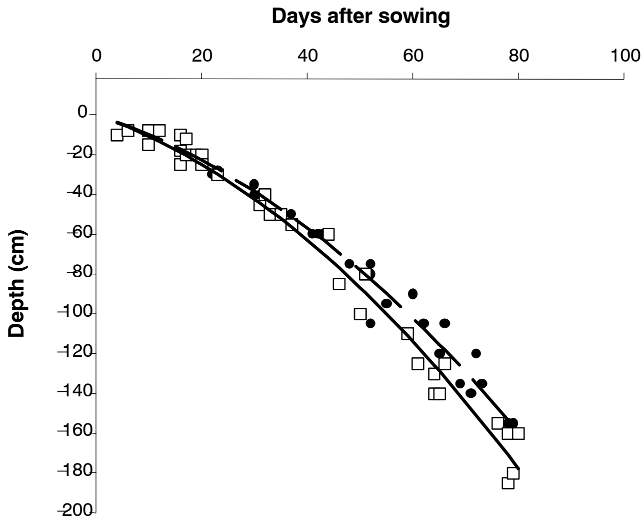

Figure 5. Rooting depths for soybean sown in December (late sowing dates) in the vertic argiudolls at Oliveros (closed circles) and in the hapludolls at approximately 200 km southwest from the Oliveros site (open squares). Fitted lines were: $y = -0.014x^2 - 0.852x$, $r^2 = 0.98$ (dashed line), and $y = -0.016x^2 - 0.918x$, $r^2 = 0.98$ (solid line), for vertic argiudolls and hapludolls, respectively (redrawn from Andriani, 2000).

Kiesling et al. (1995) found that in soil without hard pans, classical soybean taproot systems tended to develop, but with pans the root system tended to follow old root channels and fractures through the pan, and root morphology was strongly modified below the pan.

The reduction of $\gamma_{c,L}$ values for layers below the argillic horizons was most significant at Balcarce. The argillic soil horizons at Balcarce were deeper and thicker (37 to 85 cm) than at Oliveros (30 to 70 cm), and thus the proliferation of a uniform root system may be more limited. As a result of a regression spline model, the breakpoints indicated that the critical clay content values for $\gamma_{I,L}$ and $\gamma_{c,L}$ were 35.7% and 32.4%, respectively (fig. 7). Those breakpoint values were significantly different ($p = 0.0186$), indicating that clumping effects occur at lower clay contents than soil impedance restrictions. On the other hand, as the clay content over the critical threshold increases, the $\gamma_{c,L}$ values decrease at a higher rate than the $\gamma_{I,L}$ values. This difference could be supported by the assumption that changes in time of rooting depth in compacted layers will be slower than potential rates just before roots find cracks and root penetration goes back to normal rates (Tardieu, 1994). The assumption that roots grow preferentially in a vertical direction and that soils have cracks and other structural characteristics that reduce the effective impedance for downward root growth (Calmon et al., 1999a) were reinforced by the results of this study.

The $\gamma_{c,L}$ values dropped rapidly after the critical clay content threshold was achieved. This drastic drop indicates that clumping of roots strongly increased after the roots found an impeding layer and grew in large pre–existing pores. The analysis of soil water records under sorghum during a long drought period in pelluderts, with 65% clay content (Ritchie et al., 2003), indicated that the rate of water uptake was reduced by 80% of the maximum value. This 80% reduction is close to the 82% rate reduction found in the B2t soil horizon at Oliveros, according to the minimum $\gamma_{c,L}$ (0.18) found at that site. It seems that large pre–existing pores, as usually found in vertic argiudolls or pelluderts, promote roots to become clumped together and restrict the rate of water uptake; much of the flow of water may occur as vapor (Passioura, 1988). The 80% reduction in water uptake rate might be the result of that process, but more research is needed to confirm these findings.

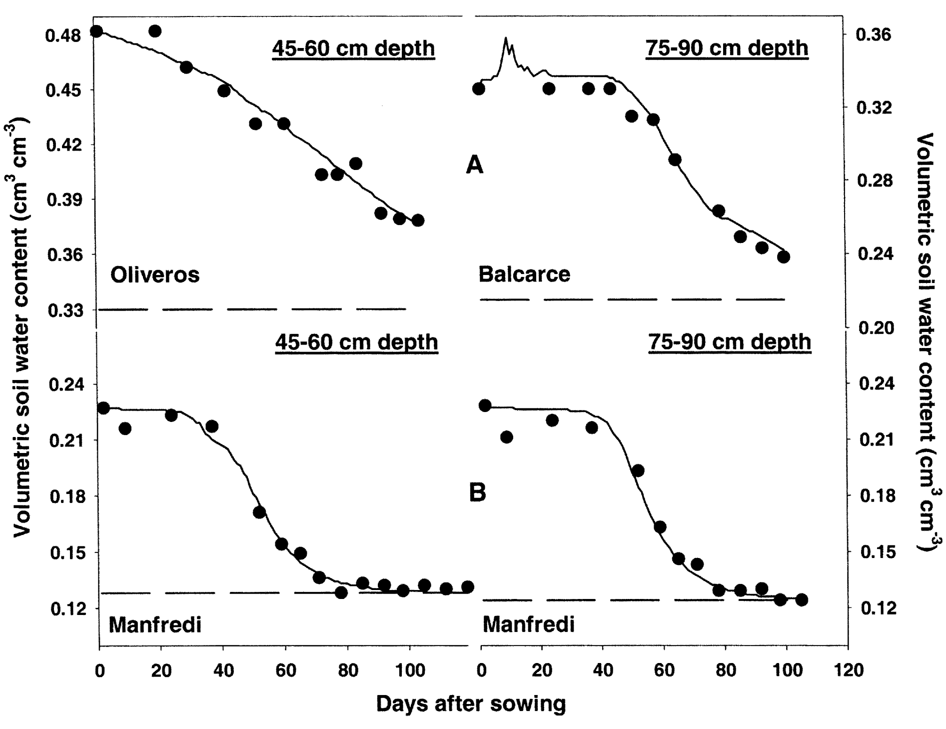

Figure 6. Predicted (lines) and observed (circles) volumetric soil water content changes over time: (A) for selected soil layers that presented the minimum root clumping factor (Oliveros at the 45–60 cm depth and Balcarce at the 75–90 cm depth), and (B) for soil layers without clumping effects at similar depths (Manfredi at the 45–60 cm and 75–90 cm depths). The corresponding water content at the lower limit (dashed line) is also depicted.

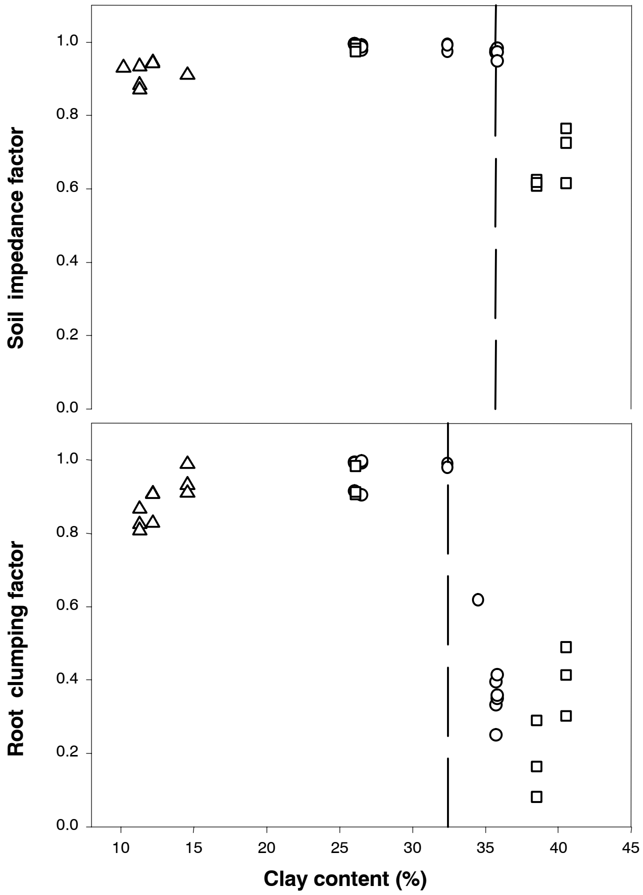

Figure 7. Relationship between clay content and soil impedance factor, and root clumping factor, using data from Oliveros (squares), Balcarce (circles), and Manfredi (triangles). Dashed vertical lines indicate the breakpoint obtained by a regression spline model (Stasinopoulos and Rigby, 1992).

Conclusions

The "revised" CROPGRO–Soybean model was able to predict soil water extraction for three Argentine soils with different soil textures. The effectiveness of the model was expressed by low percent errors of estimation. The incorporation of soil impedance and root clumping factors allowed us to assess the effects of the argillic horizons in restricting root depth growth and root proliferation, and thus in decreasing the potential root water uptake rates. The argillic horizons had more significant effects on clumping of roots than on restricting root depth. The clumping of roots caused by the presence of cracking horizons also reduced the rate of water uptake below those layers. Critical clay content thresholds as predictors of soil impedance and root clumping were found, providing a method for predicting soil impedance and root clumping factors for argillic soils.

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