Chemical, spontaneous and mechanical dispersion of clays in arid-zone soils

E. Amezketa*, R. Aragüés, R. Carranza and B. Urgel

*Unidad de Suelos y Riegos. Servicio de Investigación Agroalimentaria. Diputación General de Aragón.
Apdo. 727. 50080 Zaragoza. Spain*

Abstract

Surface sealing and crusting is a common feature in many irrigated soils that negatively affects their productivity and sustainability. Soil crusting is provoked by the mechanical breakdown of aggregates and/or by the physical and chemical dispersion of soil clays. Our objectives were to examine the clay-dispersive behavior in 36 illitic soils of the middle Ebro river basin (Spain) as affected by irrigation and rainwater quality, soil wetting and mechanical stress, and identify major soil properties affecting clay-dispersion behavior. The applicability to these soils of the Sumner *et al.* (1998) flocculation-dispersion nomogram was also analyzed. Three laboratory tests (i.e., flocculation, spontaneous dispersion and mechanical dispersion of clays) were applied to the air-dry, ground and sieved soil samples (0-20 cm depth). Based on their flocculation values, 10 and 32 soils will tend to chemically disperse, respectively, when equilibrated with the electrolyte concentrations of the irrigation (4 mmol$_c$ L^{-1}) and rain (1 mmol$_c$ L^{-1}) waters. None of the studied soils were susceptible to spontaneous clay dispersion when wetted in the absence of mechanical stress, whereas nearly 75% of them were mechanically dispersive and thus potentially sensitive to crusting by impacting raindrops or intensive cultivation. The Sumner *et al.* (1998) flocculation-dispersion nomogram classified adequately the clay-dispersive behavior in 92% of the studied soils, demonstrating its appropriate predictive capability for these illitic soils. Various conceptually-consistent relationships were found between some soil properties and the dispersive behavior of soil clays, but their statistical significances were insufficient for predicting purposes.

Key words: clay dispersion, crusting, water quality, wetting, mechanical disturbance, soil properties.

Resumen

Dispersión química, espontánea y mecánica de arcillas en suelos de zonas áridas

El encostramiento del suelo es un problema frecuente en muchos regadíos, que afecta negativamente a su productividad/sostenibilidad. Es producido por la ruptura mecánica de agregados y/o por la dispersión física y química de arcillas. Nuestros objetivos fueron analizar el comportamiento dispersivo de 36 suelos ilíticos de la cuenca media del Ebro (España) frente a la calidad de las aguas de riego y lluvia, la humectación y el estrés mecánico, e identificar las principales características del suelo responsables de dicho comportamiento. Asimismo se analizó la aplicabilidad a estos suelos del nomograma de floculación-dispersión de Sumner *et al.* (1998). El grado de dispersibilidad de los suelos se determinó mediante tres pruebas de laboratorio (tests de floculación y de dispersión espontánea y mecánica de arcillas) aplicadas a muestras de suelo (0-20 cm de profundidad) secas al aire y tamizadas. En base a los valores de floculación, 10 y 32 suelos fueron susceptibles de dispersión química cuando se equilibraron, respectivamente, con las aguas de riego (4 mmol$_c$L^{-1}) y lluvia (1 mmol$_c$L^{-1}). Ningún suelo fue susceptible a dispersión espontánea de arcillas al humectarse en ausencia de estrés, mientras que el 75% de ellos fueron dispersados al ser sometidos a estrés mecánico. El nomograma de floculación-dispersión de Sumner *et al.* (1998) clasificó adecuadamente el comportamiento dispersivo del 92% de los suelos, demostrando su capacidad predictiva para estos suelos ilíticos. Se han encontrado relaciones consistentes conceptualmente entre algunas propiedades de los suelos y su comportamiento dispersivo, aunque su nivel de significación fue insuficiente para fines predictivos.

Palabras clave: dispersión de arcillas, encostramiento, calidad del agua, humectación, estrés mecánico, propiedades de los suelos.

Introduction

Surface sealing of soils and its subsequent crusting upon drying is a common feature in many irrigated soils (Sumner and Stewart, 1992), including those of the middle Ebro river basin (Spain). Crusting decreases seedling emergence, soil infiltration rate and crop productivity, and may increase production costs, surface runoff and soil erosion.

The formation of surface seals is the result of two complementary mechanisms: physical disintegration of surface soil aggregates, and physico-chemical dispersion of soil clays that migrate into the soil with the infiltrating water and clog the pores immediately beneath the surface (Agassi *et al.*, 1981; Sumner and Stewart, 1992). The first mechanism is mechanical in nature and is basically caused by the impact energy of raindrops, the slaking of aggregates and by intensive tillage operations. The second mechanism is mainly controlled by the concentration and cation composition of the electrolyte, although it also depends on the breakdown of aggregates that render new exposed surfaces for clay dispersion (Curtin *et al.*, 1994; Barzegar *et al.*, 1994b).

The relative importance of these two mechanisms on seal formation is soil-dependent, so that the size of the fragments resulting from aggregate breakdown is most important in some soils whereas clay dispersion is prevalent in others. Thus, Mullins *et al.* (1987) and Le Bissonnais (1996) indicated that particle size distribution resulting from disaggregation determined the susceptibility of soils to crusting and the hydraulic properties of the seals. On the other hand, Young and Mullins (1991) concluded that in certain soils the $< 60 \, \mu m$ size-fraction was more important than the $< 2 \, \mu m$ size-fraction in determining soil structural stability. Shainberg *et al.* (1997), however, suggested that seal formation and its final permeability basically depended on clay dispersion.

The dispersion of clays and the subsequent potential sealing of soils are promoted by low concentrations and high sodium adsorption ratio (SAR) and pH values of the electrolyte (Shainberg y Letey, 1984). Rengasamy *et al.* (1984) indicated that dispersion also depended on the mechanical stress imposed on soils upon wetting, and Sumner and Stewart (1992) found that clay dispersion in non-sodic soils was only relevant under the influence of mechanical stresses that promoted the disruption of aggregates and the subsequent release of suspended clay particles. Rengasamy *et al.* (1984) and Sumner (1993) highlighted the need

for analyzing the dispersive behavior of clays under conditions prevalent at the soil surface, such as the application of low-salinity waters, disaggregation by fast wetting, the impact of raindrops and/or intensive cultivation operations. Consequently, the quantification of the chemical, spontaneous and mechanical dispersion of clay soils in the laboratory could be used to ascertain the structural stability of soils and its susceptibility to sealing and crusting (Rengasamy *et al.*, 1984; Barzegar *et al.*, 1997).

Rengasamy *et al.* (1984) designed an scheme for describing the dispersive behavior of sodium-affected soils and tried to predict clay dispersion from the total cation concentration ($TCC_{1:5}$) and $SAR_{1:5}$ measured in 1:5 (soil:water) extracts. However, when this method was tested, they found a number of aberrant soils that deviated from the proposed dispersion- $TCC_{1:5}$- $SAR_{1:5}$ relationships, and recommended that pH and organic matter content should also be determined in these soils. Sumner *et al.* (1998) modified the previous scheme by shifting the position of the lines separating dispersed from flocculated soils. This new scheme was calibrated in illitic-type soils with $EC_{1:5}$ values ranging from zero to 3 dS m^{-1} and $SAR_{1:5}$ values ranging from zero to higher than 20. This method predicts soil dispersibility from the $EC_{1:5}$ and $SAR_{1:5}$ soil solution parameters bearing in mind that other soil properties may also affect clay dispersibility. These authors indicated that the applicability of this classification scheme to other soils should be tested and modifications be made when required.

The objectives of our study were to (i) analyze the dispersive behavior and crusting susceptibility of thirty six soils of the middle Ebro river basin (Spain) as affected by irrigation and rain water quality (i.e., chemical dispersion), soil wetting (i.e., spontaneous dispersion), and mechanical stress (i.e., mechanical dispersion), (ii) test in these soils the applicability of the dispersion scheme proposed by Sumner *et al.* (1998), and (iii) identify major soil properties affecting soil dispersion.

Material and Methods

Thirty-six soils, located in the Bardenas and Monegros irrigated areas (Ebro river basin, Spain), were sampled at a depth of 0-20 cm, air-dried, ground and sieved ($< 2 \, mm$). The soils varied in cropping history, management, and physical and chemical properties (Table 1), except for their regular clay mineralogy, pre-

Table 1. Taxonomic classification and physical and chemical properties of the 36 studied soils

Soils	Classification	Soil saturation extract ECe (dS m⁻¹) $dS\,m^{-1}$	SARe $(mmol\,L^{-1})^{0.5}$	SARe/ECe	pHe	Soil texture⊗ Sand ($g\,kg^{-1}$)	Silt	Clay	Water content at 0.03 MPa	1.5 MPa	Total OM %	Equivalent CaCO₃ %	CEC $cmol\,kg^{-1}$	CBD-extractable* Mn	Fe ($g\,kg^{-1}$)	Al
Bardenas I																
SA 2/E7	Typic xerorthent	1.0	1.3	1.3	8.4	342	381	277	249	100	2.6	39.8	16.8			
EC 2/E8	Typic xerofluvent	0.9	1.6	1.8	8.5	46	467	487	270	100	2.8	32.9	15.7			
SA 3/1	Petrocalcic xerochrept	0.5	0.2	0.4	8.1	383	280	338	267	153	2.1	30.6	19.0	0.3	11.8	1.2
SA 13/1	Typic xerorthent	1.4	4.2	3.0	9.0	388	345	267	226	131	1.4	36.6	12.9	0.2	8.2	0.7
SA 16/1	Calcixerollic xerochrept	0.6	0.4	0.7	8.5	415	249	336	245	144	2	28.0	22.7	0.4	12.0	1.1
SA 20/1	Gypsic xerochrept	0.9	2.3	2.5	8.8	286	500	214	221	108	1.1	42.2	22.0	0.2	6.6	0.5
SA 20/5	Gypsic xerochrept	3.6	3.0	0.8	8.1	173	462	365	254	153	1	31.3	23.2			
SA 21/1	Calcixerollic xerochrept	0.6	0.7	1.2	8.7	519	260	222	210	119	1.6	38.5	22.7	0.2	7.9	0.7
SA 26/2	Gypsic xerochrept	9.7	9.0	0.9	7.8	224	494	282	255	155	1.8	39.7	14.2			
SA 27/2	Gypsic xerochrept	0.8	0.8	1.0	8.4	32	480	489	266	187	1.6	32.4	24.0			
SA 30/5	Typic xerofluvent	1.2	4.1	3.4	8.8	267	525	209	239	139	1.6	38.5	16.4			
SA 31/1	Typic xerofluvent	16.1	23.6	1.5	8.0	214	502	284	234	147	2.2	44.0	21.6			
SA 37/1		1.3	1.1	0.9	8.4	377	374	249	227	135	1.6	36.8	16.0			
SA 42/1		12.6	14.5	1.2	8.1	30	588	382	311	197		35.7	4.5	0.3	12.1	1.0
SA 44/1		4.9	9.2	1.9	8.2	142	507	352	268	162		34.9	20.4	0.4	10.1	1.1
SA 49/1		10.9	17.5	1.6	8.1	50	617	333	268	150		40.2	13.4			
SA 60/1		1.0	1.1	1.1	8.5	234	513	253	243	140		38.4	13.0			
SA 63/1		2.2	2.1	1.0	8.3	246	435	319	230	146		40.6	19.0			
SA 81/1		2.9	2.9	1.0	8.3	66	486	448	327	210		23.8	24.7	0.4	12.3	1.1
SA 92/1		1.1	0.9	0.9	8.5	315	486	200	210	94		39.6	12.1	1.6	7.1	5.3
Monegros I																
Callen 1	Typic xerofluvent	19.2	111.4	5.8	9.1	453	362	186			1.5	21.4	11.8	0.3	11.7	0.9
Tramaced 2	Typic natrixeralf	4.2	5.6	1.3		82	543	375			3.1	20.6	17.6	0.4	18.2	1.3
Sariñena 4	Xeric petrocalcid	0.8	0.3	0.4		316	364	320			4.1	12.1	26.0	0.5	19.0	1.8
Violada 10	Gypsic haploxerept	3.2	0.2	0.1		176	519	305			4.6	35.5	21.3			
SJF 8		3.5	1.7	0.5		342	399	259			3.2	31.0	13.2			
Fraella 1	Typic natrixeralf	0.7	1.3	1.9		261	524	215	278	82	2.1	22.1	8.3			
Fraella 2	Typic natrixeralf	6.3	136.2	21.6		1	456	543	410	174	0.6	18.7	12.0			
Flumen	Typic xerofluvent	59.3	73.9	1.3		341	495	164	231	68	0.8	27.4	5.0			
Valfonda 1	Gypsic haploxerept	7.1	7.7	1.1	7.6	514	579	369	330	212	1.6	30.4	17.7			
Montesusin 1B	Typic xerofluvent	2.8	3.0	1.1		92	531	377	287	181	2.4	28.6	7.1			
Barbués 2/1	Typic xerofluvent	1.3	3.9	2.9	7.8	291	518	191	244	108	1.7	23.4	8.8	0.2	9.8	0.6
Barbués 3/1	Xeric torriorthent	6.2	13.6	2.2	8.0	300	526	174	222	115	1.4	25.8	5.2	0.1	9.9	8.6
Barbués 3/2	Xeric torriorthent	4.1	15.7	3.9	8.3	171	524	305	220	127	0.7	29.0	9.5			
Grañén T1	Typic xerofluvent	1.8	0.8	0.4	8.3	153	467	380	246	163	2.3	29.6	15.4	0.3	11.5	0.9
Grañén T2	Typic calcixerept	0.8	0.4	0.5	8.4	550	195	255	179	106	3	25.6	10.4	0.3	9.6	0.7
Grañén 1	Typic xerofluvent	3.4	7.1	2.1	8.0	299	569	132	257	113	2.5	24.5	16.9	0.3	13.2	0.9

⊗ Soil texture: sand (50-2,000 μm); silt (2-50 μm); clay (<2 μm). * CBD extractable Mn, Fe and Al: citrate-bicarbonate-dithionite-extractable Mn, Fe and Al.

dominant in hydrated micas (> 70% of total clay) and absent in smectites. Chemical and physical properties were analysed by standard methods (Carter, 1993).

Three dispersion tests were applied to the soil samples: (1) flocculation test (Amézketa and Aragüés, 1995) that analyzes the effect of electrolyte concentration on the chemical dispersion of clays, (2) spontaneous dispersion test (Rengasamy *et al.*, 1984) that analyzes the dispersion of clays induced by wetting of the soil samples, and (3) mechanical dispersion test (Rengasamy *et al.*, 1984) that analyzes the dispersion of clays provoked by wetting and mechanical stirring of the soil samples.

In the flocculation test, triplicate 100-mg soil samples (< 0.5 mm in diameter) were suspended in nine 30-ml CaCl$_2$ solutions with concentrations of 0.01 (i.e., deionized water), 0.4, 0.8, 1.2, 1.8, 3.0, 4.6, 6.0 and 8.0 mmol$_c$ L^{-1}. The SAR = 0 of these solutions simulated the composition of the Bardenas and Monegros canal irrigation waters, typically low in SAR (< 0.4). The soil suspensions were stirred on a reciprocal shaker for one hour and settled for 24 hours. The top 10-cm of the supernatant solutions were pipetted and the turbidity (given in ntu or nephelometric turbidity units) was measured at a wavelength of 550 nm on a Hach turbidimeter (model 18900). The electrical conductivity (EC), SAR and pH of the supernatant solutions were also measured. Due to the low soil:solution ratio of the soil suspensions, the EC, SAR and pH of the supernatant and the applied solutions did not change appreciably (data not given). The turbidity values, a measure of clay dispersion, were regressed against the electrolyte concentrations using a piecewise linear response function. The flocculation value (FV) of each soil, defined as the minimum or threshold electrolyte concentrations without clay dispersion, was obtained from the corresponding response function.

In the spontaneous dispersion test, quadruplicated 20-g soil samples (< 2 mm in diameter) were placed in test tubes (120 mm high and 38 mm in diameter) and 100-ml deionized water was slowly added down the sides of the tubes without disturbing the soil samples. After 22 h of settling, the supernatants were gently stirred without disturbing the soil and, after allowing for the appropriate settling time of the > 2 µm particles, the top 5-cm of the supernatant solutions were pipetted. The spontaneously dispersed clay (SDC, given as percent of total clay in the soil) was measured gravimetrically after drying of 20-ml aliquots in the oven at 105°C. Corrections were made for the weight of dissolved salts.

The mechanical dispersion test is identical to the spontaneous dispersion test described above, except in that after the addition of deionized water the test tubes were shaken for one hour on a reciprocal shaker. The mechanically dispersed clay (MDC) was given as percent of total clay in the soil.

The EC, SAR and pH values of the supernatant solutions in the spontaneous and mechanical dispersion tests were also measured. These values correspond to the 1:5 soil:water extracts used in the dispersion schemes proposed by Rengasamy *et al.* (1984) and Sumner *et al.* (1998).

All the statistical analyses were performed using the Statgraph *Plus* 2.1 software. One-way ANOVA was carried out to compare the means of the dispersion indices among soils. When these analyses showed significant differences at P ≤ 0.05, a Duncan's multiple range test was conducted to separate soils' dispersibility. Also, simple correlation analysis, a non-parametric statistical test (Spearman rank correlation test) and simple regressions were carried out when needed. The statistical significances were reported at the 0.05 ([*]), 0.01 ([**]), and 0.001 ([***]) probability levels.

Results

Dispersive behavior of soil clays against irrigation and rain water quality

The results of the flocculation test were reliable, as shown by the coefficients of variation (CV) of the mean turbidity values for all soils and replications (i.e., 108 turbidimetric readings for each electrolyte concentration) which varied between 9 and 11% in the five more diluted solutions. The CV in the four more concentrated solutions were somewhat higher (between 11 and 15%) probably due to their very low turbidity values, closer to the sensitivity (± 2 ntu) of the turbidimeter. Small differences among these low turbidity values were irrelevant in fitting of the data to the linear response functions. The average CV for all treatments, soils and replications (i.e., a total of 972 ntu readings) was 11%, indicating the overall consistency and reproducibility of the flocculation test. In addition, the correlation coefficients of the linear response functions (Fig. 1) were higher than 0.90 (i.e., all of them significant at P < 0.001, except one significant at P < 0.01), indicating the excellent fitting of the data to the regression model and the correspon-
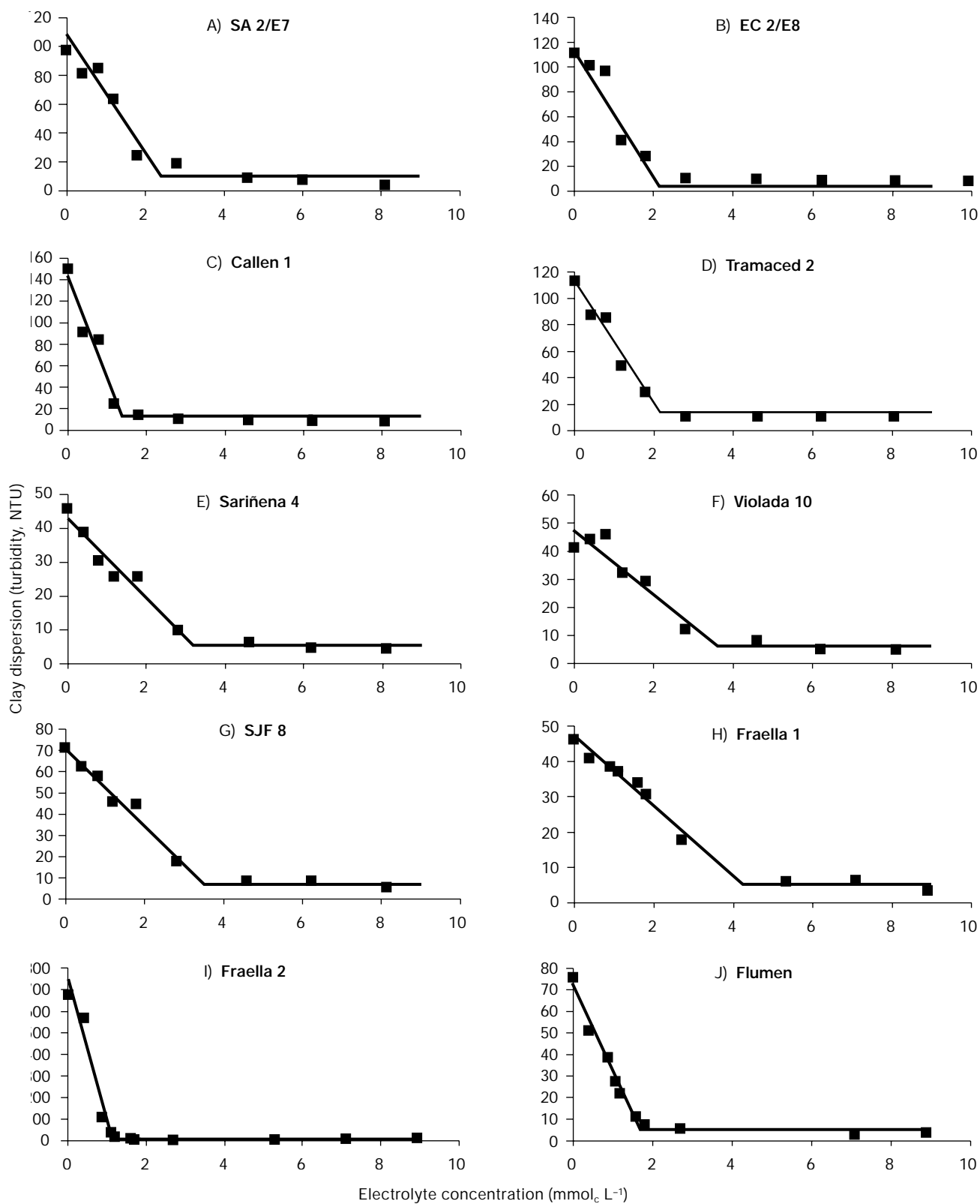
Figure 1. Flocculation test: effect of electrolyte concentration on clay dispersion measured through supernatant turbidimetry. Example of results for 10 of the 36 studied soils. Each point is the mean of three replicates. The solid lines represent the fitted piecewise linear response functions.
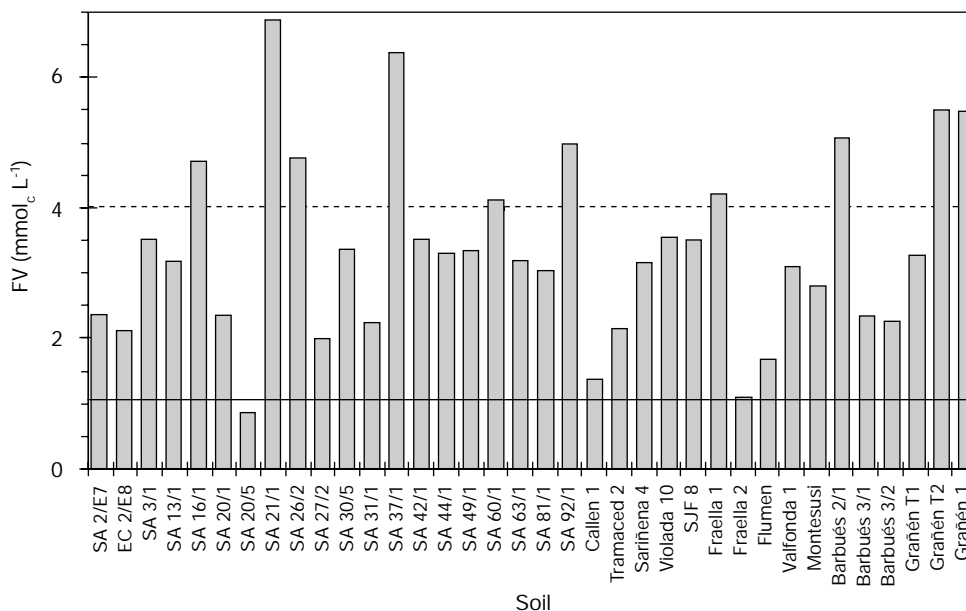
Figure 2. Flocculation values (FV) of the 36 studied soils. The solid and dashed lines represent, respectively, the average electrolyte concentrations of rainwater and irrigation water.

ding low standard errors of the flocculation value (FV) estimates.

The FVs of the 36 studied soils varied between 0.88 and 6.9 $mmol_c$ L^{-1} (Fig. 2), and the mean FV was 3.36, with a CV of 42%, reflecting the different chemical dispersion behavior of the soils despite their similar clay mineralogy.

Dispersive behavior of soil clays against soil wetting

The results of the spontaneous dispersion test were consistent and reproducible, as shown by the generally small standard errors of the SDC means (Fig. 3) and by the average CV of 13% for all soils
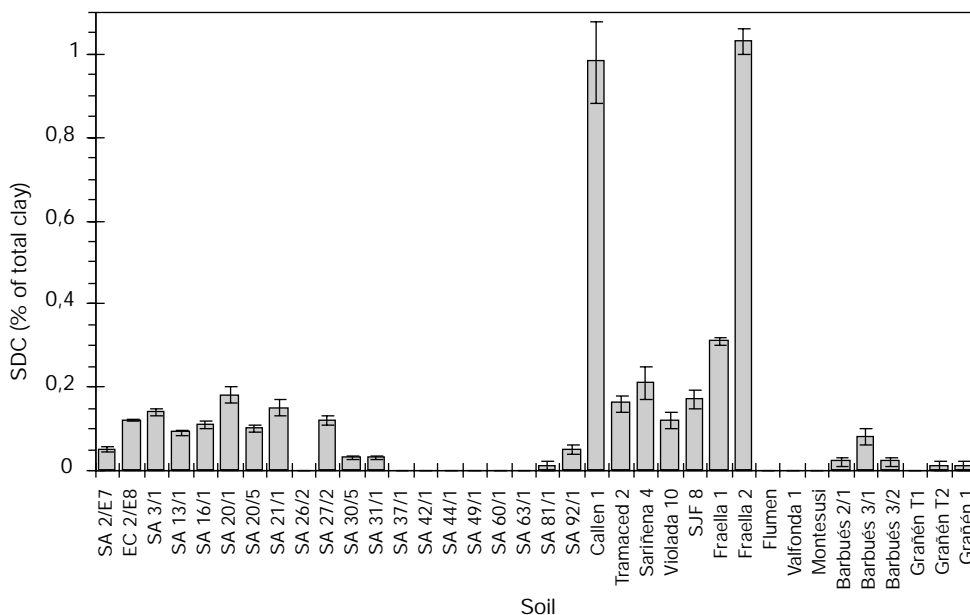
Figure 3. Spontaneously dispersed clay (SDC) of the 36 studied soils. Vertical bars represent standard errors of the means of four replications.

and replications (i.e., a total of 144 SDC measurements).

The spontaneously dispersed clay was very small (< 1% of total clay in all soils) (Fig. 3). The mean SDC for the 36 soils was 0.12%, with a very high CV of 192%, a reflection of the different dispersive behavior of the soils when subjected to wetting. The Duncan test separated the soils into five groups according to their SDC values (data not given). Thirty four soils had SDC < 0.31% (equivalent to around 0.7 g clay kg⁻¹ soil) and only two soils (Callen 1 and Fraella 2) had SDC values of around 1% (equivalent to 1.83 and 5.6 g clay kg⁻¹ soil respectively) (Fig. 3).

Dispersive behavior of soil clays against soil wetting and mechanical stirring

The results of the mechanical dispersion test were consistent and reproducible, as shown by the small standard errors of the MDC means (Fig. 4). The average CV for all soils and replications (i.e., a total of 144 MDC measurements) was 20%. This relatively high CV was due to small variations in the MDC values measured in the non-dispersed soils. Thus, when only the dispersive soils (i.e., soils with MDC > 1%) were considered, the average CV of the mean MDC values was 6%, indicating the reliability of the test.

The mechanically dispersed clay of the 36 studied soils was generally high (Fig. 4). The mean MDC was 26%, with a high CV of 113%, reflecting the different dispersive behavior of the wetted soils when subject to mechanical stress. The Duncan test separated the soils in 16 groups according to their MDC values (data not given).

Finally, the EC values obtained in the mechanical dispersion test were, on the average, 3.2 times greater than those obtained in the spontaneous dispersion test.

Discussion

Dispersive behavior of soil clays against irrigation and rain water quality

The FV obtained in this work, similar to those reported by Amézketa and Aragüés (1995), were greater than the values reported in the literature (i.e., values generally lower than 0.5 mmol$_c$ L⁻¹) for reference clays or clays extracted from the soil system (van Olphen, 1977; Oster *et al.*, 1980). Amézketa and Aragüés (1995) indicated that the dispersion behavior of soil clays should be determined without previous extraction of the clays from the soil suspensions because additional soil factors such as organic matter content, Al
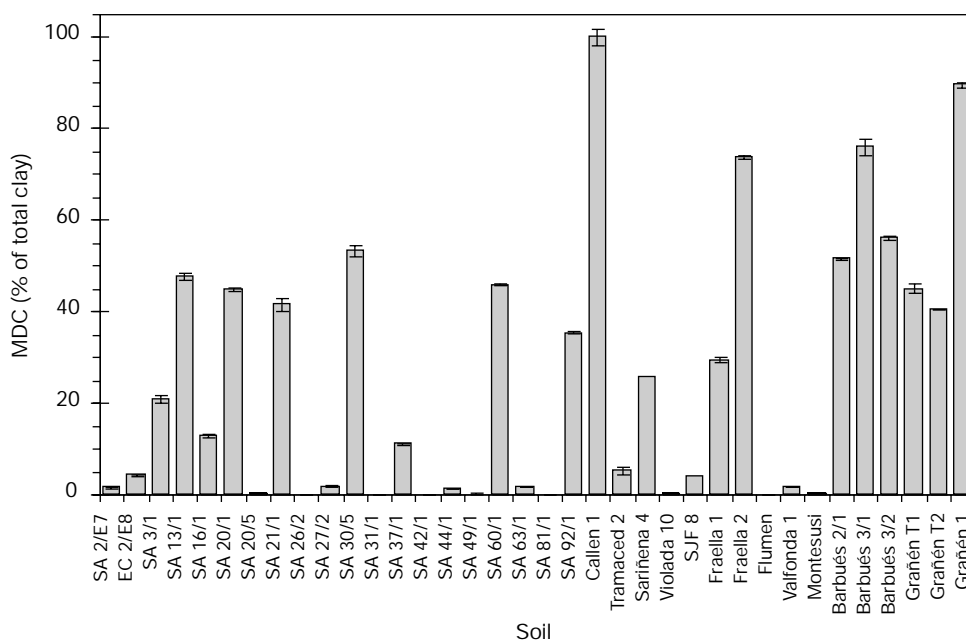

Figure 4. Mechanically dispersed clay (MDC) of the 36 studied soils. Vertical bars represent standard errors of the means of four replications.

and Fe oxides and other minerals as $CaCO_3$ may affect the colloidal stability of soils.

Since the FV is defined as the minimum electrolyte concentration without clay dispersion, it follows that soils with high FVs should be more sensitive to the chemical dispersion and the subsequent sealing/crusting induced by low-salinity waters. Thus, the ten soils with FVs above 4 $mmol_c$ L^{-1} (Fig. 2) will tend to disperse when irrigated with the Bardenas and Monegros canal waters, and soils SA 21/1, SA 37/1 and Grañén 1 and T2 will be the most susceptible to clay dispersion, as they have the highest FVs. Based on the average electrolyte concentration of 1 $mmol_c$ L^{-1} for rainwater, the conclusion is that all the soils, except perhaps soils SA 20/5 and Fraella 2, will tend to disperse upon raining, as they have FVs well above the salinity of rainwater. The prevention of clay dispersion and potential soil sealing/crusting in these soils will therefore require the superficial addition of chemical amendments such as gypsum.

Dispersive behavior of soil clays against soil wetting

The spontaneously dispersed clay (SDC) values obtained in this work were below the SDC values of 1.4 to 3.5% reported by Yousaf *et al.* (1987) to cause substantial reductions in the hydraulic conductivity of their soils. The two soils with SDC values of around 1% (Callen 1 and Fraella 2) have the highest SARe and SARe/ECe values of all the studied soils (Table 1). Rengasamy *et al.* (1984) measured the SDC of 138 soils and observed that only the 28 soils with $SAR_{1:5}$ values above 3 dispersed spontaneously. Barzegar *et al.* (1997) showed that the amount of spontaneously dispersed clay in two illitic soils (50% illite) was around 1% irrespective of SAR, whereas the amount in a 75% smectite-rich randomly interstratified illite-smectite soil was almost 15% at SAR 30.

According to Rengasamy *et al.* (1984), the spontaneously dispersed clay (i.e., clay dispersed when the soils are wetted in the absence of imposed external forces) will reflect the behavior during rainfall or irrigation events of mulched soils (i.e., surface of the soils effectively protected by plant materials such as stubble, pasture or full-cover field crops) and with zero-tillage cultivation. Emerson (1994) indicated that the spontaneous dispersion of air-dry aggregates illustrates the ease with which structural changes can occur

in the field. We therefore concluded that our studied soils were not susceptible to clay dispersion when wetted in the absence of mechanical stress (i.e., mulching and zero-tillage operations).

Dispersive behavior of soil clays against soil wetting and mechanical stirring

Twenty seven soils had MDC values greater than 1%, which is the threshold value proposed by Rengasamy *et al.* (1984) for minimum soil aggregate breakdown in the field. Similarly, the MDC reported in g clay kg^{-1} soil was higher than four in the same 27 soils, a value reported by Yousaf *et al.* (1987) as sufficient to reduce significantly the hydraulic conductivity of their studied soils. Based on these authors, we concluded that only the nine soils with MDC values lower than 1% or around 4 g clay kg^{-1} soil (Fig. 4) were not susceptible to the mechanical dispersion of clays. In contrast, some soils presented extremely high MDC values, as Callen 1 (100%), Grañén 1 (90%), Barbués 3/1 (76%) and Fraella 2 (74%). Callen 1 had the highest SARe and SARe/ECe ratio of all soils (Table 1). Nelson *et al.* (1998) also found a sodic soil (ESP ≈ 26%) with all of the clay dispersed after one hour of shaking.

Rengasamy *et al.* (1984) indicated that the MDC could be used as a qualitative index of dispersive behavior in the field when bare soils are subjected to raindrops impact or intensive cultivation. Furthermore, Sumner (1993) suggested that MDC could also reflect the clay behavior when the velocity of water in the soil pores is high enough to cause clay particles to become dispersed. Our results would indicate that 75% of the studied soils were potentially dispersive and sensitive to soil sealing and crusting when mechanically disturbed by impacting raindrops (i.e., bare soils subject to rainstorms or to high-intensity sprinkler irrigation) or intensive cultivation. It should be noted that soils with SARe values well below the threshold SARe levels defining a soil as sodic (SARe = 13, USSL Staff, 1954; SARe = 4, McIntyre, 1979) exhibited large mechanical dispersion of clays, suggesting that non-sodic soils where also prone to mechanical dispersion when subject to stress conditions.

Soil mulching and conservation tillage are recommended practices for alleviating the potential sealing/crusting in these soils highly susceptible to clay mechanical dispersion.

Relations between FV, SDC and MDC

The values of standardized skewness and standardized kurtosis indicate that the indices SDC and MDC departed from normality, therefore invalidating the linear regression analysis. For that reason we deleted the two soils (Callen 1 and Fraella 2) with extreme values in SDC or MDC and performed the FV-SDC-MDC regression analysis on the 34 remaining soils. The results indicate that the only correlation coefficient close to a $P < 0.05$ significance level was between FV and MDC ($r = 0.328$). This correlation is conceptually consistent, since both indices were obtained after stirring of the soil samples. The positive correlation suggests that the soils with the highest FV were also the most susceptible to mechanical dispersion, although the correlation is too weak for predicting purposes.

The Spearman rank correlation (r_s) test was performed for the 36 soils, since it does not require normality. The results show that SDC and MDC were significantly correlated ($r_s = 0.37*$), although this significance disappears when only the sodic soils (i.e., $SAR_{1:5} > 3$) were included in the analysis. This result disagrees with the high significance found by Barzegar *et al.* (1994a) between these parameters for sodic (i.e., $SAR_{1:5} > 3$) soils.

Besides the amount of dispersed clay, its particle size seems also to be important, although the results are still controversial. Thus, Barzegar *et al.* (1995) found that the size of the spontaneously dispersed clay particles was smaller than that of the mechanically dispersed clay, whereas Nelson *et al.* (1999) observed that the «easily dispersed clay» (i.e., equivalent to the spontaneously dispersed clay) had a larger particle size than the «difficult dispersed clay» (i.e., clay requiring ultrasound energy to be dispersed).

Finally, the EC values obtained in the mechanical dispersion test were, on the average, 3.2 times greater than those obtained in the spontaneous dispersion test. Rengasamy *et al.* (1984) also observed that the total cation concentration (TCC) in solutions obtained after shaking were much higher than those of the undisturbed solutions, suggesting that the reason for this difference was the rate of diffusion of salts from the soil aggregates to the soil solution.

Applicability of the Sumner *et al.* (1998) dispersion scheme to our studied soils

The scheme proposed by Sumner *et al.* (1998) establishes the dispersive behavior of soil clays (i.e., flocculated, mechanically dispersed and spontaneously dispersed clays) against the combination of the salinity (EC) and the sodicity (SAR) values measured in the supernatants of the mechanical dispersion test (i.e., 1:5 soil:water extracts) (Fig. 5). The upper solid line separating flocculated and mechanically dispersive soils is almost similar to the line proposed by Rhoades (1982) for separating flocculated and dispersed soils.

On top of this scheme we plotted the average EC and SAR values of the 36 studied soils measured in the supernatants of the mechanical dispersion test. Six soils (Violada 10, SA 20/5, SA 26/2, SA 42/1, SA 49/1 and SA 81/1) lied in the area of flocculated soils, three soils (SA 31/1, SA 44/1 and Fraella 2) were in the limit between flocculated and mechanically dispersed soils, and two soils (Valfonda 1 and Flumen) were outside the Sumner *et al.* (1998) scheme, although the extrapolation of the upper line will indicate that they were also in the flocculated area. Finally, the 25 remaining soils lied in the mechanically dispersive area. None of the studied soils were located in the spontaneously dispersive area.

A comparison of the predicted (Fig. 5) and observed (Fig. 4) mechanically dispersive soils indicates that: (i) the six soils predicted to be flocculated also behaved as flocculated on the basis of the MDC index (i.e., soils with MDC < 1%); (ii) of the three soils lying in the limit between flocculated and mechanically dispersed, SA 31/1 behaved as flocculated, SA 44/1 had a MDC value of 1.2% (i.e., close to the threshold value of 1%) and Fraella 2 was clearly dispersive (MDC = 74%); (iii) the two soils outside the area of the scheme, tentatively classified as flocculated, behaved as flocculated (Flumen) or close to flocculation (Valfonda 1, MDC = 1.6%); and (iv) all the soils (except Montesusin 1B) predicted to be mechanically dispersive behaved also as dispersive on the basis of their MDC values. Finally, in agreement with the lack of observed spontaneously dispersed clays (Fig. 3), none of the soils were predicted to be spontaneously dispersive on the basis of the Sumner *et al.* (1998) scheme (Fig. 5).

In summary, only three (Fraella 2, SA 31/1 and Montesusin 1B) out of the 36 soils were not correctly predicted by the Sumner *et al.* (1998) flocculation-dispersion nomogram. Fraella 2 was the soil with the largest deviation between the flocculated-predicted and the dispersed-observed clay behavior, probably due to its high $pH_{1:5}$ of 9 which could promote clay dispersion irrespective of its salinity-sodicity combination. The negative effect of high pH values in re-
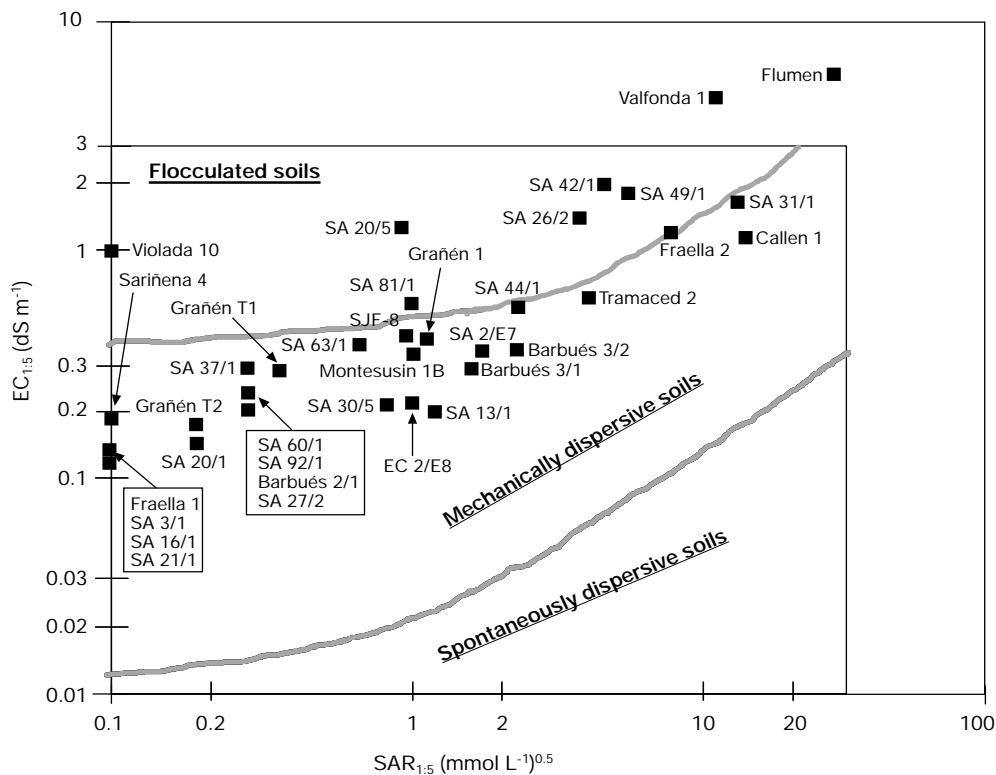
Figure 5. Scheme proposed by Sumner *et al.* (1998) describing the salinity ($EC_{1:5}$)-sodicity ($SAR_{1:5}$)-structural stability (flocculated-dispersed soils) relationships. $EC_{1:5}$ and $SAR_{1:5}$ were measured in the supernatants of the mechanical dispersion test. The solid lines represent the threshold $EC_{1:5}$-$SAR_{1:5}$ values separating flocculated, mechanically dispersive and spontaneously dispersive soils. On top of this scheme the 36 studied soils are plotted on the basis of the EC and SAR values measured in the supernatants of the mechanical dispersion test.

ducing the structural stability and the hydraulic conductivity of soils is well documented (Suarez *et al.*, 1984; Chorom *et al.*, 1994) and raises the need for incorporating soil pH in the Summer *et al.* (1998) diagram. The other two soils that were predicted as mechanically dispersible were close (Montesusin 1B) or very close (SA 31/1) to the upper flocculation line (Fig. 5) and, therefore, did not deviate significantly from their observed flocculation state (Fig. 4). We therefore concluded that the new scheme proposed by Sumner *et al.* (1998) predicted satisfactorily the dispersive behavior of most of the illitic soils sampled in the middle Ebro river basin (Spain).

Soil properties affecting clay dispersion

As previously indicated, all the studied soils were predominant in illite which, according to Arora and Coleman (1979), Oster *et al.* (1980) and Shainberg and Letey (1984), is the most sensitive clay to dispersion.

However, in spite of their similar clay mineralogy, the dispersive behavior of these soils was quite variable (i.e., CV of the means = 42% for FV, 192% for SDC and 113% for MDC), suggesting that other soil properties were also affecting clay dispersibility.

We analyzed potential relationships between the soil properties summarized in Table 1 and the dispersive behavior of clays (i.e., FV, SDC and MDC indices) through the Spearman rank correlation test, which does not require normality in the distribution of the observations.

The FV was negatively correlated with ECe (*) and SARe (**) (Table 2). However, these correlations were not consistent, since they were not significant (P > 0.05) when the extreme soils were deleted from the sample population. In any case, it should be noted that the FV was determined in electrolytes of SAR = 0, so that it is not an appropriate index for ranking the susceptibility to chemical dispersion of soils with SAR values higher than zero. Thus, only in soils equilibrated with irrigation waters of SAR values close to zero (as the Barde-

Table 2. Spearman rank correlation coefficients among the indices FV (flocculation value), SDC (spontaneously dispersed clay) and MDC (mechanically dispersed clay) and the soil properties presented in Table 1. Levels of significance: * P < 0.05, ** P < 0.01

Indices	Soil properties														
	ECe	SARe	SARe/CEe	pHe	Sand	Silt	Clay	Fc[1]	Wp[2]	OM	CaCO$_3$	CEC	Mn	Fe	Al
FV (mmol$_c$ L^{-1})	−0.40*	−0.47**	−0.33	−0.06	0.41*	−0.08	−0.37*	−0.24	−0.20	0.46*	0.17	−0.04	0.08	−0.23	−0.04
SDC (%)	−0.33*	−0.22	0.13	0.49*	0.23	−0.36*	−0.04	−0.08	−0.31	0.02	−0.32	0.23	−0.07	−0.0	0.03
MDC (%)	−0.29	−0.04	0.44*	0.37	0.36*	−0.14	−0.42*	−0.35	−0.34	−0.20	−0.35*	−0.24	−0.57*	−0.35	−0.62*
MDC (g kg^{-1})	−0.30	−0.0	0.37*	0.41*	0.32	−0.22	−0.31	−0.35	−0.26	−0.23	−0.36*	−0.23	−0.53*	−0.34	−0.57*

[1] Fc: field capacity. [2] Wp: wilting point.

nas and Monegros canal waters) the FV could be a suitable index for predicting clay dispersibility.

The FV was negatively correlated with the clay content (*) and positively correlated with the sand (*) and the organic matter (OM) (*) contents (Table 2). As noted by Shainberg *et al.* (1992) and Le Bissonnais (1996), the reactive clays act as binding structures and promote aggregation (i.e., soils will have lower FV). The positive correlation between FV and the chemically-inert sand could be a consequence of the clay-sand autocorrelation (r = −0.72***). The positive correlation between FV and OM is more controversial, since it is generally accepted that OM enhances aggregate stability (Tisdall and Oades, 1982) and, hence, high OM soils should have lower rather than higher FV. However, Lebron and Suarez (1992) observed increases in the critical coagulation concentrations (CCC) of the studied Ebro river basin soils with increasing OM at high pH and SAR values, and Kretzschmar *et al.* (1993) found a positive correlation between OM and the CCC of kaolinitic soils. The last authors suggested that the humic substances increase clay dispersion through a steric stabilization mechanism, which increased the negative charge of the clay particles, resulting in stronger electrostatic repulsion forces.

The spontaneously dispersed clay (SDC) was negatively correlated with ECe (*) and silt content (*) and positively correlated with pHe (*) (Table 2), reflecting the well-established beneficial effect of high electrolyte EC and detrimental effect of high pH and silt content on clay dispersion (Shainberg and Letey, 1984). However, the Spearman rank correlation coefficients (r$_s$) were too low to establish a consistent ranking of spontaneous clay dispersion on the basis on these soil properties.

The r$_s$ values between the mechanically dispersed clay (MDC) (given as percent of total clay and g clay kg^{-1} soil) and the soil properties (Table 2) were conceptually consistent, suggesting that the mechanical dispersion of clays increased with an increase in the SARe/ECe ratio and in the pHe, and a decrease in CaCO$_3$, Mn and Al contents. Thus, the adverse effects of sodicity and pH (Quirk and Schofield, 1955; Shainberg and Letey, 1984; Suarez *et al.*, 1984; Amézketa and Aragüés, 1995) and the beneficial effects of EC, calcite dissolution and Al oxides (Alperovitch *et al.*, 1981; Ben-Hur *et al.*, 1985; Goldberg *et al.*, 1990) on clay dispersion are well established.

Although MDC given in percent of total clay was significantly (*) correlated with the clay content of soils, they were not correlated when MDC was given in absolute terms (i.e., g clay kg^{-1} soil) (Table 2), therefore suggesting that other clay properties as its size and arrangement could also play a significant role on the amount of the mechanically dispersed clay. Kay and Dexter (1990) showed that higher MDC values were due to both larger exposed aggregate surface areas and the higher dispersibility of the clays present in the exposed surfaces. Barzegar *et al.* (1995) found that the amounts of SDC and MDC were negatively correlated with the average size of clay particles, suggesting that the dispersibility of finer clay particles was greater. In contrast, Nelson *et al.* (1999) found that clays with a high charge density and a high surface area (i.e., finer particles) were less dispersible because of increased inter-particle interactions. These authors emphasized that the clay-OM interactions had an important influence on clay dispersion, so that «easily dispersible clay» (i.e., SDC) had lower organic C contents and high proportions of amino acids, whereas «difficult dispersible clay» (i.e., clays requiring ultrasound energy to disperse) had higher organic C contents and high proportions of aliphatic materials in the topsoil and carbohydrates in the subsoil. Based on these divergent results,

additional research will be required to characterize (i) the exposed surface area of aggregates before and after the mechanical treatment, (ii) the clay particle-size distribution and charge, (iii) the size distribution and the charge of SDC and MDC, (iv) the content and nature of the organic matter in the clay fraction.

The Al-oxides were superior to the Fe-oxides in preventing the mechanically dispersed clay, as shown by the higher r_s values for Al than for Fe (Table 2). This trend is consistent with that found by Seta and Karathanasis (1996) in samples with diverse physicochemical and mineralogical composition, where the correlation coefficients relating Al-oxides to colloid dispersibility (i.e., water-dispersible colloids and sodium-dispersible colloids) were greater than those for Fe-oxides. The higher efficiency of the Al polymers may be a result of their higher point of zero charge (Goldberg and Glaubig, 1987) which lead to a higher charge density and stronger clay-polymers attraction forces, and the planar shape of the Al precipitates (contrary to spherical shape of the Fe polymers) which increases the contacting surfaces and bindings with the clay particles.

It should be noted that the OM content was not significantly correlated with either SDC or MDC (Table 2), suggesting that it did not influence the dispersive behavior of our soil clays. The role of OM on dispersion remains controversial since it has been both positively (Van den Broek, 1989; Heil and Sposito, 1995) and negatively related (Rasiah *et al.*, 1992).

Finally, the potential relationships between MDC and the chemical characteristics (i.e., EC, SAR, pH and SAR/EC) of the supernatant solutions (i.e, 1:5 soil:water extracts) were also analyzed by means of the Spearman rank correlation test. Similar qualitative conclusions were obtained, but the r_s values increased (data not given) in comparison to those obtained in the saturation extract (Table 2). Thus, the chemical properties of the supernatants seemed to be more important in controlling the mechanically dispersed clay than those in the saturation extract. This is a consistent result, since soil stirring in a 1:5 soil:water ratio is much higher than soil stirring in the saturated paste method, where the soil:water ratio is approximately ten times higher.

Acknowledgments

References

AGASSI M., SHAINBERG I., MORIN J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Sci Soc Am J 45, 848-851.

ALPEROVITCH N., SHAINBERG I., KEREN R., 1981. Specific effect of magnesium on the hydraulic conductivity of sodic soils. J Soil Sci 32, 543-554.

AMÉZKETA E., ARAGÜÉS R., 1995. Flocculation-dispersion behavior of arid-zone soil clays as affected by electrolyte concentration and composition. Invest Agr: Prod Prot Veg 10 (1), 101-112.

ARORA H.S., COLEMAN N.T., 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci 127, 134-139.

BARZEGAR A.R., MURRAY R.S., CHURCHMAN G.J., RENGASAMY P., 1994a. The strength of remoulded soils as affected by exchangeable cations and dispersible clay. Aust J Soil Res 32, 185-199.

BARZEGAR A.R., NELSON P.N., OADES J.M., RENGASAMY P., 1997. Organic matter, sodicity and clay type: Influence on soil aggregation. Soil Sci Soc Am J 61, 1131-1137.

BARZEGAR A.R., OADES J.M., RENGASAMY P., GILES L., 1994b. Effect of sodicity and salinity on disaggregation and tensile strength of an alfisol under different cropping systems. Soil Till Res 32, 329-345.

BARZEGAR A.R., OADES J.M., RENGASAMY P., MURRAY R.S., 1995. Tensile strength of dry, remoulded soils as affected by properties of the clay fraction. Geoderma 65, 93-108.

BEN-HUR M., SHAINBERG I., BAKKER D., KEREN R., 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soil as related to water salinity. Irrig Sci 6, 281-294.

CARTER M.R., 1993. Soil sampling and methods of analysis. Lewis publishers, Boca Raton, Florida, 823 pp.

CHOROM M., RENGASAMY P., MURRAY R.S., 1994. Clay dispersion as influenced by pH and net particle charge of sodic soils. Aust J Soil Res 32, 1243-1252.

CURTIN D., CAMPBELL C.A., ZENTNER R.P., LAFOND G.P., 1994. Long-term management and clay dispersibility in two haploborolls in Saskatchewan. Soil Sci Soc Am J 58, 962-967.

EMERSON W.W., 1994. Aggregate slaking and dispersion class, bulk properties of soil. Aust J Soil Res 32, 173-184.

GOLDBERG S., GLAUBIG R.A., 1987. Effect of saturating cation, pH and aluminum and iron oxide on the flocculation of kaolinite and montmorillonite. Clay Clay Miner 35, 220-227.

GOLDBERG S., KAPOOR B.S., RHOADES J.D., 1990. Effect of aluminum and iron oxides and organic matter on

flocculation and dispersion of arid zone soils. Soil Sci 150, 588-593.

HEIL D., SPOSITO G., 1995. Organic matter role in illitic soil colloids flocculation: III. Scanning force microscopy. Soil Sci Soc Am J 59, 266-269.

KAY B.D., DEXTER A.R., 1990. Influence of aggregate diameter, surface area and antecedent water content on the dispersibility of clay. Can J Soil Sci 70, 655-671.

KRETZSCHMAR R., ROBARGE W.P., WEED S.B., 1993. Flocculation of kaolinitic soil clays: Effects of humic substances and iron oxides. Soil Sci Soc Am J 57, 1277-1283.

LE BISSONNAIS Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur J Soil Sci 47, 425-437.

LEBRON I., SUAREZ D.L., 1992. Variations in soil stability within and among soil types. Soil Sci Soc Am J 56, 1412-1421.

McINTYRE D.S., 1979. Exchangeable sodium, subplasticity and hydraulic conductivity of some Australian soils. Aust J Soil Res 17, 115-120.

MULLINS C.E., YOUNG I.M., BENGOUGH A.G., LEY G.J., 1987. Hard-setting soils. Soil Use Manage 3, 79-83.

NELSON P.N., BALDOCK J.A., OADES J.M., 1998. Changes in dispersible clay content, organic carbon content, and electrolyte composition following incubation of sodic soil. Aust J Soil Res 36, 883-897.

NELSON P.N., BALDOCK J.A., CLARKE P., OADES J.M., CHURCHMAN G.J., 1999. Dispersed clay and organic matter in soil: their nature and associations. Aust J Soil Res 37, 289-315.

OSTER J.D., SHAINBERG I., WOOD J.D., 1980. Flocculation value and gel structure of sodium/calcium montmorillonite and illite suspensions. Soil Sci Soc Am J 44, 955-959.

QUIRK J.P., SCHOFIELD R.K., 1955. The effect of electrolyte concentration on soil permeability. J Soil Sci 6, 65-178.

RASIAH V., KAY B.D., MARIN T., 1992. Variation of structural stability with water content: Influence of selected soil properties. Soil Sci Soc Am J 56, 1604-1609.

RENGASAMY P., GREENE R.S.B., FORD G.W., MEHANNI A.H., 1984. Identification of dispersive behavior and the management of red-brown earths. Aust J Soil Res 22, 413-431.

RHOADES J.D., 1982. Reclamation and management of salt-affected soils after drainage. Proc. of the First Annual Western Provincial Conf., Lethbridge, Alberta, Canada. 29 November. pp. 123-197.

SETA A.K., KARATHANASIS A.D., 1996. Water dispersible colloids and factors influencing their dispersibility from soil aggregates. Geoderma 74, 255-266.

SHAINBERG I., LETEY J., 1984. Response of soils to sodic and saline conditions. Hilgardia 52, 1-57.

SHAINBERG I., LEVY G.J., LEVIN J., GOLDSTEIN D., 1997. Aggregate size and seal properties. Soil Sci 162, 470-478.

SHAINBERG I., LEVY G.J., RENGASAMY P., FRENKEL H., 1992. Aggregate stability and seal formation as affected by drops' impact energy and soil amendments. Soil Sci 154, 113-119.

SUAREZ D.L., RHOADES J.D., LAVADO R., GRIEVE C.M., 1984. Effect of pH on saturated hydraulic conductivity and soil dispersion. Soil Sci Soc Am J 48, 50-55.

SUMNER M.E., 1993. Sodic soils: New perspectives. Aust J Soil Res 31, 683-750.

SUMNER M.E., RENGASAMY P., R. NAIDU., 1998. Sodic soils: A reappraisal. In: Sodic soils: Distribution, properties, management, and environmental consequences. (Sumner M.E., Naidu R., eds.). Oxford University Press, NY, Oxford, pp. 3-17.

SUMNER M.E., STEWART B.A., 1992. Soil crusting: Chemical and physical processes. Lewis Publishers, Boca Raton, Florida. 372 pp.

TISDALL J.M., OADES J.M., 1982. Organic matter and water-stable aggregates in soils. J Soil Sci 33, 141-163.

USSL STAFF, 1954. Diagnosis and improvement of saline and alkali soils. Agric. Handbook 60. USDA, Washington D.C. 160 pp.

VAN DEN BROEK T.M.W., 1989. Clay dispersion and pedogenesis of soils with an abrupt contrast in texture, a hydro-pedological approach on subcatchment scale. Ph.D. dissertation. Univ. Amsterdam, The Netherlands. 109 pp.

VAN OLPHEN H., 1977. An introduction to clay colloid chemistry. 2nd ed. Interscience Publ New York., 318 pp.

YOUNG I.M., MULLINS C.E., 1991. Water-suspensible solids and structural stability. Soil Till Res 19, 89-94.

YOUSAF M., ALI O.M., RHOADES J.D., 1987. Dispersion of clay from some salt-affected arid land soil aggregates. Soil Sci Soc Am J 51, 920-924.