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RELATING LOSS OF SOIL FERTILITY TO WATER AGGREGATE STABILITY AND NUTRIENT AVAILABILITY IN MOUNTAIN AGRICULTURAL CALCARIC SOILS

RELATON ENTRE PERTE DE FERTILITÉ, STABILITÉ DANS L'EAU DES AGREGATS ET DISPONIBILITÉ DES ELEMENTS NUTRITIFS DES SOLS CALCAIRES MONTAGNEUX À USAGE AGRICOLE

RELAZIONE TRA PERDITA DI FERTILITÀ, STABILITÀ IN ACQUA DEGLI AGGREGATI E DISPONIBILITÀ DEGLI ELEMENTI IN SUOLI CALCAREI MONTANI AD USO AGRICOLO

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Abstract

We investigated the topsoil from some mountain Regosols for their nutrient status and loss of fertility due to aggregate breakdown, establishing also the relationship between the nutrient losses, the soil characteristics and the aggregates stability. The aggregate stability varied from 57 to 80%. The nutrient losses differed among elements and varied from 20 to 96%. The availability of nutrients directly influenced the quality of nutrient losses, but did not influence the quantity of nutrients lost. K, Mg and Ca were the most susceptible element to the water abrasion (>85% of their total loss was due to water abrasion). Instead for C, N, and partly P, important loss occurred because of the water saturation alone and their losses were related to the aggregates ruptures due to fast wetting (r=0.98, 0.99 and 0.81, respectively). These findings suggest a high vulnerability to soil fertility losses, and that a great depletion can occur even because of rainfall of low intensity, but sufficient to water saturated the topsoil.

Key-words: *erosion; Regosols; nutrients status; fast wetting; water abrasion*

Résumé

Les horizons superficiels des Regosols provenant d'une zone montagneuse ont étés analysés pour d'une part déterminer leur statut nutritif et leur perte de fertilité du à la rupture des agrégats, et d'autre part établir les relations entre la perte des éléments nutritifs, les caracteristiques du sol et la stabilité des agrégats. La stabilité des agrégats varie de 57 à 80%. La perte des éléments nutritifs est différent selon les éléments et varie de 20 à 96%. La disponibilité des éléments nutritifs influence directement la qualité des pertes, mais n'influence pas la quantité des éléments perdus. K, Mg et Ca sont les éléments les plus susceptibles à l'abrasion de l'eau

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(>85% des pertes totales sont dues à l'abrasion de l'eau). Au contraire, pour C, N, et en partie P, d'importantes pertes ont été déjà atteintes pendant la seule phase de saturation des agrégats à l'eau, et leurs pertes sont corrélées à la rupture des agrégats pendant le fast wetting (r=0.98, 0.99 et 0.81, respectivement). Ces données montrent un'élevé vulnérabilité de ces sols à la perte de fertilité et indiquent qu'une importante perte d'éléments nutritifs pourrait intervenir aussi en cas de pluie faible mais dont la quantité d'eau tombée suffirait à saturer l'horizon superficiel. -

Mots clées: *érosion; Regosols; status nutritif; fast wetting; abrasion de l'eau*

Riassunto

In questo studio, i topsoil di alcuni Regosols di un'area montana sono stati investigati per il loro status nutritivo e le perdite di fertilità dovute alla rottura degli aggregati, e le relazioni tra perdita di nutrienti, caratteristiche del suolo e stabilità degli aggregati sono state definite. La stabilità degli aggregati varia da 57 a 80%. La perdita di nutrienti differisce tra gli elementi e varia da 20 a 96. La disponibilità di elementi influenza direttamente la qualità della perdita di elementi nutritivi, ma non la loro quantità. K, Mg e Ca sono i più vulnerabili all'azione abrasiva dell'acqua (>85% della loro perdita totale è dovuta all'abrasione). Invece, per C, N, e parzialmente P, importanti perdite si verificano già a causa della saturazione in acqua degli aggregati e la loro perdita è correlata alla rottura degli aggregati dovuta al fast wetting (r=0.98, 0.99 e 0.81, rispettivamente). Questi risultati suggeriscono un'elevata vulnerabilità di questi suoli nei confronti della perdita di fertilità, e che un grande impoverimento può verificarsi anche a causa di piogge con bassa intensità, ma sufficienti a saturare il topsoil.

Parole chiave: *erosione; Regosols; status nutritivo; fast wetting; abrasione dell'acqua*

Introduction

The soil is the main resource for agriculture and it preservation against deterioration or erosion, and the maintenance of the fertilizing elements for crop production are fundamental.

The soil is a reservoir of essential nutrients characterised by their different status, i.e., by their availability together with their concentration at a certain availability level. The availability of a nutrient in soil is the ease with which the nutrient is taken up by plants, and its concentration is determined by a competition among the plant root system, the soil solution, and soil solid phases (Sposito, 1989). An available element can exist as an ionic solute in the soil solution and/or adsorbed on soil solid phase. The competition for the solvated-ion in the soil solution involves adsorption and complexation with both inorganic and organic ligands. However, large quantities of nutrient elements persist in forms originally present in soil parent material, particularly in poorly developed where soil processes are not sufficiently expressed to strongly influence soil properties (Bockheim and

Gennadiyev 2000), and soil characteristics are largely inherited from the parent material. The elements of parent material become available only slowly through the mineral weathering, and they represent the principal reservoir for the vegetation (Oertli, 2008).

In mountain areas soils are often poorly developed and water erosion has a significant impact on the soil fertility since it involves removal and loss of the topsoil layer, where the available nutrient pools are mainly concentrated, and quickly exhausts the nutrient reserves. Despite the importance of this phenomenon, the literature contains few studies on this subject compared with those that evaluate the physical losses of soil and erosion rates (Romero-Dìaz et al., 2012).

The soils at middle elevation are among the most extensive soils for agricultural use in mountain areas, because climatic condition is not a limiting factor, but a large part of these agricultural soils were affected by water erosion as testified by a low or very low organic matter and nutrients content (Costantini et al., 2004). As such, to connect water effect and nutrient cycles, a greater understanding of the water erosion mechanisms and their consequence on the soil nutrients loss is needed.

Aggregate stability is acknowledged for its importance in the protection against soil loss by water erosion (Bronick and Lal, 2005), and it is defined as to the resistance of the soil particles to the structural rearrangement when exposed to stresses (Cass, 1999). The most common methods for its evaluation are based on Yoder's (1936) wet sieving procedure (e.g., Kemper and Rosenau, 1986; Williams et al., 1966). They quantify the loss of stability caused by wetting (slaking, swelling and dispersion) and the shaking actions (water abrasion). The use of pretreatments has been suggested as a way to elucidate the mechanisms involved in aggregate breakdown (e.g., Hénin et al., 1958; Le Bissonnais, 1990). Le Bissonnais (1996) proposed a method of wet sieving after prewetting with ethanol to limit the breakdown of aggregates due to fast wetting and discriminate between the losses due to wetting and shaking action.

According to Baker and Laflen (1983), nutrients may be lost by water action in three ways: percolation through the soil profile, being dissolved in the runoff water, and adsorption to the sediment carried by the runoff water. During aggregate wet sieving tests, similar processes can lead to the loss of dissolved nutrients and those adsorbed or present in the solid phase.

In this study, we analyse the nutrients contained in the water and in the soil solid phase generate by the aggregate breakdown due to wet sieving procedure, discriminating the losses due to the two main mechanisms of aggregate rupture (i.e., fast wetting and abrasion). The aim of this study is to evaluate the nutrients status and the loss of fertility suffered by some mountain agricultural soils in the northern Italian Appennine and, as the availability of nutrients in the topsoil is expected to directly influences the concentration of these nutrients in the water and soil particulate, we also try to establish a relation between the original characteristics of the soils and the losses by wet sieving. The sampling site is agrarian and since 2004 had known history of organic cultivation, neither nutrients nor organic matter inputs were supplied. The soils developed on calcareous shales. As such, the site is able to provide a natural baseline for nutrients availability and aggregate properties in similar soils and parent materials, as well as yield insight into relationships between loss of soil fertility and water aggregate stability in calcareous mountain regions.

Material and Methods

Study area and soil sampling

Three soil profiles (A, B and C), representative of the some of the most common soil types of agricultural land in the northern Italian Appennine, were described and sampled in the Monte Pastore area (500 m a.s.l.) near to Bologne (44°22' N, 11°08'E). The soil developed on shales and calcilutites (E-R Ambiente, Servzio geologico sismico e dei suoli, 2006). The sampling sites were chosen on a moderate slope (15%). The area has a temperate warm subcontinental climate, the mean annual rainfall is 820 mm and the mean temperatures ranges from 10 to 15°C. The soil moisture and temperature regime was ustic and mesic respectively. According to the World Reference Bases of soil resources (IUSS Working Group WRB, 2006), the soils were classified as Leptic Regosol (site A) and Colluvic Regosols (sites B and C). In Table 1, the main characteristics of soil profiles were reported.

In the study area, since 2004 crops rotation was practised with certified organic wheat, peas, barley and clover. Each year, soil structure was disturbed by tillage with mouldboard plough, working to 20 cm depth, for the control of weeds.

In autumn 2010 after tillage of fields, two pits in each site were dug and soil samples were taken from the 0-20 cm topsoil of each pits.

Main physico-chemical characteristics

Topsoil samples were air-dried and sieved to pass a 2-mm screen obtained the so called <2 mm fine earth fraction. Then, the 1-2 mm aggregates were separated from the fine earth fraction by dry sieving to 1 mm and weighted. Both the <2 mm fine earth and 1-2 mm aggregates fractions were analysed for the main physico-chemical characteristics.

The pH was determined potentiometrically in a 1:2.5 soil to deionised water suspension. The texture was determined by the pipette method after dispersion of the sample with a sodium hexametaphosphate solution (Gee and Bauder 1986). The carbonate content was measured by volumetric analysis of the carbon dioxide liberated by a 6 M HCl solution (Loeppert and Suarez, 1996). The total Fe and Al concentrations (Al_t and Fe_t) were measured by ICP-OES after HNO_3:HCl (1:3) microwave-digestion of sample. The dithionite-citrate extractable Al and Fe (Al_d and Fe_d; Mehra and Jackson, 1960) were determined by ICP-OES.

Nutrient status

The nutrient status were determined in the <2 mm fine earth and 1-2 mm aggregates fractions of the topsoil.

Total organic C (C_{org}) and total nitrogen (N) were determined by dry combustion (Thermo Scientific Lab EA-1110) on carbonate-C free samples. The concentration of soluble elements (Ca_{sol}, Mg_{sol}, K_{sol}, Na_{sol} and P_{sol}) was measured by ICP-OES in a 1:2.5 soil to deionised water suspension, after centrifugation and filtration of the water extracts (van Reeuwijk, 2002). The concentration of exchangeable cations (Ca_{exch}, Mg_{exch}, K_{exch}, Na_{exch}) and the cation exchangeable capacity (CEC) were determined by ICP-OES after exchange with 0.05 N cobaltihexamine chloride solution (Orsini and Rèmy, 1976, modified by Ciesielski and Sterckeman, 1997). The P available (P_{Olsen}) was extracted with 0.5 M sodium bicarbonate solution at pH 8.5 (Olsen and Sommers, 1982) and the P concentration was measured by ICP-OES. The total element concentrations (Ca_t, Mg_t, K_t, Na_t, and P_t) were measured by ICP-OES after HNO_3:HCl (1:3) microwave-digestion of sample.

Table 1. *Description of soil profiles according to Schoeneberg et al. (2002)*

Site	**Horizon**	**Depth**	**Munsell colour**	**Mottles colour**	**Structure** [a)]			**Texture** [b)]	**Roots** [c)]		**WRB soil classification**
		cm	**dry**		**G**	**S**	**T**		**Q**	**S**	
A	Ap	0-24/25	2.5Y 3/2	-	2	co	sbk	c	2	vf,f	**Leptic Regosol**
	CB	24/25-32/33	Gley 5/5GY, 10YR 7/8	-	1	co	sbk	cl	1	f	
	CR	33-70+	Gley 5/5GY	-	1	co	sbk	cl	0	f	
B	Ap$_1$	0-28/35	7.5YR 3/1	-	3	co	sbk	c	2	vf,f	**Colluvic Regosol**
	A$_{p2}$	28/35-60/65	10YR 3/2	-	3	vco	sbk	c	1	f	
	Ab	60/65-80	10YR 3/2	-	2	m	sbk	cl	0	f	
	C	80-95+	2.5 YR 4/3	-	2	m	sbk	cl	0	f	
C	Ap1	0-25/28	10YR 4/4	-	2	co	sbk	c	2	vf,f	**Thapto-Endogleic Colluvic Regosol**
	Ap2	25/28-54/60	2.5Y 5/4	-	2	co	sbk	cl	1	f	
	Ab	54/60-67/70	10YR 4/3	-	2	co	sbk	cl	0	f	
	Bgb	67/70+	10YR 5/4	10YR5/8, Gley2.5/10BG	2	co	sbk	cl	0	f	

[a)] structure: (**G**) Grade, 1=weak, 2=moderate; 3=strong; (**S**) Size, m=medium, co=coarse, vco=very coarse; (**T**) Type, sbk=subangular blocky

[b)] texture: c=clay, cl= clay loam

[c)] roots: (**Q**) Quantity, 0=very few, 1=few, 2=common; (**S**) Size, vf=very fine, f=fine

Aggregate stability and losses of nutrients

For the standard test of aggregate water stability, 10 g of the 1–2 mm aggregates were placed in 0.2-mm sieves and gently immersed in water for 10 min (fast wetting). Thereafter, the aggregates were wet sieved at 60 cycles min^{-1} in beakers containing deionized water (water abrasion). The sieving time was set at 10 min. After the completion of the sieving period, the material remaining in the sieves was oven dried at 40°C and weighted. The water aggregate stability (WAS_T) related to fast wetting and water abrasion was determined as follows:

$$WAS_T = \frac{weight\ retained - weight\ of\ coarse\ sand}{total\ sample\ weight - weight\ of\ coarse\ sand} \cdot 100$$

The coarse sand was determined on the 1–2 mm aggregate fraction after H_2O_2 oxidation. The percentage of aggregate total loss ($Loss_T$) was calculated as 100-WAS_T. To test the wet cohesion independently from the breakdown due to water saturation (i.e., fast wetting) and thus to determine the wet aggregate stability against the abrasion, 10 g of the 1–2 mm aggregates were placed in sieves and gently immersed in 95% solution of ethanol for 10 min (Le Bissonnais, 1996) and then wet sieved for 10 min. The material remaining in the sieves was oven dried, weighted and the stability indexes related to the abrasion (WAS_{ABR} and $Loss_{ABR}$) were calculated. From the difference between WAS_T and WAS_{ABR}, or $Loss_T$ and $Loss_{ABR}$, we calculated the breakdown caused by fast wetting (WAS_{FW} and $Loss_{FW}$, respectively; Falsone and Bonifacio, 2006).

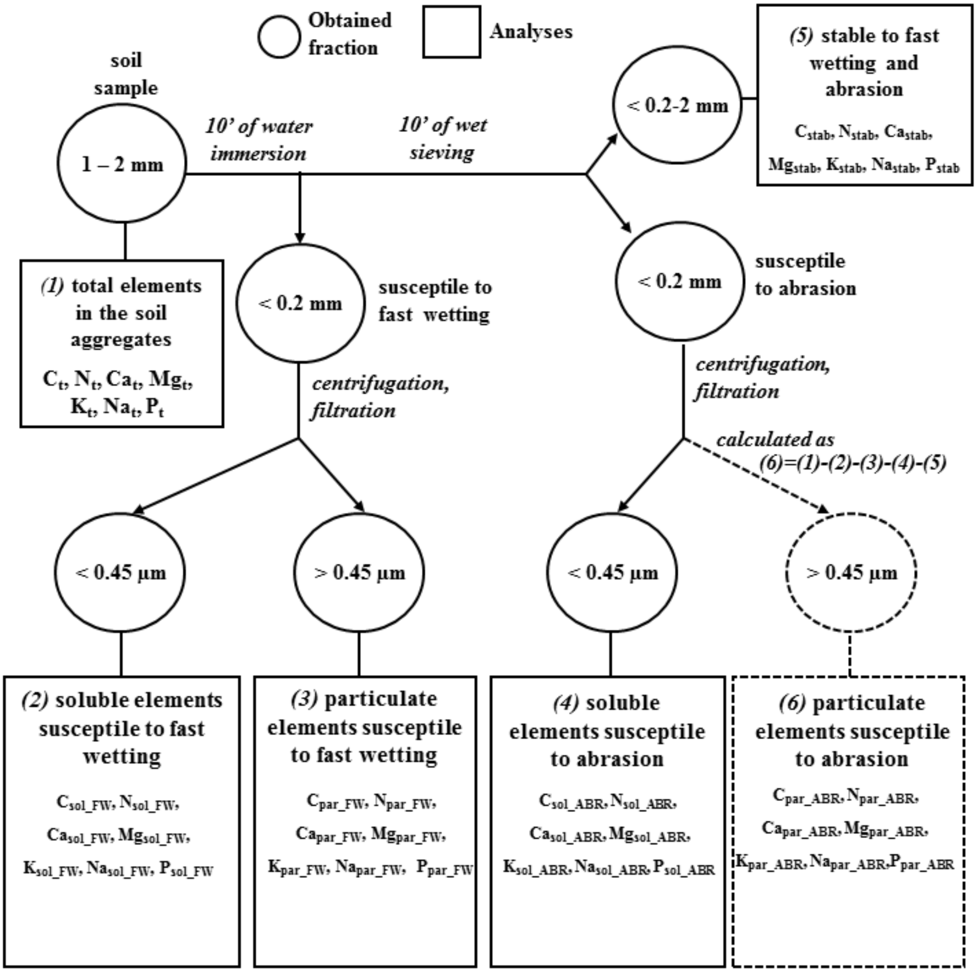
From the standard test of aggregate stability, we determined the loss of C, N, P, K, Ca, Mg, and Na due to fast wetting and water abrasion (Figure 1). The excess water in beakers, containing the material passed through the sieve after 10 minutes of water immersion (i.e., elements losses due to fast wetting) was centrifuged at 10.000 rpm and filtrated <0.45 µm to separate the liquid and solid phases. In the liquid phase, the organic C and N lost as soluble forms (C_{sol} and N_{sol}) were measured by a TOC-TN analyzer (Shimadzu, TOC-V/CPN), the elements in aqueous solution (P_{sol}, K_{sol}, Ca_{sol}, Mg_{sol}, Na_{sol}) were determined by ICP-OES. In the solid phase, the organic C and N lost as particulate (C_{par} and N_{par}) were determined by dry combustion (Thermo Scientific Lab EA-1110) on carbonate-C free samples and element concentrations (P_{par}, K_{par}, Ca_{par}, Mg_{par}, Na_{par}) were measured by ICP-OES after HNO_3:HCl (1:3) microwave-digestion of sample (Figure 1). The nutrients lost were labelled as fast wetting susceptible (FW). An aliquot of the excess water in beakers, containing the material passed through the sieve after 10 minutes of wet sieving (i.e., elements losses due to abrasion), was centrifuged at 10.000 rpm and filtrated <0.45 µm to isolate the liquid phase. The C, N, P, K, Ca, Mg, and Na lost as soluble forms were measured as described above and labelled as abrasion susceptible (ABR; Figure 1). On the remaining material after 10 minutes of water immersion and 10 minutes of wet sieving, we determined the organic C and N content by dry combustion (C_{stab} and N_{stab}), the element concentrations (P_{stab}, K_{stab}, Ca_{stab}, Mg_{stab}, Na_{stab}) after HNO_3:HCl (1:3) microwave-digestion of sample, and they represents the element stable to both fast wetting and abrasion. From the difference between the nutrients concentration in the sample before the stability tests, the elements stable, the elements susceptible to fast wetting and the soluble elements susceptible to abrasion, we calculated the elements losses as particulate due to abrasion (Figure 1).

Results

Fine earth and aggregate properties

The fine earth fraction from the topsoil was moderately alkaline, with a calcium carbonate contents varying from 37 and 88 g kg^{-1} (Table 2). The content of organic C was homogenous among the sites (from 13.2 to 18.1 g kg^{-1}) as well as the C_{org}/N ratio (from 6.8 to 8.0).

Figure 1. *Scheme of the sequence of fractionation of nutrients loss*



The pedogenetic Al oxides content was very low, as was to be expected given the low degree of soil development, and represented only the 3% of the total Al content (Al_d/Al_T). The amount of Fe_d represented the 22% of the total Fe content without any differences among sites.

The amounts of aggregates was about 40% of the fine earth (Table 2). Their texture was clay. The aggregate properties were very similar to those of corresponding fine earth fraction and they were enriched neither in organic C nor in $CaCO_3$ or Fe_d with respect to the fine earth.

As regards the nutrients content, the N value of both fine earth and aggregates was on the average 2 g kg^{-1} and was parallel to that of organic C, suggesting that N in

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inorganic form (available to plants) was lower than organic form. The organic C content also affected the CEC (r^2=0.80, p<0.01).

Table 2. *Fine earth (<2 mm) and aggregate (1-2 mm) properties of the topsoil. In parentheses, the standard deviation is given. Coefficient of variation is always lower than 10% with the exception of $CaCO_3$, whose coefficient of variation is up to 42%*

Fraction	site	pH	$CaCO_3$	C_{org}	N	C_{org}/N	Fe_d	Al_d	Fe_d/Fe_t	Al_d/Al_t
			g kg^{-1}				g kg^{-1}			
<2 mm	A	8.3	88	13.2	2.0	6.8	12.7	2.1	0.22	0.03
	B	8.3	49	18.1	2.5	7.4	10.4	1.6	0.18	0.02
	C	8.4	37	14.4	1.8	8.0	12.8	1.7	0.24	0.03

Fraction	site	Ca_{sol}	Mg_{sol}	K_{sol}	Na_{sol}	P_{Olsen}	CEC	Ca_{exch}	Mg_{exch}	K_{exch}
		mg L^{-1}				mg kg^{-1}	$cmol_c kg^{-1}$			
<2 mm	A	24.7	2.7	3.6	3.3	2.24	29.3	25.9	2.3	0.3
	B	26.6	2.5	2.2	5.0	2.51	35.2	32.4	2.3	0.3
	C	33.3	3.4	1.9	7.4	2.26	34.7	30.8	2.4	0.3

Fraction	site	% of aggregates	$CaCO_3$	C_{org}	N	Fe_d	sand	coarse silt	fine silt	clay
			g kg^{-1}							
1-2 mm	A	39.1	110	12.3	1.8	11.4	227	65	305	398
	B	42.4	60	17.6	2.3	11.7	208	64	317	421
	C	40.0	50	15.2	2.0	13.7	214	71	314	407

Fraction	site	Ca_{sol}	Mg_{sol}	K_{sol}	Na_{sol}	P_{Olsen}	CEC	Ca_{exch}	Mg_{exch}	K_{exch}
		mg L^{-1}				mg kg^{-1}	$cmol_c kg^{-1}$			
	A	35.3	4.1	3.1	4.5	2.18	30.0	25.5	2.0	0.3
1-2 mm	B	31.0	2.7	2.3	5.7	2.46	36.1	31.5	2.2	0.3
	C	29.4	3.0	1.8	5.8	1.90	35.1	31.3	2.5	0.3

The pools of the P, K, Ca, Mg and Na showed that the distribution between easily available form (i.e, soluble) and exchangeable form varied according to the element species and again in a similar way between the fine earth and aggregates (Table 2 and Figure 2). Given the presence of calcareous materials, the available P was very low and represented less than 1% of total P (Figure 2). Also the K and Mg were mainly present as total form, and only the 2-3% were available (of which 0.7% was as soluble form). The available Na was as Na soluble, and it accounted for 15-30% of the total Na; in contrast Ca was mainly as exchangeable form (13-33% of total Ca).

Aggregate stability and soil losses

The wet aggregate stability index (WAS_T; Table 3) was 57% in the A site and about 80% in the B and C sites. The A site was more fragile than B and C sites both to the fast wetting and water abrasion, as showed by the amount of soil lost by fast wetting and abrasion ($Loss_{FW}$ and $Loss_{ABR}$, respectively; Table 3). However, the relative percentage of abrasion, thus the incidence of water abrasion on the total soil losses, showed that for all the sites the most relevant mechanism of aggregate breakdown was the abrasion (always >60%).

The total loss of each element was calculated from the sum of the concentration of the nutrient lost as soluble and particulate due to the fast wetting and the water

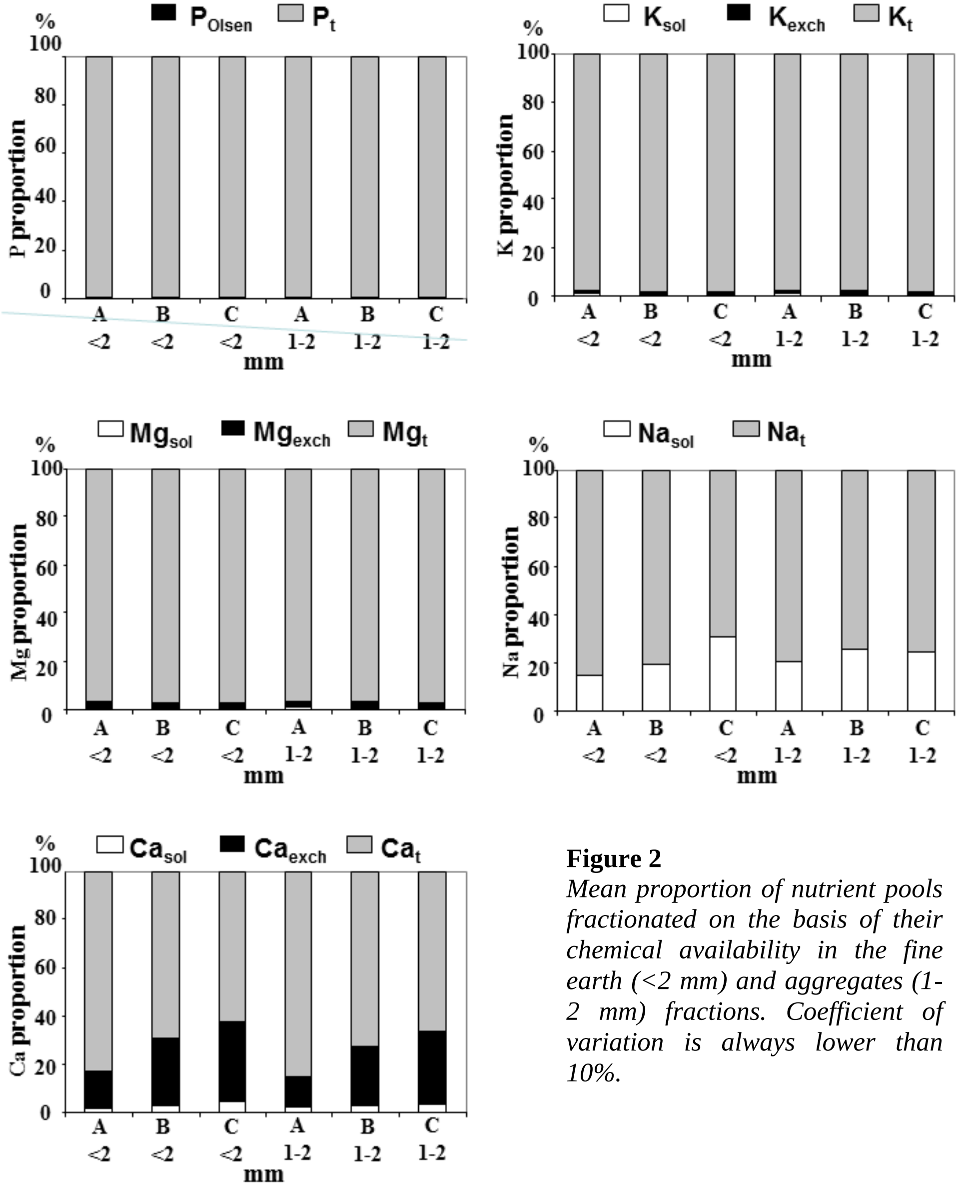

Figure 2
Mean proportion of nutrient pools fractionated on the basis of their chemical availability in the fine earth (<2 mm) and aggregates (1-2 mm) fractions. Coefficient of variation is always lower than 10%.

abrasion (Table 4). On the average, the total loss of C from the aggregates was 3.1 g kg^{-1} of the initial mass of aggregates, the loss of N was 0.4 g kg^{-1}, P was 140 mg kg^{-1}, and K 2.0 g kg^{-1} (Table 4).

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Table 3. *Aggregate stability indexes. In parentheses, the standard deviation is given. Coefficient of variation is always lower than 10%-*

site	WAS$_T$ %	Loss$_T$ %	Loss$_{FW}$ %	Loss$_{ABR}$ %	RP$_{ABR}$ %a)
A	57.3	42.7	16.6	26.1	61.4
B	80.9	19.1	2.4	16.7	87.4
C	79.5	20.5	4.4	16.1	78.6

a) RP$_{ABR}$: relative percentage of water abrasion, calculated as the ratio between Loss$_{ABR}$ and Loss$_T$

Table 4. *Fractionation of nutrients pools on the basis of their physical stability. Data are expressed as g or mg of nutrient kg^{-1} of initial mass of aggregates*

nutrient	nutrient pools a)	A		B		C		Average	
		loss of nutrient pool	Σ total loss b)	loss of nutrient pool	Σ total loss	loss of nutrient pool	Σ total loss	loss of nutrient pool	Σ total loss
C g kg^{-1}	C_{sol_FW}	0.26	4.12	0.21	1.43	0.53	3.71	0.33	3.09
	C_{sol_ABR}	0.28		0.28		0.22		0.26	
	C_{par_FW}	2.04		0.43		0.65		1.04	
	C_{par_ABR}	1.53		0.51		2.31		1.45	
N g kg^{-1}	N_{sol_FW}	0.03	0.55	0.02	0.21	0.53	0.38	0.19	0.38
	N_{sol_ABR}	0.10		0.03		0.02		0.05	
	N_{par_FW}	0.32		0.06		0.09		0.16	
	N_{par_ABR}	0.10		0.10		0.24		0.15	
P mg kg^{-1}	P_{sol_FW}	bdl	251	bdl	68	bdl	110	-	140
	P_{sol_ABR}	bdl		bdl		bdl		-	
	P_{par_FW}	105		16		29		50	
	P_{par_ABR}	144		47		79		90	
K g kg^{-1}	K_{sol_FW}	0.04	3.80	0.02	0.73	0.06	1.28	0.04	1.94
	K_{sol_ABR}	0.04		0.14		0.07		0.08	
	K_{par_FW}	0.71		0.23		0.42		0.45	
	K_{par_ABR}	3.01		0.69		1.46		1.72	
Ca g kg^{-1}	Ca_{sol_FW}	0.19	7.88	0.23	10.61	0.18	9.94	0.20	9.47
	Ca_{sol_ABR}	0.65		0.65		0.62		0.64	
	Ca_{par_FW}	1.25		0.53		1.69		1.15	
	Ca_{par_ABR}	5.79		9.20		7.46		7.48	
Mg g kg^{-1}	Mg_{sol_FW}	0.02	5.02	0.01	0.66	0.02	1.27	0.02	2.31
	Mg_{sol_ABR}	0.04		0.05		0.04		0.04	
	Mg_{par_FW}	0.20		0.26		0.45		0.30	
	Mg_{par_ABR}	4.77		0.67		0.76		2.06	
Na g kg^{-1}	Na_{sol_FW}	0.03	0.45	0.07	0.58	0.01	0.63	0.04	0.56
	Na_{sol_ABR}	0.19		0.27		0.24		0.23	
	Na_{par_FW}	0.23		0.24		0.39		0.29	
	Na_{par_ABR}	bdl		bdl		bdl		-	

a) Nutrient pools codes reported according to those in Figure 1

b) Σ total loss: sum of the concentration of the loss of nutrient pools bdl: below detection limit

The losses of the other elements were: Ca 9.5 g kg^{-1}, Mg 2.3 g kg^{-1}, and Na 0.6 g kg^{-1}. With respect to the initial element concentration in the aggregates, the losses greatly varied among nutrients: they accounted for 20% of C, 27% of N, 22% of P, 24% of K, 33% of Ca, 22% of Mg and 96% of Na. This is evident in all sites, independently from their aggregate stability, suggesting a nutrient species effect.

The loss of nutrients and total loss of aggregates (Loss$_T$) were significant correlated in the case of P, K and Mg (0.93, 0.92 and 0.93, respectively; Table 5), while there was no correlation between the amounts of the total C, N, Ca, Na loss and Loss$_T$.

The same was found for $Loss_{ABR}$ and, although for all sites the most relevant mechanism of aggregate breakdown was the water abrasion, the total fertility loss due to the water abrasion was not significant related to the $Loss_{ABR}$ (Table 5). This was due to the different behaviour among nutrients. In fact, the amount of element lost due to the abrasion (soluble and particulate) varied among nutrient species (Table 4), and it accounted for >85% of the total loss for K, Ca and Mg, but <55% for C, N and Na. The abrasion affected in an intermediate way the loss of P (64% on average). Consequently, our findings pointed to relatively high losses of C, N, Na, and partly of P, due to fast wetting even if the incidence of fast wetting on the total soil aggregates losses was low.

In the case of C and N, the loss of fertility due to fast wetting was related to the amount of aggregates lost during water immersion ($Loss_{FW}$; r=0.99, Table 5). The same happened for P (r=0.81, Table 5).

As regards elements form, all the nutrients were mainly lost as particulate (always >80% of the total loss), with the exception of N and Na for which the loss as soluble form was high (on the average 63 and 48% of the total loss, respectively; Table 4). However, if we took into account the different nutrients pools on the basis of their initial chemical availability (i.e., soluble, exchangeable and total elements), the amount of loss of any nutrient was not related to the initial element content in the aggregates.

Table 5. *Pearson's coefficient correlation (r) among loss of aggregates due to different aggregate breakdown mechanism (i.e., total breakdown – T, water abrasion – ABR, and fast wetting – FW) and the loss of nutrient (C, N, P, K, Ca, Mg, Na and total) due to the same mechanisms.*

total breakdown			water abrasion			fast wetting		
Aggregate loss	element loss a)	r	Aggregate loss	element loss b)	r	Aggregate loss	element loss c)	r
$Loss_T$	C	0.447	$Loss_{ABR}$	C	0.152	$Loss_{FW}$	C	0.976**
	N	0.786		N	-0.069		N	0.996**
	P	0.932**		P	0.909*		P	0.813*
	K	0.915*		K	0.857*		K	0.767
	Ca	-0.247		Ca	-0.217		Ca	0.408
	Mg	0.934**		Mg	0.769*		Mg	-0.196
	Na	-0.379		Na	-0.729		Na	0.066
	Σ total	0.563		Σ total	0.446		Σ total	0.735

a) element loss= $element_{sol\_FW}$+ $element_{sol\_ABR}$+ $element_{par\_FW}$+ $element_{par\_ABR}$

b) element loss= $element_{sol\_ABR}$+ $element_{par\_ABR}$

c) element loss= $element_{sol\_FW}$+ $element_{par\_FW}$

Σ total: sum of the element losses; **: p<0.01; *: p<0.05

Discussion

Nutrient status

The studied soils were Regosols, thus very weakly developed soils marked by incipient soil formation whose characteristics were largely inherited from parent material (IUSS Working Group WRB, 2006). The aggregates of the three studied sites did not differ in term of chemical properties from the fine earth fraction, confirming that chemical properties of the 1-2 mm aggregates well represent those of bulk soil.

The amount of total P was in the usual reported range of soil P (from 500 to 800 mg kg^{-1}; Stevenson, 1986) and it represented about 99% of the P in the soils. Due to calcareous origin of soils, the soil pH was above the pH of insolubility of Ca phosphates, therefore the P plant-available form was low, and soil P mainly occurred as insoluble form (Sims and Pierzynski, 2005). Parent material composition strongly influenced also soil cation nutrient status: the soil solution and exchangeable sites were Ca-dominated, whereas Mg and K in soil solution and to exchange sites accounted for <3%. Similar results were found by Stutter et al. (2003) that investigated the content of exchangeable base cations in soils derived from different parent material, ranging from acidic granite to basic limestone. They found high content of Ca and low of Mg in calcareous soils, showing a close relation to the parent material. Among the major nutritional cation in soil, the available K accounted for very small proportions of the total K. The concentration of K in the soil solution, which was in the reported range for agricultural soil of temperate regions (from 2 to 5 mg l^{-1}; Haby et al., 1990), was too low to meet the requirement of K by a crop during growing season (Huang, 2005). With the exception of Ca, the other element inherited from parent material were thus few available. The content of organic C in these soils was also low and affected the organic N fractions and the cation exchangeable capacity of these soils. Therefore, in these soils organic matter control the largest reservoir of potentially available N in soils (Stevenson, 1994) and the concentration of available cations (Sposito, 1989). Therefore, low organic C content suggested a low availability of these soil nutrients. Thus, in addition to soil development degree and parent material, also the agricultural use and soil organic matter management further affected the nutrient status in the studied soils. Neither nutrients nor organic matter inputs were supplied and the organic C in these soils derived totally from the remains of plants.

Relation among soil original characteristics, water aggregate stability and loss of soil fertility

On the basis of chemical availability of nutrients, it was expected high losses of P, K, Ca and Mg as particulate, and high loss of Na as soluble form. Of all the nutrients required for plant growth, N is by far the most mobile and subject to greatest loss form the soil system (Stevenson, 1994). It is well known that in agroecosystems a great amount of N is lost by leaching, mainly as NO_3^-, but also as dissolved organic N (McLauchlan, 2006). Therefore, even if we did not make any speciation of N, we expected a certain loss of N as soluble form. This initial hypothesis was partly confirmed by the data of loss of fertility. In fact, as regards the quality of losses, N and Na had great losses as soluble forms. On the contrary the other nutrients were mainly lost as particulate. However, from the quantitative point of view, the loss of nutrients was not related to the initial concentration of nutrients in the aggregates. We found instead strong links between the loss of aggregate mass and nutrient losses.

A high proportion of C was lost during fast wetting, and the amount of C lost was related to the quantity of solids released, suggesting that C-rich materials are lost immediately. It is well known that soil organic C acts as a binding agent and as a nucleus in the formation of aggregates, affecting their stability (Bronick and Lal, 2005) and therefore the losses of C-rich materials are often limited. However, in agricultural soils, tillage disrupts soil aggregates, lowering soil organic C positive effects, and enables soil erosion (Plante and McGill, 2002). As a consequence, organic C is lost through erosion and transferred downslope or to the water (McLauchlau, 2006). In our studied soils, the C was lost mainly as particulate, therefore the risk of C transfer from soil system to the water seemed to be of few relevance. On the contrary, a great amount of N was lost as soluble form. These findings partly confirmed our initial hypothesis on fertility losses formulated on the basis of the chemical data, however, also for N, the loss was linked to the amount of solids released during fast wetting. Therefore, C and N-rich materials were lost immediately due to the wetting alone. The P loss also partly confirmed the initial hypothesis: P was lost as particulate, because of its association with soil particles (Sims and Pierzynski, 2005). We also found a good correlation between the release of P and the aggregates losses, both due to fast wetting and abrasion. It could thus suggested that part of P-rich materials are lost immediately and that additional material broken down during wet sieving further contributes to P loss.

As expected from the chemical data, particulate forms also prevailed in the loss of K, Mg and Ca. Over the life cycle of a field crop, most of the K, Mg and Ca would be supplied by ions absorbed to the exchange complex of soil particles (Hossner, 2008). Therefore, both unavailable and available forms of basic cation were lost during aggregate breakdown. Water abrasion mainly contributed to the loss of these elements, and K and Mg released were related to the loss of aggregates. This suggested that the loss of K, Mg and Ca occurred mainly during wet sieving, and that the materials released are K and Mg-rich.

Even if Na is not among the chemical elements essential to plant growth in soil, during the aggregate breakdown process it was noted that its behaviour greatly varied from those of the other basic cations. First of all, about 50% of Na was lost as soluble form.. Moreover, Na was quite totally lost. It is often reported the worsening effect of Na on the soil structure properties (Bronick and Lal, 2005): the Na^+ is a highly dispersive agent resulting directly in the breakdown of aggregates and indirectly affected aggregation; in soil solution and at exchange sites Na contributes to repulsive charges that disperse soil particles. In our soils, it could be possible that particle surrounded by Na^+ were preferentially detached or dispersed and consequently Na was preferentially lost. Large Na loss occurred during fast wetting, probably because dispersion results from the reduction of attractive forces between colloidal particles during wetting (Emerson, 1967; Sumner and Stewart, 1992).

Conclusions

With the exception of Ca, the studied soils were poor in available nutrients. The type of parent material on which they develop, the weak degree of their evolution

and their agricultural use affected the soil fertility status.

The availability of nutrients in the topsoil directly influences the quality of nutrients losses, but did not influence the quantity of nutrients lost. This latter was instead affected by the severity of aggregate breakdown due to water saturation and/or water abrasion. However, the mechanisms of aggregate breakdown affected the amount of loss of fertility in a different way among nutrients. In particular P, K and Mg were the most susceptible to water abrasion. Instead C, N and P also were mainly susceptible to wetting, and important loss C, N and P occurred during water immersion.

These findings suggest a general high risk of soil nutrient depletion, and that even rainfall of low intensity, but sufficient to water saturated the topsoil, may lead to further decrease in the fertility status of these soils. The protection of the surface is crucial in these soils. The preservation of soil cover might help in this sense by acting as a mechanical barrier against rapid soil saturation and abrasion energy of soil water.

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