Geoderma 159 (2010) 228–236

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina

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ARTICLE INFO

Article history:
Received 30 March 2009
Received in revised form 5 July 2010
Accepted 18 July 2010
Available online 21 August 2010

Keywords:
Wind erosion
Dry aggregate stability
Erodible fraction
Soil degradation indexes

ABSTRACT

The size and stability of soil aggregates are primary factors that affect the soil susceptibility to wind erosion. Relationships among several soil properties and both the wind erodible fraction (EF) and the dry aggregate stability (DAS) can allow the development of simple mathematical models which can be useful to quantify soil resistance against wind erosion. Considering this we studied 28 cultivated (CULT) and uncultivated (UNCULT) soils of the central semiarid region of Argentina with variable clay, organic carbon (OC), $CaCO_3$, and amorphous Al (Alo) and Fe (Feo) oxides contents. Results showed that cultivation increased EF and reduced DAS in medium textured soils (silt + clay between 215 and 500 g kg^{-1}), but not in sandy (silt + clay < 215 g kg^{-1}) nor in fine textured soils (silt + clay > 500 g kg^{-1}). Cultivation of medium textured soils produced the weakening of soil structure through the loss of OC and the breaking down of aggregates. These soils did not contain enough inorganic cementing agents like clay or Alo, which may avoid the deterioration of soil structure. In fine textured soils the formation of large and resistant clods by tillage of cultivated soils produced more similar EF and DAS than in uncultivated conditions. It seems that the lack of EF and DAS differentiation between management systems in sandy soils were produced by their low contents of organic and inorganic cementing agents, even in uncultivated conditions. EF and DAS were related to OC, Alo and clay contents in a logarithmic or an exponentially way. Such relationships allowed the identification of critical OC, Alo and clay contents below which the resistance of the soil against wind erosion is reduced drastically. DAS showed critical values at OC contents of 10 g kg^{-1} in CULT and 29 g kg^{-1} in UNCULT and clay contents of 100 g kg^{-1} in UNCULT. Alo critical contents were 1000 g kg^{-1} for EF and DAS in both managements. There were no effects of Feo and $CaCO_3$ on EF and DAS in the studied soils. We concluded that the control of wind erosion requires different technologies according to soil texture: management practices which tend to increase the organic matter contents can be successful for the development of large and resistant aggregates which are effective in controlling wind erosion in medium textured soils. The large and stable clods formed by tillage in cultivated fine textured soils are effective in controlling wind erosion. In sandy soils, probably management practices which tend to increase the amount of organic cementing agents of the soil will not be effective in controlling wind erosion. Such goal must be achieved through the increase of coverage of the soil surface with plant residues or canopy.

1. Introduction

Wind erosion is an important soil degradation process of arid and semiarid regions of the world (Lal, 1990), including the Semiarid Argentinean Pampas (SAP) (Buschiazzo et al., 1999).

The size and stability of soil aggregates are primary factors that affect the soil susceptibility to wind erosion. Aggregates smaller than 0.84 mm in diameter are considered as erodible by wind (Chepil, 1953a). The proportion of these aggregates in the upper 25.4 mm of the soil surface defines the wind erodible fraction (EF). This parameter represents the soil erodibility index of some wind erosion prediction models, like WEQ (Woodruff and Siddoway, 1965) and RWEQ (Fryrear et al., 2000).

The non erodible aggregates can be transformed into erodible aggregates by many processes, like abrasion during wind transport, the breaking down produced by tillage practices or the impact of rain drops. Aggregates resistance against disrupting forces can be estimated by means of their dry aggregate stability (DAS), which is considered an index of soil resistance against wind erosion (Chepil, 1958).

Many factors affect EF and DAS such as long term climate variations (Merrill et al., 1999), seasonal climatic changes (Layton et al., 1993), crops (Skidmore et al., 1986), tillage practices (Hevia et al., 2007), water content at time of tillage (Wagner et al., 1992), and

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doi:10.1016/j.geoderma.2010.07.016

several soil properties (Zobeck, 1991). Organic carbon (OC) and clay contents are the main soil properties affecting EF and DAS, as they bind individual particles increasing soil aggregation (Skidmore and Layton, 1992; Fryrear et al., 1994). This effect has been demonstrated for the SAP, in which amorphous Al oxides, probably produced by the weathering of volcanic ashes, have a positive effect on DAS (Buschiazzo et al., 1995).

The wet aggregate stability has been widely used as an index of soil resistance against water erosion, and the factors affecting this parameter in diverse environments have been also well established (Lal, 1991; Amezketa, 1999; Nimmo and Perkins, 2002; Brosnick and Lal, 2005). This is not the case of DAS, an index of soil resistance against wind erosion, which has been less studied as well as the factors affecting it.

Buschiazzo (2006) stated that DAS depends on OC contents in SAP soils; however Quiroga et al. (1998), who studied a wide range of soils within the SAP, did not find a relationship between DAS and OC. Differences between these findings probably were originated in the way that the relationships between variables were developed in each case: Quiroga et al. (1998) used only linear regressions while Buschiazzo (2006) used a logarithmic model. Both studies did not find differences of DAS between management systems in a wide range of soil textures.

Hevia et al. (2007) found that dry aggregation was different in a soil submitted to different management practices, while López et al. (2001) found similar trends in a wide range of soils with different textures and chemical composition.

The soils of the SAP have some amounts of volcanic ashes which present variable spatial distribution and weathering states (Buschiazzo et al., 1998). Weathering of these ashes produced variable amounts of Al oxides. Buschiazzo et al. (1995) showed that these oxides contribute to the formation of soil aggregates in the SAP.

Former results indicate that the influence of soil properties on DAS and EF must be analyzed on the basis of management and soil type.

Wind erosion removes the finest soil aggregates and particles, changing the soil texture, carrying nutrients and OC and decreasing soil depth. Therefore wind erosion has been considered an irreversible soil degradation process (Leys, 2002; Buschiazzo, 2006). Thus, we speculate that the relationships between both DAS and EF with different soil properties can be used as empiric models to define the rate of soil resistance against wind erosion. Such relationships can be useful to define critical DAS and EF values, below which the process becomes an irreversible soil degradation process. Such knowledge can contribute to the monitoring of soil quality in the study region.

The objectives of this study were to determinate the utility of EF and DAS as indexes of the soil degradation rate against wind erosion, and to define critical values based on relationships between both parameters with selected soil properties.

2. Materials and methods

2.1. Study area

This study was carried out in the Semiarid Argentinean Pampas (SAP, Fig. 1). The mean annual air temperature of this region is 16 °C and the mean annual rainfall 550 mm. Average annual wind velocity is 15 km h^{-1} and highest wind velocities occur between August and October averaging 20 to 25 km h^{-1} with gusts higher than 60 km h^{-1} (Casagrande and Vergara, 1996). Soils developed on Holocene loessical sediments predominating Entic Haplustolls (INTA et al., 1980). Aeolian parental materials of these soils show high contents of volcanic ashes. Such minerals were transported by wind from the Andes during volcanic eruptions in the Pleistocene and are currently mixed with the loess (Buschiazzo et al., 1998).

2.2. Soil sites selection and experimental design

We selected fourteen plain sites of the SAP on the basis of their textures, previous management and different volcanic ash deposition patterns of their soils. Such selection was made to obtain soil populations with variable amounts of clay, organic carbon (OC), and amorphous Al and Fe contents. Soil texture of selected soils varied from approximately 100 to 800 g kg^{-1} of silt plus clay (S + C) due to the variability of texture of the parental material, caused by different

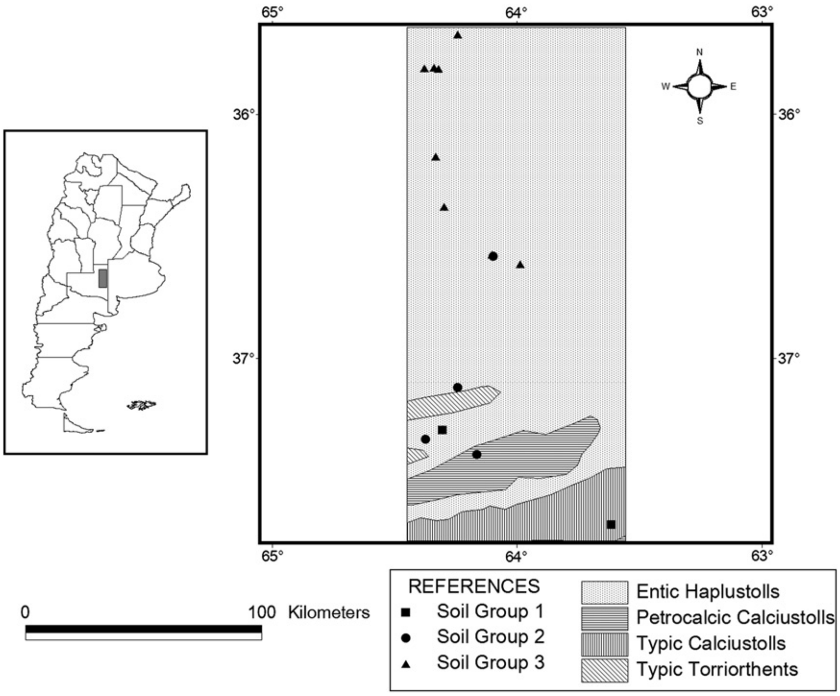

Fig. 1. Placement of the studied sites.

sedimentation patterns of loess from SW to NE (Buschiazzo et al., 1991). According to Buschiazzo et al. (1998) and Hepper et al. (2006), amorphous Al and Fe contents varied from north to south due to different volcanic events. As a consequence of this we defined three initial soil groups (Table 1); Soils group 1: $S+C<215$ g kg^{-1} with low Alo and Feo contents (South placed); Soils group 2: 215 g kg^{-1}$<S+C<$500 g kg^{-1} with medium Alo and Feo contents and Soils group 3: $S+C>500$ g kg^{-1} with high Alo and Feo contents (North placed).

At each site two pedons were sampled and each one of them was submitted to contrasting management conditions:

i) an uncultivated soil (UNCULT), placed in the *Caldenal* savanna-like ecosystem. This is an undisturbed natural grassland environment, submitted to extensive grazing for more than 50 years. UNCULT soils have never been ploughed and represent the original condition of the soils. The *Caldenal* is an ecosystem composed by a tree strata dominated by Calden (*Prosopis caldenia,* Burkart) and a grass strata dominated by *Stipa tennuis* (Phill) and *Panicum sp.*

ii) a cultivated soil (CULT) ploughed with conventional tillage (disk and harrow disk up to 20 cm depth) for more than 50 years, since Calden deforestation. Most common crops were non-fertilized wheat (*Triticum aestivum*), oats (*Avena sativa*), corn (*Zea mays*) and sunflower (*Heliannus annus*). A typical crop rotation carried out on these soils is wheat – cattle grazed oat – summer crops (sunflower or corn). Statistical information indicates that historically the land use has been rather uniform in the entire region (Viglizzo et al., 1997).

2.3. Soil sampling and analytical determinations

Triplicate random samples of the top-soil were taken from three 10 m^2 sampling areas between August and September of 2005 in each site. We took 1–2 kg of undisturbed soil samples from the 2.5 cm top-soil with a spade at each sampling area. Samples were air dried; gentle fragmented and sieved using a rotary sieve. This device is essentially a rotating nest of concentric cylindrical sieves having 0.42, 0.84, 2, 6.4 and 19.2 mm square openings (Chepil, 1962). The percentage of aggregates <0.84 mm, the erodible fraction of the soil (EF), was calculated with the following equation:

$$EF = \frac{W<0.84}{TW} \times 100 \tag{1}$$

where EF is the erodible fraction (%), W<0.84 is the weight (g) of <0.84 mm aggregates, and *TW* is the initial weight (g) of total sample. A limitation of this procedure is that the rotary sieve is operated until aggregates separation is complete which result in different sieving time and thus different energy inputs (Diaz-Zorita et al., 2002). Nevertheless, this device is accepted as the standard technique to determinate dry aggregate size distribution for wind erosion assessment (Skidmore et al., 1994).

The dry aggregate stability (DAS) was evaluated using a second dry sieving of each aggregate size, after the first sieving (Skidmore et al., 1994) using Eq. (2)

$$DAS = \left[1 - \frac{W<0.84_2}{W>0.84_1}\right] \times 100 \tag{2}$$

where W<0.84 $_2$ is the weight (g) of aggregates that passed though the 0.84 mm sieve after a second sieving and W>0.84 $_1$ is the weight (g) of aggregates retained on the 0.84 mm sieve after the first sieving.

Disturbed soil samples from the A horizon were air dried and passed through a 2 mm sieve. Samples were analyzed for particle size distribution using the combined wet sieving and pipette method described by Gee and Bauder (1986). Organic carbon (OC) was determined using the Walkley and Black (1934) procedure and free calcium carbonate by gas-volumetric analysis with a Scheibler apparatus (Schlichting et al., 1995). Amorphous Al (Alo) and Fe (Feo) were extracted in darkness with oxalic acid and determined by atomic absorption spectrometry (Schlichting et al., op. cit.).

Table 1
Mean values of clay, silt, texture class, organic carbon (OC), amorphous Al oxides (Alo), amorphous Fe oxides (Feo) and calcium carbonate ($CaCO_3$) of each soil ($n=3$).

Site group	Site	Management	Clay		Silt		Texture	OC		Alo		Feo		$CaCO_3$	
			(g kg^{-1})		(g kg^{-1})			(g kg^{-1})		(mg kg^{-1})		(mg kg^{-1})		(g kg^{-1})	
1	1	CULT	55	(2.1)	65	(15.0)	S	4	(1)	398	(24.7)	874	(41.1)	5	(2.6)
		UNCULT	57	(2.6)	70	(3.1)	S	5	(1)	397	(11.6)	699	(60.7)	4	(1.5)
	2	CULT	144	(12.8)	174	(12.5)	LS	11	(1)	1947	(1104.7)	779	(7.6)	5	(1.7)
		UNCULT	105	(22.2)	121	(32.1)	LS	18	(4)	615	(108.9)	774	(101.7)	4	(0)
2	3	CULT	89	(12.7)	236	(11.5)	SL	12	(1)	1290	(176.2)	766	(35.5)	9	(1.7)
		UNCULT	76	(3.2)	196	(8.7)	SL	12	(4)	987	(88.1)	652	(59.5)	6	(2.9)
	4	CULT	96	(9.3)	125	(2.5)	SL	8	(2)	663	(65.3)	519	(43.3)	4	(1.5)
		UNCULT	104	(13.2)	177	(13.6)	LS	14	(2)	698	(98.3)	749	(74.1)	5	(0.6)
	5	CULT	93	(7.0)	238	(14.6)	SL	17	(2)	847	(43.1)	662	(33.8)	4	(2.1)
		UNCULT	138	(15.0)	306	(16.3)	SL	36	(10)	1283	(106.8)	842	(47.3)	4	(0)
	6	CULT	101	(14.6)	281	(7.2)	SL	18	(1)	1153	(59.6)	609	(19.5)	3	(0.6)
		UNCULT	136	(12.4)	316	(13.0)	SL	55	(12)	1333	(74.9)	802	(119.3)	3	(0.6)
	7	CULT	59	(11.0)	314	(43.3)	SL	15	(0)	1042	(65.4)	401	(24.0)	5	(3.5)
		UNCULT	158	(15.9)	295	(9.2)	SL	50	(1)	1362	(27.5)	851	(66.9)	7	(2.6)
3	8	CULT	108	(6.4)	370	(16)	SL	14	(1)	800	(31.2)	702	(8.0)	5	(2.6)
		UNCULT	204	(14.2)	396	(14.6)	L	49	(17)	1452	(286.8)	1009	(186.4)	6	(1.0)
	9	CULT	204	(10.2)	405	(20)	SL	11	(1)	1172	(389.6)	476	(32.3)	2	(0.6)
		UNCULT	209	(32.1)	442	(36.2)	L	41	(8)	2337	(826.6)	902	(70.0)	3	(0.6)
	10	CULT	172	(5.9)	451	(6.6)	L	17	(1)	1668	(245.5)	565	(43.5)	3	(0.6)
		UNCULT	233	(14.0)	428	(55.43)	L	48	(6)	1803	(103.9)	1080	(75.8)	3	(0)
	11	CULT	294	(11.8)	467	(32.5)	L	16	(1)	865	(52.9)	1429	(28.8)	7	(3.1)
		UNCULT	192	(7.0)	500	(39.7)	L	20	(2)	1138	(124.1)	1687	(170.7)	9	(1.5)
	12	CULT	215	(19.1)	464	(14.7)	L	14	(2)	875	(22.9)	367	(25.7)	9	(2.1)
		UNCULT	243	(60.6)	487	(59.6)	L	25	(17)	920	(206.2)	522	(133.7)	9	(0.6)
	13	CULT	166	(4.5)	335	(11.9)	SL	9	(2)	1580	(204.7)	331	(88.05)	19	(6.1)
		UNCULT	228	(21.4)	535	(23.25)	SlL	68	(17)	2257	(388.2)	1071	(110.5)	4	(1.0)
	14	CULT	250	(8.3)	469	(25.15)	L	9	(21)	1587	(222.3)	1037	(165.1)	3	(1.5)
		UNCULT	276	(72.5)	563	(36.6)	SlL	85	(47)	1705	(342.5)	1162	(359.79)	2	(1.1)

UNCULT = uncultivated, CULT = cultivated, S = sandy, LS = Loam sandy, SL = sandy loam, L = loam and SlL = silty loam. Standard deviations are in parentheses.

2.4. Statistical analysis

Mean effect of treatments on EF and DAS were analyzed with a two-way ANOVA with management and site as main factors to test interaction effect. Once we checked for interaction, we tested the initial soils groups by performing an interaction analysis using Scheffé's post hoc orthogonal contrasts (Sokal and Rolf, 1981). This step wise procedure analyses different orthogonal combination of sites until the sum of variance of interaction is discomposed. This method produced new groups, within them no interaction existed. This allowed the analysis of site group means, increasing the strength of comparisons. Management means were compared using a Student's *t* test inside new site groups using the INFOSTAT software (INFOSTAT, 2002). Tests were performed at a 0.05 probability level.

Relationships of EF and DAS with soil properties were studied with linear and non linear regression models using the Curve Expert 1.37 program (Hyams, 2005). Possible critical values in non linear regression models were located when the absolute value of the first derivative ($\Delta y/\Delta x$) of the functions was lower than 0.01 (Goldstein et al., 1980).

3. Results and discussion

3.1. Erodible fraction (EF)

The ANOVA analysis detected a high significant *management × site* interaction for EF ($P<0.001$). The only significant contrast that explained the interaction effect was the combination of soils 3, 4, 5, 6 and 7 (soils group 2) *versus* the combination of the remaining soils (soils groups 1 and 3). As there was not existence of interaction effect between soils groups 1 and 3, we were able to analyze them together. Soils group 2 was composed by medium textured soils, with silt plus clay (S + C) contents in UNCULT ranging between 215 and 500 g kg^{-1}. Soils group 1 had less than 215 g kg^{-1} of S + C, and soils group 3 had more than 500 g kg^{-1} of S + C. Fig. 2 shows that EF had a tendency for decreasing from soils group 1 to 3, in agreement with increasing clay, OC and Alo contents.

In soils group 2, EF was higher in CULT (39.5%, $P<0.001$) than in UNCULT (21%), indicating an 18.5% EF increment because of anthropogenic activities. Similar results were reported by Bravo and Silenzi (2000) who found that a conventional tilled Petrocalcic Paleustoll had higher EF contents than the uncultivated condition. These authors attributed such results to the destruction of coarse aggregates and their transformation into fine aggregates by tillage practices. One third of CULT samples of soils group 2 had EF contents higher than 40%, a threshold EF value above which wind erosion reaches values above the tolerable level (Woodruff and Siddoway, 1965; Leys et al., 1996). EF was not higher than 40% in UNCULT of soils group 2, indicating that these soils are less erodible. This agrees with results of López et al. (2007) who found similar results in soils of a semiarid environment of Argentina.

EF was not different between management conditions when soils groups 1 and 3 were considered together ($P = 0.7$), indicating that EF was not a sensible soil degradation parameter in these soils type. EF of coarse textured soils (soils group 1) was 35.6% in CULT and 35.3% in UNCULT. The lack of differences between management systems in this soils group, and EF values above 40% in half of UNCULT soils, suggest that these soils cannot probably generate enough wind erosion resistant structures (Tatarko, 2001). In the finest textured soils (soils group 3) EF varied between 4 and 35% in both CULT and UNCULT. These results agree with those of Skimore et al. (1975), who found no differences between EF of an uncultivated and an adjacent cultivated silty loam soil of Kansas. These authors attributed such results to the high clay and silt contents of these soils, which ensured a good structure formation and produced no differences between management systems.

The latter results demonstrated that EF is a useful index for the determination of the degradation rate of medium textured soils, as it is highly sensible to management practices. In fine textured soils, clay contents play a dominant role in the formation of structure and management is subordinated to them. Although their significant OC losses due to agriculture (Buschiazzo et al., 1991), they had enough clay to form large aggregates. Sandy soils seem to contain insufficient binding agents (inorganic or organic) to form enough wind erosion resistant aggregates. However as findings of this study are based on only two sites, further research will be in need to achieve a better understanding of mechanisms involved in aggregation processes in these soils.

3.2. Dry aggregate stability (DAS)

Two-way ANOVA analyses showed a strong interaction ($P<0.001$) between site and management for DAS. The results were similar to those of EF, only sites of group 2 determined the interaction effect. Fig. 3 shows that DAS values tend to increase from soils group 1 to 3, in agreement with increasing silt + clay, Alo and OC contents.

Soils group 2 had lower DAS ($P<0.001$) in CULT (74.5%) than in UNCULT (86.5%), indicating that cultivation reduced their capacity to resist wind erosion as compared to their initial state. These results agree with those of Bravo and Silenzi (2000) who found that DAS decreased with tillage intensity associated to OC losses. Zobeck et al. (1995), using the crushing energy method for the determination of

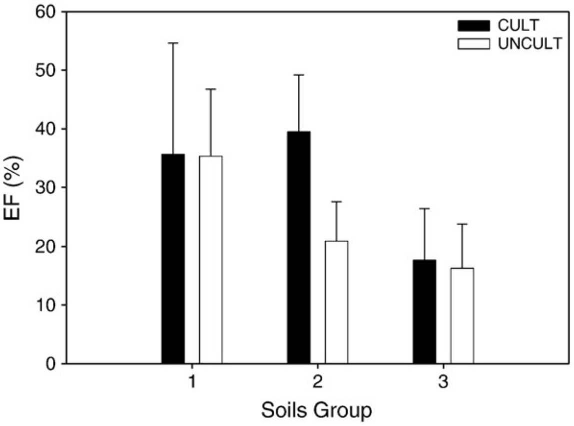

Fig. 2. Erodible fraction (EF) of each soils group and management conditions. CULT = cultivated, UNCULT = uncultivated. Vertical bars represent standard deviation of the means.

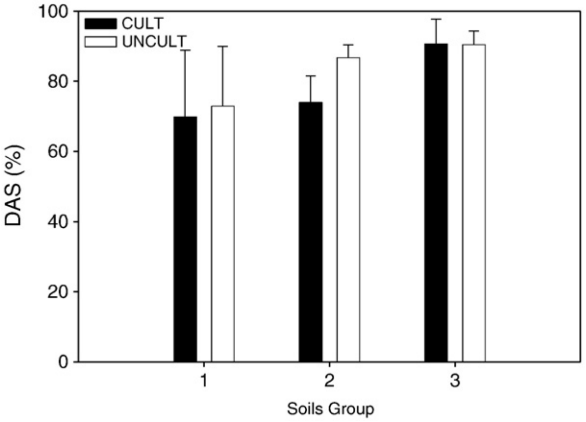

Fig. 3. Dry aggregate stability (DAS) of each soils group and management condition. CULT = cultivated, UNCULT = uncultivated. Vertical bars represent standard deviation of the means.

DAS, found no differences between a cultivated and a grassland sandy loam soil of Texas. These authors attributed the lack of differences between management conditions to the high variability of the used method, as the coefficients of variation (*cv*) varied between 50% and 105%. In our study *cv* of DAS was much lower: 13% in UNCULT and 16% in CULT.

DAS was similar in both management conditions in soils groups 1 and 3 ($P = 0.72$). This agrees with results of Buschiazzo et al. (1995), who found no DAS differences among three soil management systems in soils with S + C contents ranging from 100 to 840 g kg^{-1}. The differences respect to our results in soils group 2 can be attributed to the use of a population of finer textured soils (70%>500 g kg^{-1} of S + C) in that study.

Probably similar and low DAS values of UNCULT and CULT in coarse textured soils (soils group 1) were produced by the low amount of organic and inorganic binding agents, which did not produce stable aggregates. However this result was based on a very small sample population and needs further study.

Soils group 3 exhibited high and similar DAS in both management conditions. Probably, the high DAS values of CULT were produced by their high clay contents, which is a very efficient cementation substance in the studied soils (Buschiazzo et al., 1995). Another process to be considered is the formation of pseudo-aggregates (clods) by compaction by tillage operations. This is a common process in soils with fine textures and low OC contents (Quiroga et al., 1999). Under these conditions DAS can increase by a compression effect which forces the particles into closer proximity and creates a compact unit more resistant in a dry state (Powers and Skidmore, 1984).

Differential behaviour of DAS in different textured soils submitted to different management conditions was described by Eynard et al. (2004) who reported higher DAS values in pasture related to cultivated soils in Ustolls but not in Usterts.

3.3. Relation of FE and DAS with selected soil properties

Fig. 4 shows that EF was related to OC in UNCULT soils. A 40% EF value was reached at OC contents of 6 g kg^{-1}. Below this OC content EF increased sharply, while at higher OC contents EF decreased at slow rates and reached a critical OC value at 100 g kg—^{1}. At this content the first derivate of the function (Δ EF/Δ OC) became lower than 0.01. This high OC content is rare in temperate inorganic soils, and only possible in few virgin soils (Buschiazzo et al., 1991). This means that even when the slope of the relationship decreased when increasing OC contents, EF will be not saturated at normal OC contents in these soils.

Non linear models have not been described in the literature for the fitting between EF and OC, this relationship has been only fitted by linear models (Fryrear et al., 1994; López et al., 2007). A non linear relationship has different slopes over its range. When it has a plateau dynamic it is possible to identify a domain value from which the dependent variable remains almost unchanged. This makes feasible set up critical values or thresholds in empirical derived relations between key soil properties and soil processes.

In CULT soils there was no relationship between OC and EF. Unger (1997) found that OC was not related to the amount of aggregates>0.84 mm (inverse of EF) in a Paleustoll. However he found a positive relationship between the percentage of 0.84–2 mm aggregates and OC concentration on those aggregates and the opposite trend in aggregates size of >18.3 mm. This author suggests that OC plays an important role in the development and stability of 0.84–2 mm dry aggregate size, but it has no effect on aggregates larger than 18.3 mm, since these were clods resulting from tillage operations. That was the possible reason for the negative relationship in UNCULT, where OC enhanced soil structure through aggregation processes even in large aggregates (Yang and Wander, 1998). In CULT soils, data exhibited a large variability due to the mixing of two opposite processes: a positive effect of OC in aggregates of >0.84 mm, and a negative effect by the formation of clods through the increase of compaction susceptibility in fine textured soils.

Fig. 5 shows that DAS correlated positively with OC in CULT and UNCULT soils. These results agree with those of Buschiazzo et al. (1995) who found a logarithmic positive relationship between DAS and OC, indicating that organic cements contribute to form stable dry aggregates by bonding soil particles together (Powers and Skidmore, 1984). A logistic model was the best to fit both relationships between DAS and OC, showing a maximum DAS value of 85% at a critical OC content of 10 g kg^{-1} in CULT and 90% of DAS in 29 g kg^{-1} OC in UNCULT. Above this value, DAS remained high and unchanged. These results are close with those of Buschiazzo (2006) who suggest a critical organic matter value of 3% for DAS in SAP soils. Bravo (1994) found similar results in a Petrocalcic Paleustoll, where DAS remained unchanged above 20 g kg^{-1} OC. Loveland and Webb (2003) stated that no quantitative evidences of a critical OC threshold content were found in temperate soils, but most of the relationships described by these authors were linear. Results showed that sandy soils will never reach the critical DAS value, since OC contents, even in uncultivated soils, are lower than 20 g kg^{-1}. Some finest textured CULT soils seem to diverge from the model, exhibiting high DAS below 20 g kg^{-1} OC. Probably, tillage in such soils with high silt plus clay but low OC contents, induced the formation of denser and abrasion-resistant clods by compression (Powers and Skidmore, 1984).

EF was negatively related to clay contents (Fig. 4). A power equation fitted both variables in UNCULT meanwhile a logarithmic did it in CULT. Similar results were found by López et al. (2001) for soils of a semiarid environment of Spain, and by Chepil (1953b) for soils of US. The latter study found that a decreasing relationship was valid up to clay contents of 270 g kg^{-1}, while higher clay contents produced an EF increment. Probably the difference with respect to our finding was produced by the lack of freeze–thaw cycles in our soils (Leys et al., 1996).

DAS was positively related to clay contents (Fig. 5). An exponential model described this relationship. The critical clay content was 100 g kg^{-1} in UNCULT, meanwhile in CULT the model did not reach a critical condition in the range of clay tested. Skidmore and Layton (1992), using a crushing method, found that DAS was sensitive to clay content up to 250 g kg^{-1} in different soils of Kansas.

Alo contents varied between 370 and 3290 mg kg^{-1}. These high Alo contents are probably related to the chemical weathering of volcanic ashes (Wada, 1977; Buschiazzo et al., 1998). The ashes have become sediment during volcanic eruptions occurred in the Andes since the Pleistocene. The weathering of these ashes can increase the content of amorphous Al oxides in the studied soils (Buschiazzo et al., 1998). EF was related negatively to Alo contents (Fig. 4). An exponential was the best fitting model for this relationship in both managements. EF showed a critical value at an Alo content of 1000 mg kg^{-1}.

DAS was related exponentially to Alo in both managements (Fig. 5), and it became insensitive at an Alo content of 1000 mg kg^{-1}. Several studies demonstrated the positive effect of Al on wet aggregation, especially on microaggregates (Amezketa, 1999). Buschiazzo et al. (1995) found a positive correlation between DAS and crystallized and amorphous Al contents, and identified the amorphous Al compounds as binding substances of silt sized particles. Hepper et al. (2006) found higher amounts of montmorillonite in volcanic ash-enriched soils that those compared soils with low ash contents. It has been demonstrated that soils with mixed clay mineralogy showed more stable aggregates (Denef et al., 2002).

Feo contents affected neither EF nor DAS (Fig. 4 and 5). Similar results were reported by Buschiazzo et al. (1995), and can probably be related to the fact that under acidic soil pedogenesis mineral weathering gives rise to aluminous- rather than to ferric ions. Under these conditions aluminous oxides rather than Fe oxides contribute to aggregates formation (Huygens et al., 2005). Amezketa (1999)

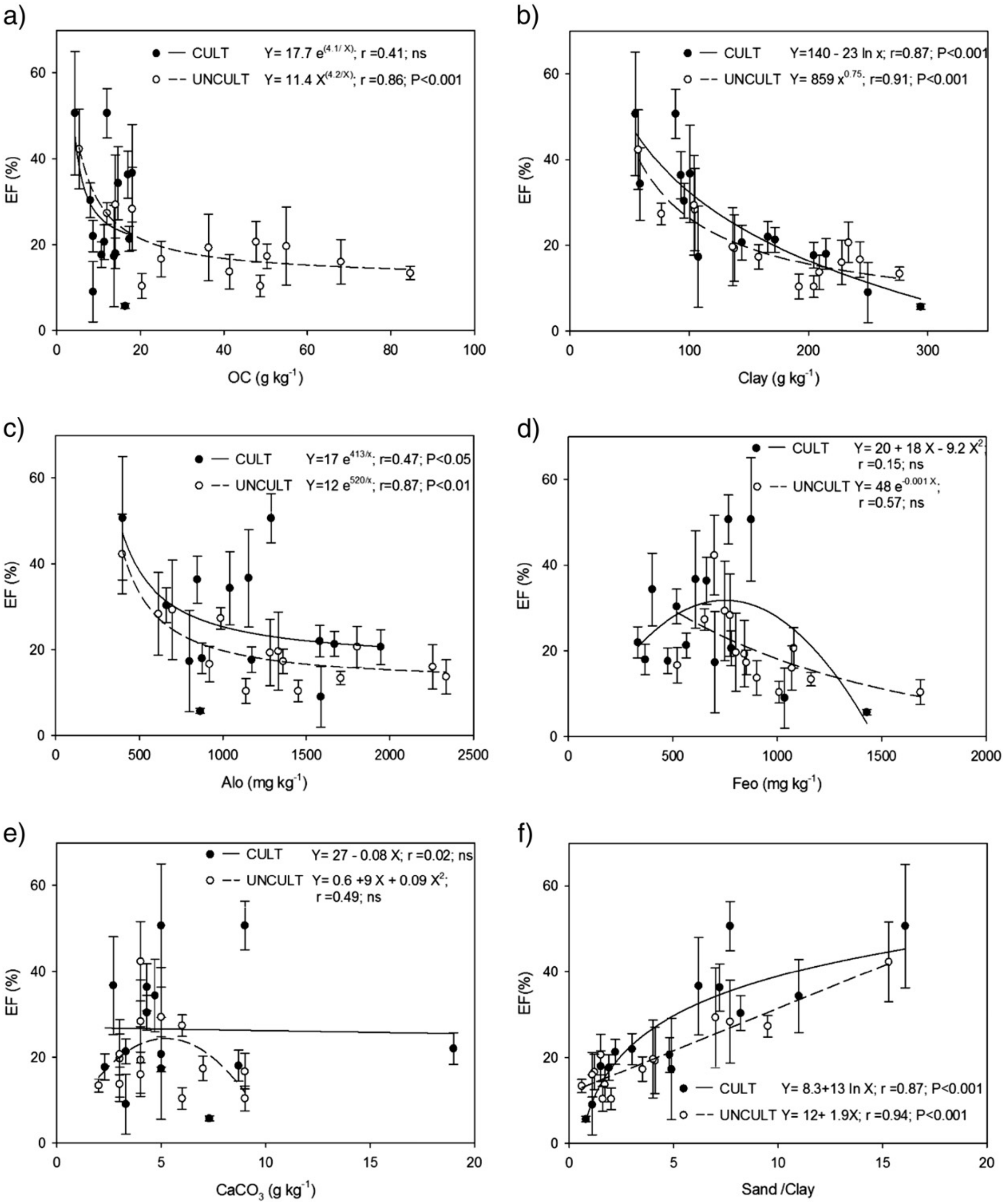

Fig. 4. Relationships between the erodible fraction (EF) and a) Organic Carbon (OC), b) Clay contents, c) Amorphous aluminium oxides (Alo), d) Amorphous iron oxides (Feo), e) Calcium Carbonate ($CaCO_3$) and f) Sand/Clay ratio, in cultivated (CULT) and uncultivated (UNCULT) soils. Vertical bars represent standard deviation of each point ($n = 3$), ns = no significant.

showed that Al polymers are more efficient in forming aggregation than Fe polymers due to their high charge density, which produced stronger clay-polymers attraction forces and higher binding surfaces.

Neither EF nor DAS were affected by $CaCO_3$ contents in the studied soils (Fig. 4 and 5). Even though, these results agreed with those of López et al. (2001, 2007), they disagreed with those of Chepil (1954). Probably, the differences among these findings were due to the different soil population considered in each case: López et al. (2001, 2007) analyzed together soils with a wide range of textures, while Chepil (1954) analyzed soil populations separately, according to their texture.

According to Chepil (1954), lime improved aggregation only in sandy and loamy sand soils. However, in the studied soils there were not any significant relationships between EF or DAS and $CaCO_3$, even when sandy and loam sandy soils of soils group 1 were analyzed separately ($r < 0.25$, $P > 0.05$). Such results can be attributed to the low $CaCO_3$ contents of the soils, as in 95% of the studied soils $CaCO_3$ contents were lower than 10 g kg^{-1}. We think that $CaCO_3$ is not an

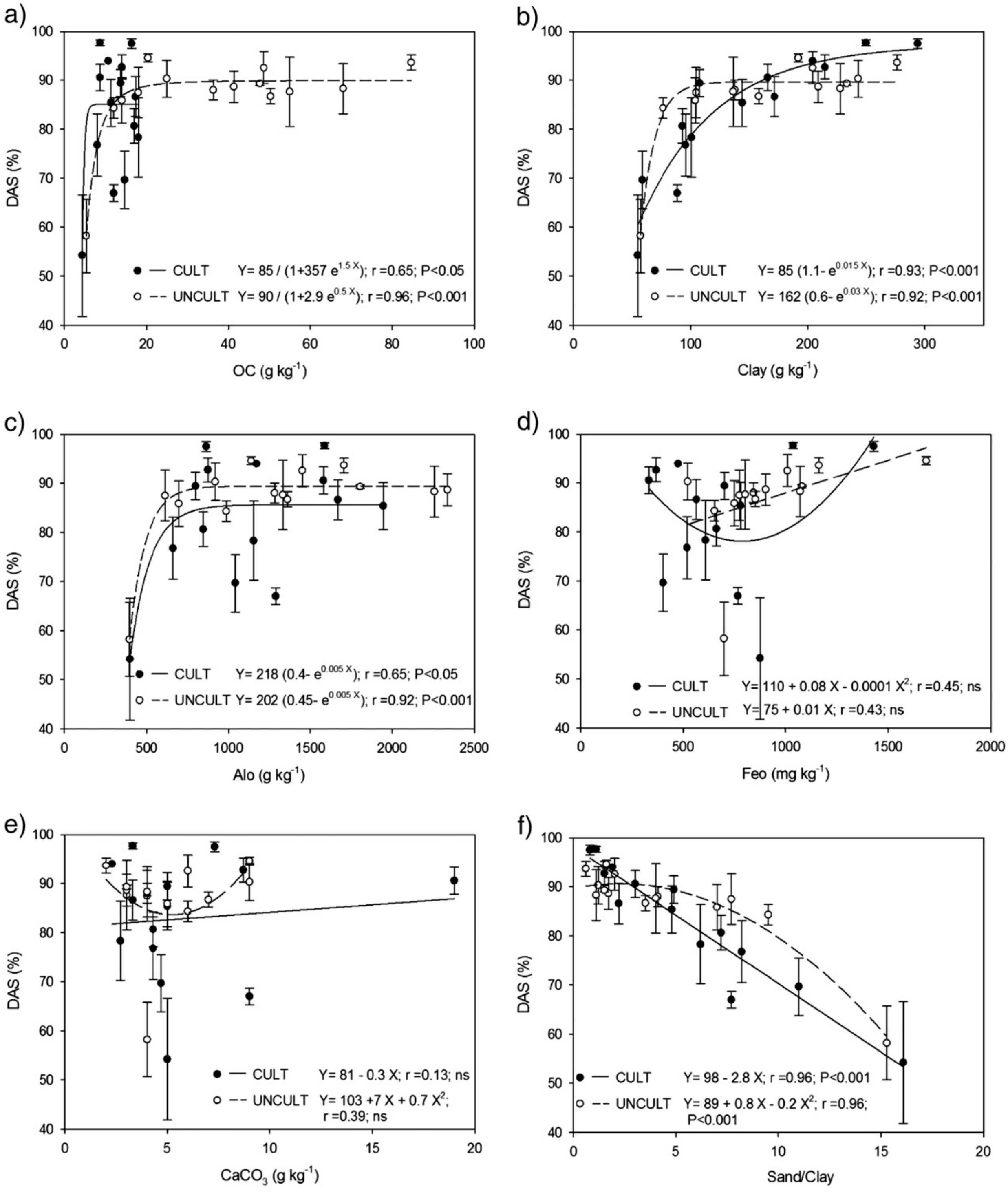

Fig. 5. Relationships between the dry aggregate stability (DAS) and a) Organic Carbon (OC), b) Clay contents, c) Amorphous aluminium oxides (Alo), d) Amorphous iron oxides (Feo), e) Calcium Carbonate (CaCO$_3$) and f) Sand/Clay ratio, in cultivated (CULT) and uncultivated (UNCULT) soils. Vertical bars represent standard deviation of each point ($n = 3$), ns = no significant.

important cementation agent for dry aggregation in A horizons of the studied soils.

EF was related linearly and positively with the sand/clay ratio (S/C) in UNCULT, while a quadratic model explained this relationship in CULT soils. This means that the relationship between EF and texture depends on management. Therefore, it supports the interaction effect between texture and management mentioned above. These results agree with those of López et al. (2001) who found that a quadratic model was the best for explaining the relationship between EF and the ratio sand/(S + C) in cultivated soils of semiarid Spain, and with those of López et al. (2007) who found that EF and S/C were linearly related in cultivated and uncultivated soils of Argentina and Spain. Different fitting curves between EF and S/C for CULT and UNCULT produced a different maximum EF value at sand/clay ratios of 5 to 10. This means that the studied soils are more susceptible to lose their capacity to resist wind erosion when submitted to agriculture.

DAS correlated negatively with S/C. While a quadratic model fitted this relationship in UNCULT, a linear model fitted it in CULT.

Maximum differences between management systems were in the range of 5 to 10 S/C units. Probably, such differences were due to OC losses associated to tillage operations in agricultural soils (Hevia et al., 2007), wich at these textures plays an important role as a binding agent. In finer textured soils (S/C<5), though OC losses occurred, clay contents allowed an increase of DAS by compaction, meanwhile in coarse textured soils (S/C>10), it seems that no differences in DAS can be explained by low clay contents and no significant OC differences between managements (Buschiazzo et al., 1991). However as we have only three soils with S/C ratios >10 we need further investigation in these soils.

4. Conclusions

Both, EF and DAS, showed interaction between management and soil type, especially with texture. This indicates that the effect of management on these parameters will depend on texture. EF and DAS were sensible to management only in medium texture soils exceeding tolerable levels in some cultivated soils.

Medium textured loamy sand soils, with silt plus clay contents ranging from 215 to 500 g kg^{-1}, are able to form large and stables aggregates which are efficient in controlling wind erosion in natural conditions. This is not the case of cultivated soils, which showed fine and weak aggregates due to the loss of organic cementing agents. Management practices which tend to increase organic matter contents and to develop large aggregates can be efficient in controlling wind erosion in these soils.

Fine textured loam and silty loam soils, with silt plus clay contents higher than 500 g kg^{-1}, showed the highest amounts of non erodible and stable aggregates. No differences existed between management systems in these soils, though their OC losses due to tillage (Buschiazzo et al., 1991). This lack of differences was attributed to the presence of high organic and inorganic binding agents in natural soils, and the formation of large and stable pseudo-aggregates (clods) in cultivated soils.

In the studied sandy soils, those with silt plus clay contents lower than 215 g kg^{-1}, the lack of organic and inorganic cementing agents probably produced not enough large wind erosion resistant aggregates, even in natural conditions (Tatarko, 2001). Probably, technologies tending to increase the amounts of organic cementing agents alone will not be effective in controlling wind erosion in these soils. Such goal must be achieved through the use of measures which tend to increase the coverage of the soil surface. The findings of this study were based on only two study sites, therefore, further research is needed to achieve a better understanding of mechanisms involved in aggregation formation in these soils.

In medium textured soils (sand/clay between 5 and 10), clay, Al amorphous oxides and OC contributed to form a stable and wind erosion resistant structure. Under low Alo (<1000 mg kg^{-1}) and OC contents (<10 g kg^{-1}), the capacity of the soil to maintain a wind erosion resistant structure began to decrease drastically, being EF values high and therefore the resistance against wind erosion too low. These empirically derived critical levels should be interpreted as ranges rather than a unique value (Carter, 2002). At clay contents lower than 100 g kg^{-1}, OC and Alo contents regulated the formation of large and resistant aggregates, maintaining the resistance of the soil against wind erosion.

Acknowledgements

This study was financed by the following Argentinean Agencies: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Agencia Nacional de Promoción Científica y Técnica (ANPCyT), Instituto Nacional de Tecnología Agropecuaria (INTA) and Facultad de Agronomía de la Universidad Nacional de La Pampa.

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