

SOIL ORGANIC CARBON POOLS AND FORMS IN FOREST ANDOSOLS OF THE CANARY ISLANDS: SOIL ERODIBILITY AND CARBON LOSSES BY EROSION

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Abstract

The objective of this paper is:

- to know the content and forms of soil organic carbon (SOC) in andosols and andic soils under evergreen forest vegetation (laurel and heather forest)
- to know the role of organic matter in aggregate stability and resistance of andosols to water erosion, and
- to know the losses of SOC that are produced by water erosion in Andosols after deforestation and the forms of organic carbon most affected by these losses.

The study has been performed in a sampling area of some 40 km² in the Garajonay National Park (La Gomera, Canary Is.). Predominant andosols in this area (Melanudands, Fulvudands and Hapludands) have been grouped in two main categories: allophanic and non-allophanic (or organomineral) andosols.

A total of 163 sampling sites were studied and soil samples were collected at each in the first 30-40 cms at 3 randomly distributed sampling points.

In the soil samples sieved through 2mm-mesh, were determined: Walkley-Black soil organic carbon (SOC), pyrophosphate extractable SOC, Fe and Al, potassium sulphate extractable SOC, dissolved SOC and acid oxalate extractable Fe, Al and Si. In addition, the following analyses were performed: fulvic and humic acids, K-factor of USLE and aggregate stability by disaggregation and water-drop tests.

The studied andosols present a high capacity to accumulate carbon (up to 14.5±5.9 kgCm⁻², 113 gCkg⁻¹), a high percentage of which (57.2 per cent) is found in pyrophosphate extractable forms (8.3±3kgCm⁻²), that is, complexed with the active forms of Fe and Al. The dissolved organic carbon in these soils is around 112.4±44.7 gL⁻¹. Non-allophanic (organomineral) andosols tend to accumulate more organic C (with a prevalence of stable adsorbed forms), related to allophanic andosols (that have higher amounts of non-pyrophosphate extractable organic C).

Raindrop impact seems to be the only important disaggregation mechanism in non allophanic andosols, although it is frequent in both types of soils and related to the content in pyrophosphate extractable organic carbon. The disaggregation due to aggregate humectation is absent from non allophanic andosols and is characteristic of allophanic andosols stabilized by allophane-humus complexes.

In order to assess the rates of soil organic carbon loss by water erosion in forest allophanic andosols, a study was performed in experimental erosion plots. Soils occurring on them are classified as Ultic Melanudands (allophanic Andosols). The mean soil loss by interrill erosion in these soils is 9.6 t ha⁻¹ yr⁻¹, with a runoff percentage of 13.0 per cent and a rain erosivity index, according to USLE's R factor of 640 Mjmmha⁻¹h⁻¹. Soil samples have been collected from the top layer (0-5 cms) on the bare soils. In the sample of soil sieved through 2-mm mesh, were determined the same parameters as above. These determinations have also have made in sediment samples.

Important losses of organic carbon in these soils are caused by erosion (114.4 gC m⁻²yr⁻¹), which are fundamentally bonded to the solid phase since DOC losses in runoff water are negligible (1.03 gC m⁻²yr⁻¹).

Although complexed forms of organic carbon predominate at the soil surface as allophane-Al-humus or Al-humus complexes (73.3 per cent of total soil organic carbon), the predominating form in the sediments corresponds to non pyrophosphate extractable and non complexed forms of organic carbon (53.4 per cent).

Key words: Andosols, Canary Islands, Soil Organic Carbon, Soil erodibility, Andic properties, Eroded carbon

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Introduction

Volcanic ash soils and, more concretely, Andosols (Soil Survey Staff, 1999) are characterized by a high organic carbon content (90 to 200-300 gkg⁻¹) that gives place to very dark-coloured humic surficial horizons (Nanzyo et al., 1993; Kimble et al., 2000).

This high organic carbon content is attributed to the fact that the organic matter in these soils is stabilized by short-range ordered minerals (allophane, imogolite, ferrihydrite), which have a large specific surface capable of adsorbing organic molecules (Schnitzer, 1978, Oades et al., 1989, Parfitt et al., 1997) or by the formation of Al-humus complexes (Dahlgren et al., 1993). In both cases, SOC becomes highly resistant to microbial attack, such that the mean residence time of organic carbon in Andosols is very high and the turnover times of organic carbon are very low (Saggar et al., 1994).

On the other hand, Andosols are characterized by a structure with highly stable crumble and granular microaggregates (0.1 nm-1 µm to 1-3 mm) (Warkentin and Maeda, 1980) where SOC, in the form of organomineral and organometallic complexes, is physically protected from microbial mineralization.

In view of all the above, Andosols are soils with a large potential to sequester C, although little is yet known about the dynamics of C in these soils and of the mechanisms governing stabilization of organic compounds (Lal et al., 1998).

It is generally admitted that Andosols generally show a strong resistance to water erosion and that this low erodibility is strongly related to the specific physical properties of Andosols (Roose et al., 1999, Khamsouk et al., 2002; Rodríguez Rodríguez et al., 2002a). However, this behaviour of volcanic ash soils is not in complete agreement with field observations on lands with Andosols, particularly when changes occur in the use and management of these soils, with the occurrence of high soil losses (Poulenard et al., 2001, Rodríguez Rodríguez et al., 2002a). Thus, the indexes normally used to assess soil erodibility do not seem to be applicable to soils with andic properties

The organic matter content and forms and the unusual mineralogical composition of andic soils is responsible for the existence of certain physical and mechanical properties characteristic of these soils (Warkentin and Maeda, 1980; Meurisse, 1985; Quantin, 1994). All these characteristics, in turn, are in close relationship with the erodibility characteristics of andic soils, hence the fact that erosive processes in soils in which short-range ordination minerals predominate in the fine fraction also present differential features with respect to soils with a mineralogy dominated by crystalline clays (Yamamoto and Anderson, 1973; El-Swaify and Dangler, 1977; Egashira et al., 1983; Kubota et al., 1990; Pla, 1992).

In this context, the determination of soil aggregation and structural stability affords and indirect measurement of erodibility (Imeson and Vis, 1984, Lal, 1988) and can be establish more closely the mechanisms of particle separation in andic soils.

Although many studies have been performed to evaluate the impact of soil erosion on SOC dynamics, many knowledge gaps still exist in regard to the importance of SOC, and the behaviour of eroded SOC as a sink or a source of CO₂ (Lal et al., 1998) and, in general, the net effect of erosion on atmospheric CO₂ evolution (IPCC, 1996, Lal, 2001a, Cihlar et al., 2002).

Since soil water erosion is a selective process that preferentially removes the smallest and lowest density components of soil (Lal, 1995), the sediments are enriched in fine silt and clay-sized particles that constitute the most stable SOC pools in soils, because of the physical protection afforded in soil aggregates (Golchin et al., 1998; Kay, 1998). Moreover, a significant part of C mobilized in soils in erosive processes is dissolved in runoff water (DOC).

Van Noordwijk et al. (1997) suggested that, potentially at least, erosion may contribute to C sequestration since eroded SOC becomes better protected from decomposition in acidic swamp environments or in fresh-water and marine sediments, while other authors consider that 70-80 per cent of SOC in eroded soils could be decomposed during transport and deposition (Beyer et al., 1993, Harden et al., 1999), which contrasts with the data of Lal (1995, 2001b), Jacinthe et al. (2001) and Jacinthe and Lal (2001), who consider that only 20% of displaced SOC is mineralized.

From the data available in the bibliography it can be deduced that an important factor in the subsequent dynamics of SOC mobilized by erosion is the nature of same in regard to its stability (DOC, labile, slowly oxidizable, passive or recalcitrant) (Eswaran et al., 1995).

This stability is closely related to the degree of complexity of the humic molecules (biochemical recalcitrance), with its position in the soil aggregates (physical protection) (Golchin et al., 1998) and with the mode of its association with metals and secondary soil minerals (chemical stabilization) (Jastrow and Miller, 1998).

In view of the above, the objective of this study was:

- to know the content and forms of soil organic carbon (SOC) in andosols and andic soils under evergreen forest vegetation (laurel and heather forest)
- to know the role of organic matter in aggregate stability and resistance of andosols to water erosion, and
- to know the true losses of SOC that are produced by water erosion in Andosols after deforestation and the forms of organic carbon most affected by these losses.

Soil organic carbon pools and forms in forest andosols

A. Materials and methods

1. Study area and environmental conditions

Andosols in the highest Canary Islands occupy the perimeter between 700 and 1500 m a.s.l., in the area of influence of the trade winds, characterized by a thermomediterranean mesophytic subhumid bioclimate (Rivas Martínez et al., 1993), with annual precipitation ranging between 650 and 900 mm, a mean annual temperature of 14-16°C and a potential evapotranspiration of 750-800 mm/yr. These conditions give place to a udic soil moisture regime and a thermic soil temperature regime (Soil Survey Staff, 1999).

The natural potential vegetation corresponds to the laurel and heather forest (*Lauro-Perseeto indicae* and *Myrico-Ericetum arboreae*).

2. Soil genesis and soil properties

Predominant andosols in these areas (Melanudands, Fulvudands and Hapludands) are developed over a complex geologic material constituted by Pliocene-Pleistocene basaltic lava flows and successive deposits of volcanic ash of varied granulometry, generally from the eruptive stage of the same eruptions.

Weathering of these materials in a climate with high soil moisture takes place rapidly, leading to the formation of allophane-like noncrystalline minerals and Al/Fe humus complexes, and the rapid installation of vegetation in these media contributes the plant remains necessary for the formation of thick, dark humus-rich epipedons.

Processes of illuviation of clay-sized materials are not possible in these soils, since the noncrystalline materials are difficult to disperse under field conditions (Shoji et al., 1993), and thus the presence of a clayey horizon at depth is interpreted as an alteration in situ of the crystalline basaltic lava flows at the base of the soils, leading to the formation of halloysite and smectites.

3. Field sampling

A study area of some 40 km² has been chosen in the Garajonay National Park (La Gomera, Canary Is.), with the mean ecological characteristics described above.

The andosols present have been grouped for our purposes into two main categories: allophanic andosols and non-allophanic (or organomineral) andosols, being the former assigned to Melanudands and the latter to Fulvudands or Hapludands (Soil Survey Staff, 1999). This division has been applied according to the "binary composition" coined by Mizota and Van Reeuwijk (1989), by which the Alp/Alo ratio (Table 2) indicates the occurrence of allophanic or non-allophanic properties, such that Alp/Alo values of less than 0.5 point to a soil mineralogy dominated by allophane and allophane-like minerals (imogolite, ferrihydrite), otherwise occurring the active Al mainly as Al-humus complexes. Some selected soil properties of representatives profiles of allophanic and non-allophanic andosols of this area, are presented in Tables 1 and 2.

Table 1. Selected morphological and physical properties of soils

Horizon (depth)	Allophanic andosols <i>Ultic Melanudands</i>		Non-allophanic andosols <i>Alfic Hapludands</i>		Methods
	Aa (0-65 cms)	Bw (65-85 cms)	Aa (0-60 cms)	Bw (60-80 cms)	
Munsell soil color (moist)	5YR 2/2	7.5 YR 2/2	7.5 YR 3/2	5YR 3/2	Munsell Soil Color Charts
Soil structure	Crumb	Massive	Crumb	Angular blocky	Morphology
Water content (gkg ⁻¹) (dry)					Richards, 1980
33 kPa	631	686	594	644	
1500 kPa	307	346	344	394	
Bulk density at 33 kPa (Mgm ⁻³)	0.60	0.7	0.70	0.63	Undisturbed samples, tin cylinders of known volume
Coarse fragments (>2 mm) (gkg ⁻¹)	61	62	66	71	Sieving
Clay (gkg ⁻¹)'	190	472	189	469	Bartoli et al., 1991
Silt (gkg ⁻¹)'	714	443	493	384	Bartoli et al., 1991
Sand (gk ⁻¹)'	63	39	209	137	Bartoli et al., 1991

'Soil texture: Na-resin method (Bartoli et al., 1991).

Table 2. Chemical and andic soil properties

Horizon (depth)	Allophanic andosols <i>Ultic Melanudands</i>		Non-allophanic andosols <i>Alfic Hapludands</i>		Methods
	Aa (0-65 cms)	Bw (65-85 cms)	Aa (0-60 cms)	Bw (60-80 cms)	
pH (H ₂ O,1:2.5)	6.0	5.8	5.9	5.7	Soil:water ratio 1:2.5
pH (KCl,1:2.5)	4.9	4.9	4.7	4.2	Soil:KCl ratio 1:2.5
Organic carbon (gkg ⁻¹)	145.5	69	91	42	Walkley and Black (Nelson and Sommers, 1982)
C/N	21	14	11.2	12.3	Calculated
CEC (cmol _c kg ⁻¹)	57	48	58.9	47.3	Ammonium acetate 1N pH7 (Bower et al., 1952)
Base saturation (%)	42	17	29.4	37.3	Ammonium acetate 1N pH7 (Bower et al., 1952)
P-retention (%)	95	96	89	nd	Blakemore et al., 1981
Alo (%)	3.8	4.9	1.52	nd	Blakemore et al., 1981
Feo (%)	1.5	1.8	1.8	nd	Blakemore et al., 1981
Sio (%)	3.1	4.1	0.34	nd	Blakemore et al., 1981
Alp (%)	1.7	1.4	2.48	nd	Blakemore et al., 1981
Fep (%)	0.4	0.4	1.95	nd	Blakemore et al., 1981
Cp (%)	8.8	nd	6.9	nd	Blakemore et al., 1981
Alo+1/2Feo (%)	4.5	5.8	2.42	nd	Calculated
Alp/Alo	0.45	0.29	1.63	nd	Calculated
(Alp + Fep)/Cp (M)	0.10	nd	0.22	nd	Calculated
Allophane content (%)	14	19	0.89	nd	Parfitt and Wilson, 1985; Mizota and van Reeuwijk, 1989

nd: no determined

CEC: Cation exchange capacity

P-retention: Phosphate retention

Alo, Feo, Sio: Al, Fe, Si acid-oxalate extractable

Alp, Fep, Cp: Al, Fe, C pyrophosphate extractable

Soil sampling was performed in a 500m x 1000m grid over the entire surface (88 sampling points), intensifying sampling density in areas showing the greatest evidence of degradation both of vegetation and soils, where samples were collected on the basis of an additional grid measuring 250m x 250m (75 samples).

A total of 163 sampling points were studied and soil samples were collected at each in the first 30-40 cms, at 3 randomly distributed sampling points. At each point soil samples were collected manually, mixed and air dried at room temperature: one part of the sample was passed through a 2-mm sieve and analysed and another part was used for aggregate stability tests.

Three separate samples for bulk density were collected, by inserting tin cylinders into the soil.

4. Laboratory analysis

The morphological description and the physical and chemical description of the horizons of the soil profile were performed in accord with the methods described in Tables 1 and 2: soil samples were taken at each horizon, identified and described in the field and the analyses were made in triplicate.

In the samples of whole soil sieved through 2 mm-mesh, were determined:

a) *Walkley-Black soil organic carbon*: The OC was determined by wet oxidation of the carbon by the dichromate Walkley-Black procedure, using a hot mixture of 1N potassium dichromate and concentrated sulphuric and phosphoric acids in accordance with Nelson and Sommers (1982). It is generally considered that, without heating, this method only oxidizes between 87 and 92 per cent of the OC present. Thus, in the calculation of the carbon content we have used 1.3 as a compensation factor for the incomplete recovery of OC in this procedure.

With this method, in 23 representatives allophanic and non-allophanic forest andosols we found (unpublished data) a recovery of OC with respect to that obtained by dry combustion LECO CSN 1000 analyzer that varies between 98 and 103 per cent, thus assuming that the carbon determined in that way constitutes the total soil organic carbon (TSOC) (Cheng and Molina, 1995).

b) *Pyrophosphate extractable soil organic carbon*: Pyrophosphate extractions are used to quantify active Al and Fe complexed with humus material (Blakemore et al., 1981, Parfitt and Henmi, 1982, Van Reeuwijk, 1993).

An extraction with 0.1 M sodium pyrophosphate solution (shaking overnight and 1:100 soil:solution ratio) selectively dissolves organic matter and associated Al and Fe (McKeague et al., 1971, Mizota and van Reeuwijk, 1989). Therefore, the OC dissolved in the pyrophosphate extract corresponds to the OC associated (complexed) with the active forms of Al and Fe, in our case probably in the form of allophane-Al-humus and Al-humus complexes.

The OC dissolved in the pyrophosphate extract was determined by wet oxidation by dichromate, as above, using diluted dichromate (0.05N) instead of 1N dichromate.

c) *Potassium sulphate extractable soil organic carbon*: The soil is extracted with 0.5 M potassium sulphate solution at a 1:5 soil:solution ratio. The soil and extractant are shaken for one hour, then filtered and analyzed for OC by oxidation by 0.05 N dichromate and sulphuric acid as for pyrophosphate extracted OC (Horwath and Paul, 1994).

The OC thus extracted seems to correspond to the more labile forms of OC found in the soil.

d) *Dissolved soil organic carbon*: 200 g of 2-mm sieved soil were weighed and added the exact amount of water to saturate the sample. The resultant pastes were left overnight, and then transferred to Buchner funnels, to which suction was applied to collect the filtrate, that was subsequently analyzed for organic carbon by oxidation by 0.05 N dichromate, as above. The carbon thus extracted was considered to be dissolved soil organic carbon (DSOC).

e) *Acid oxalate extractable iron, aluminium and silicon (Feo, Alo, Sio)*: Were measured by extracting soil with acid (pH 3) 0.2 M ammonium oxalate solution (4 hrs shaking in the dark and soil:solution ratio 1:50) and analyzing Fe, Al and Si by atomic absorption spectrometry (AAS) (Blakemore et al., 1981, Van Reeuwijk, 1993).

This extraction dissolves all active Al and active Fe components as well as the associated Si (Mizota and van Reeuwijk, 1989). This include noncrystalline minerals (allophane, imogolite, ferrihydrite) and Al/Fe-humus complexes (Parfitt and Henmi, 1982, Nanzyo et al., 1993).

Andic soil properties in Andosols that show a high degree of weathering are determined by ammonium oxalate extractable Al plus a half Fe ($A_{lo} + \frac{1}{2} Fe_o$) (Shoji et al., 1993).

f) *Pyrophosphate extractable iron and aluminium (Fep, Alp)*: Pyrophosphate extraction was used to quantify actives Al and Fe complexed to organic components. Alp and Fep were measured by extracting soil with 0.1 M sodium pyrophosphate solution (shaking overnight and 1:100 soil:solution ratio) and analyzing Fe and Al by atomic absorption spectrometry (AAS) (Blakemore et al., 1981, van Reeuwijk, 1993).

Pyrophosphate only dissolves humus-Al and by taking $A_{lo}-A_{lp}$ the Al in noncrystalline minerals such as allophane and imogolite, is obtained. The ratio A_{lp}/A_{lo} is used as an index of allophanic or non allophanic soil properties.

The molar ratio $(Al+Fe)_p/C_p$ is a measure of the complexing ability of humic substances and a maximum ratio of 0.12 is expected based on complexation of monomeric hydroxy-Al with humus (Higashi et al., 1981). Usually this ratio range between 0.1 and 0.2 for most andosols (Inoue and Higashi, 1988, Dahlgren et al., 1993)).

g) *Allophane content*: The allophane content was estimated by a method proposed by Parfitt and Wilson (1985), modified by Mizota and van Reeuwijk (1989) and based on the Al/Si compositional ratio, $(A_{lo}-A_{lp})/S_{io}$, and the Si content (S_{io}).

All samples were analyzed in triplicate and average results are reported on an oven-dried basis.

B. Results and discussion

The andosols present a high capacity to accumulate carbon (up to $14.5 \pm 5.9 \text{ kgCm}^{-2}$, 113 gCkg^{-1}), a high percentage of which (57.2 per cent) is found in pyrophosphate extractable forms ($8.3 \pm 3.0 \text{ kgCm}^{-2}$), that is, complexed with the Fe and Al actives (Table 3).

Table 3. Mean values of different forms of soil organic carbon in andosols

kgm^{-2}	OC_t	OC_p	OC_l	OC_d	C/N ratio
Andosols	14.5 ± 5.9	8.3 ± 3.0	0.42 ± 0.27	112.4 ± 44.7 (gL^{-1})	13.5 ± 4.3

OC_t = Total soil organic carbon

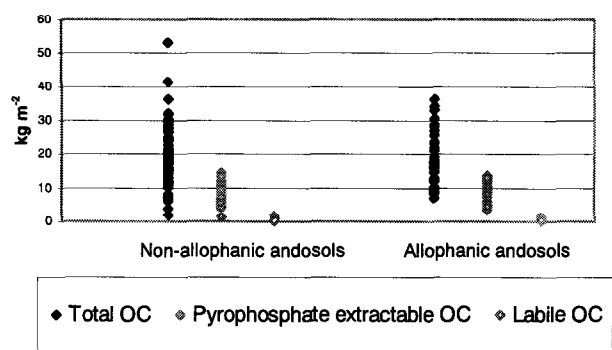
OC_p = Pyrophosphate extractable soil organic carbon

OC_l = Potassium sulphate extractable soil organic carbon

OC_d = Dissolved soil organic carbon

It has been unanimously considered that the high potential presented by andosols to function as a sink for carbon in organic form is related in some way to the formation of complexes with the active forms of Fe and Al or with highly reactive minerals such as allophane, imogolite and ferrihydride (Dahlgren et al., 1993; Parfitt et al., 1997; Lal et al., 1998, among others).

Figure 1 shows no statistically significant differences in the different forms of organic carbon between allophanic and non-allophanic andosols, which is due to the presence of a relatively high proportion of soil with an A_{lp}/A_{lo} ratio very close to 0.5, indicating that no specific mineralogical type clearly predominates and therefore they introduce a certain "noise" in the statistical treatment.



(kg m ⁻²)	U Mann-Whitney	p	Non-allophanic andosols	Allophanic andosols
Total soil OC	2040	0,479	18,0 a	18,8 a
Pyrophosphate extractable OC	2078	0,586	7,7 a	8,4 a
Labile OC	1257	0,148	0,50 a	0,58 a
C/N ratio	2186	0,935	14,9 a	15,1 a

Figure 1. Soil organic carbon pools in allophanic and non-allophanic soils

However, it can be observed in Figures 2 and 3 that, in allophanic andosols, organic carbon tends to accumulate in non-pyrophosphate extractable forms, while organic carbon is largely found in complexed forms in organominerals andosols.

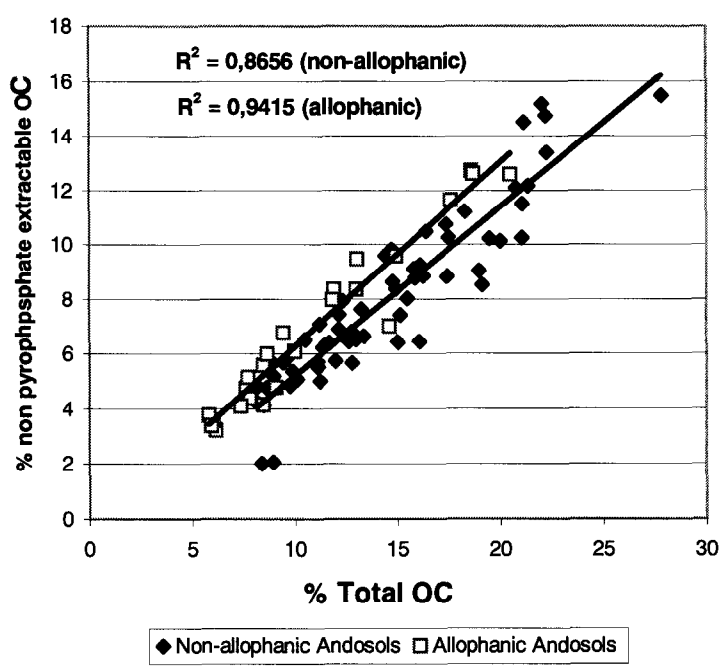


Figure 2. Relationship between total soil organic carbon and non-pyrophosphate extractable organic carbon

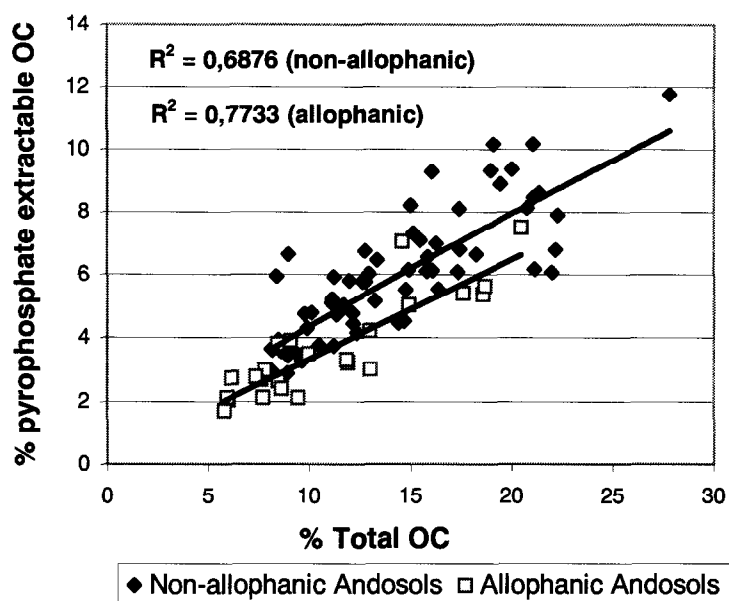


Figure 3. Relationship between total soil organic carbon and pyrophosphate extractable organic carbon

In addition, allophanic andosols display a greater tendency to accumulate total organic carbon than non allophanic andosols (Figure 4), TOC being observed to tend to increase when the Alp/Alo ratio increases, in addition to a positive correlation between the content in Al extractable with pyrophosphate and TOC ($y = 3.59x + 7.72$, $R^2 = 0.40$ for non allophanic and $y = 6.79x + 4.41$, $R^2 = 0.47$ for allophanic andosols).

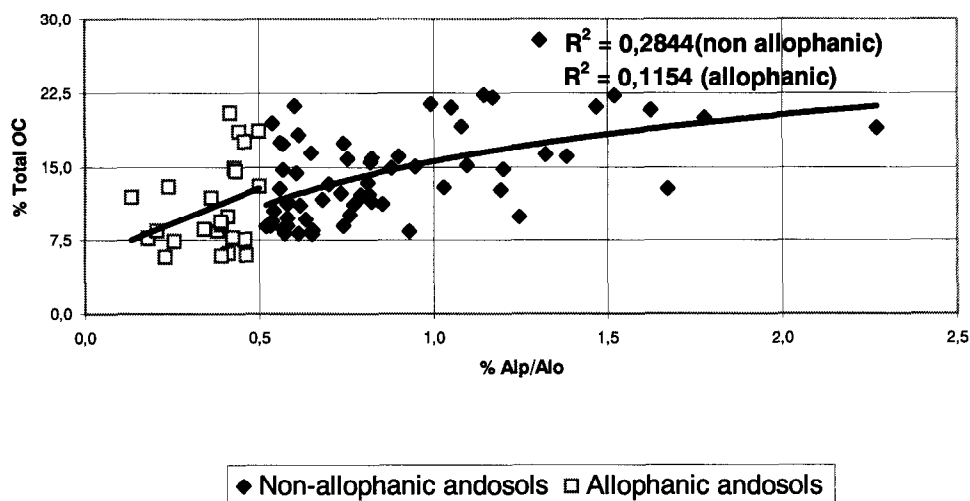


Figure 4. Per cent total soil organic carbon vs. Alp/Alo in allophanic and non-allophanic andosols

Normally it is considered that metal/carbon molar ratios reflect the complexing capacity of humic substances. According to Dahlgren et al., 1993, the metal/carbon ratio evaluated as $(Al+Fe)/Cp$ usually oscillates between 0.1 and 0.2 for the majority of andosols, the value of 0.12 being considered to be the theoretical complexation maximum of hydroxyaluminium monomers by humus.

In our case, the greater part of soils, particularly non-allophanic andosols, present values even higher than 0.25 for this ratio, which seems to indicate that in accord with the content in active Fe and Al, these soils still have the capacity to complex further humic components (Figure 5).

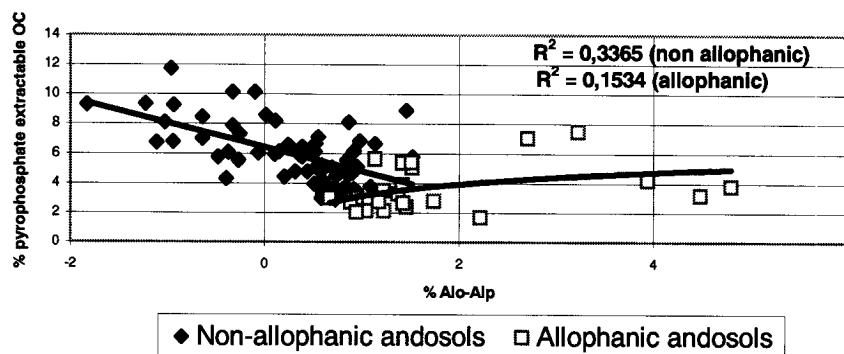


Figure 5. Alo-Alp vs. Pyrophosphate extractable soil organic carbon in allophanic and non-allophanic andosols

Despite the fact of the high levels of organic C in andosols, among these soils, non-allophanic (organomineral) andosols tend to accumulate more organic C (with a prevalence of stable adsorbed forms), related to allophanic andosols (that have higher amounts of non-pyrophosphate extractable organic C). The existence of metal/carbon ratios higher than 0.12 indicates the occurrence of active Fe and Al forms, capable to form complexes with (and therefore to sequester) organic C.

Soil organic carbon and soil erodibility

A. Materials and methods

This study was carried out with the same samples described above.

1. Laboratory analysis

In addition to the analyses reported above, the following were performed in all the samples:

- a) *Fulvic and humic acids* by Duchaufour and Jacquin, 1966 methods
- b) *Clay + silt fractions* by Na-resin method (Bartoli et al., 1991)
- c) *K-factor of USLE* by equation proposed by Wischmeier et al., 1971
- d) *Aggregate stability* by two tests:

d.1. *Disaggregation test* (Bartoli et al., 1991), as a measure of structure dispersion due to aggregate humectation. Nine brass sieves (mesh size 0.2 mm) were immersed for 2-3 cms in 200 ml distilled water contained in a plastic can. Oscillations were sinusoidal, with an amplitude of 2 cms and frequency of 98 oscillations/min. The disaggregation kinetics of the soil studied indicated that 6 hours was an appropriate time of disaggregation in water (Rodríguez Rodríguez et al., 2002b)

d.2. *Water-drop test* (Imeson and Vis., 1984), as a measure of structure dispersion due to raindrop impact. In the device used by us, a water supply system with a constant head was fitted to a burette, and water drops 0.1 g in weight (5.8 mm diameter) were obtained. The water drops were allowed to fall from a height of 1 m onto aggregates placed in a metal sieve. The time interval between drops was one second.

The test was carried out with 10-20 aggregates of 4-5 mm size situated in a 0.2 mm sieve. The CND procedure was followed: Counting the Number of Drop impacts required to disrupt the aggregate sufficiently for it pass through the 0.2 mm sieve.

All samples were analyzed in triplicate and average results are reported on an oven-dried basis.

B. Results and discussion

All the andosols present a high structural stability in regard to humectation and to water-drop impact (Table 4).

No significant differences were observed between both groups of soils in regard to K-USLE value or to the per cent of water stable aggregates after disaggregation test, although a greater stability can be observed to the water-drop impact in non allophanic andosols than in the allophanic andosols.

Table 4. Structural stability and erodibility of soils

	Statistical test of comparison*	Allophanic andosols	Non-allophanic andosols
Water stable aggregates (%)	ANOVA	76,8 ± 7,4 a	79,9 ± 10,7 a
CND (number)	Kruskal-Wallis, U Mann-Whitney	34 ± 27 a	47 ± 20 b
K-USLE (t·yr·MJ ⁻¹ ·mm ⁻¹)	ANOVA	0,10 ± 0,11 b	0,04 ± 0,03 b
* Values followed by the same character do not exhibit significant differences according the test used (p 0,05).			

If existing relationships between structural stability, K-factor of the USLE and some soil properties (Table 5) are analyzed, it can be seen that both stability tests are positively correlated, particularly in the non allophanic andosols, no relationship being observed, however, between the true susceptibility to aggregate disruption (as measured by the two test) and the erodibility estimated by K-factor (USLE).

Table 5. Correlation between erodibility and soil properties

	Non-allophanic andosols		Allophanic andosols	
	Disaggregation test	Water drop test CND	Disaggregation test	Water drop test CND
Disaggregation test	-	0,506*	-	0,497*
Water drop test CND	0,506*	-	0,497*	-
K-USLE	-0,205	0,203	-0,026	-0,192
Fine fraction (clay +silt)	0,224	-0,004	0,084	0,315
Al _o	-0,084	0,074	0,246	0,310
Fe _o	0,155	0,229	0,086	0,385
Al _o + ½Fe _o	-0,025	0,164	0,243	0,327
Fe _p	0,185	0,371*	0,672*	0,602*
Al _p	-0,179	0,214	0,622*	0,432
Al _p + ½Fe _p	-0,117	0,270*	0,642*	0,469*
C _p / (Al _p + Fe _p)	0,024	-0,057	-0,426	-0,245
Non-pyrophosphate extractable OC.	-0,174	0,126	0,438*	0,381
Pyrophosphate extractable OC	-0,032	0,318*	0,553*	0,446*
Labile OC	-0,120	0,218	0,293	0,480*

Fulvic acids	0,062	0,355*	0,553*	0,411
Humic acids	-0,121	0,115	0,376	0,298
C/N ratio	-0,116	0,145	0,208	0,476
* Significant correlation at level p 0,05				

In allophanic andosols the structure dispersion due to aggregate humectation is mainly correlated with the pyrophosphate extractable organic carbon, while in non allophanic andosols this disaggregation does not present significant correlations with the analyzed soil properties.

The water-drop impact stability is correlated in both soil groups with the pyrophosphate extractable organic carbon and with the Al and Fe actives complexed to organic compounds. In the non allophanic andosols the dispersion due to water-drop impact is the only dispersion mechanism determined by the analyzed soil properties.

According to Rodríguez Rodríguez et al., 2002b, the erosive process in the andic soils seems to come about mostly through a picking off of aggregates, due to the impact of raindrops. The results of this study also point to the existence of mechanisms of stabilization and disruption of the structure that are characteristic of the two groups of soils under consideration.

The raindrop impact seems to be the only important disaggregation mechanism in non allophanic andosols, although it is frequent in both types of soils and is directly related to the content in pyrophosphate extractable organic carbon. The disaggregation due to aggregate humectation is absent from non allophanic andosols and is characteristic of allophanic andosols stabilized by allophane-humus complexes.

The results show the limited validity of the conventional estimation of erodibility in andic soils, where the sensitivity towards water erosion is mostly related to their content in organometallic compounds.

Organic carbon losses by water erosion

A. Materials and methods

In order to assess the true rates of soil organic carbon loss by water erosion in forest allophanic andosols, a study was performed in experimental erosion plots.

1. Field plots

The study was carried out in three experimental plots installed in 1993 on the northern slopes of the island of Tenerife (Canary Is.). The environmental conditions of the zone are similar to those described earlier for the island of La Gomera and the soils are allophanic Andosols (Ultic Melanudands) represented by the profile described in Tables 1 and 2.

The plots are enclosed, allowing quantification of the production of solids and the volume of runoff, facilitating assessment of the movement of nutrients, dissolved, adsorbed and particulate organic carbon and other chemicals. Each plot has an area of 200 m² (25 x 8 m), and all have collecting deposits equipped with HS flumes, capacity probes and ultrasonic devices, connected to data collecting equipment.

For rainfall recording we used two pluviographs, with recordings every five minutes. After each significant rainshower the amount of sediment and runoff water were determined with the experimental device described above; samples of the sediments and waters were taken for subsequent analysis, manually and using an automatic sampling device, respectively.

2. Erosion factors at the plots

The mean rainfall in the plots during the years studied (9 years) is around 660 mm yr⁻¹, a high monthly and interannual variability being observed. The highest value of maximum intensity of the rain (I_{max}) recorded was 240 mmh⁻¹, although these values usually oscillate between 30 and 85 mmh⁻¹, with mean interannual values of the R-USLE factor (Wischmeier et al., 1978) of 640 Mjha⁻¹mmh⁻¹.

It can be stated that the rains always show a moderate degree of *erosivity* in these plots, with frequent, high-intensity events and periods of concentration of precipitations.

The soil erodibility calculated by the method of Wischmeier et al. (1971) is very low, a value of K = 0.11 tyr/Mjmm, being obtained for the soils of the plots, although it has already been established above and elsewhere that the erodibility of these andosols, given their particular characteristics of aggregation, is not adequately estimated by means of the K factor (Rodríguez Rodríguez et al., 2002a,b).

Topography and vegetation cover. With a slope of 24 per cent, in the plots the soil was kept bare by manually removing adventitious vegetation.

Runoff generation and sediment yields. The runoff generated in these soils is relatively low, with mean values of 13.0 per cent (85.8 mmyr⁻¹) never exceeding 45 per cent, which show the high capacity of infiltration of andosols, at least in the surficial horizons. This leads to a relatively small loss of soil due to sheet erosion with a mean value of 9.6 t ha⁻¹yr⁻¹, although significant losses of soil (up to 317 t ha⁻¹) can take place during certain events (Rodríguez Rodríguez et al., 2002b).

The greatest productions of sediments are not clearly related to the most intense rains, but rather to the soil moisture content at the time of raining. The largest rates of sediment yield and runoff were observed when the rain fell on dry soil (Rodríguez Rodríguez et al., 2002b).

3. Field sampling and laboratory analysis

All the samples were collected and determinations were carried out along 2002, with the exception of total OC at the soil surface which was also performed over 1999, 2000 and 2001 and whose results have been used to calculate the enrichment ratio (ER) presented in Table 7.

Soil surface samples were collected in the soil plot in the first 5 cms, at 10 randomly distributed sampling points. At each point soil samples were collected manually, mixed, air dried at room temperature and analyzed. Three separate samples for bulk density were collected, by inserting tin cylinders into the soil.

In the sample of soil sieved through 2-mm mesh, were determined: Walkley-Black, pyrophosphate extractable, potassium sulphate extractable and dissolved soil organic carbon and Fe, Al, Si, P, by the same methods that in determination of soil organic carbon pools. All the samples were analyzed in triplicate and average results are reported on an oven-dried basis.

After each significant rainshower the amount of sediments was determined with the experimental device installed on the plots (collecting bins and flumes). After careful decantation in the field, all sediment was manually collected, weighed and transported to laboratory for analysis.

Some untransformed plant residues (leaves, stems, roots) that were swept off by the runoff waters and were floating in the water deposits after decantation, were collected manually and weighed, although they not taken in account for this study.

A total of 14 pluviometric events were recorded as having a significant amount of sediments between 1999 and 2002 (Table 7). A sample of the sediments collected in each event was air dried at room temperature and passed through a 2 mm sieve for:

a) *Particle-size analysis*: The method used was the Na-resin treatment proposed by Bartoli et al., 1991: 2.5 g of sample was added to 200 ml distilled water and 200 ml of Na Amberlite IR-120 resin (500 μm mesh) and shaken for 16 hours at 40 rpm. Particle-size distribution was determined using the sieving and pipette method.

b) *Walkley-Black, pyrophosphate extractable and potassium sulphate extractable soil organic carbon*: with the same methods that were used for the soil samples.

All the samples were analyzed in triplicate and average results are reported on an oven-dried basis.

The amount of runoff generated was measured with an ultrasonic device connected to data collecting equipment. After each significant rainshower event a sample of water runoff was collected using a automatic sampling device.

The sample was filtered through a filter of 0.45 μm pore size and then analyzed for dissolved organic carbon (DOC) by oxidation using a mixture of 0.05N potassium dichromate and concentrated sulphuric and phosphoric acids, according to the Walkley-Black procedure. All samples were analyzed in triplicate and average results are reported.

B. Results and discussion

The content in total organic carbon in the first 5 cms from the soil surface is $120 \pm 1.5 \text{ gCkg}^{-1}$ (2.4 kgCm^{-2}), of which 73.3 ± 0.7 per cent ($88.2 \pm 0.4 \text{ gCkg}^{-1}$) is found in pyrophosphate extractable form (associated with the active forms of Al and Fe), 2.6 ± 0.10 per cent ($3.1 \pm 0.15 \text{ gCkg}^{-1}$) in potassium sulphate extractable form, 0.1 per cent ($188 \pm 1.5 \text{ mgCL}^{-1}$) appears dissolved in the soil solution (DSOC) and the remainder in other non extractable forms (Table 6).

Table 6. Forms of soil surface and eroded soil organic carbon

	Soil surface (0-5 cms) Mean \pm SD (gkg^{-1})	Sediments (n=14) Mean \pm SD (gkg^{-1})	Runoff (n=14) Mean \pm SD (mgL^{-1})	Enrichment Ratio
Total SOC	120 \pm 1.5	116 \pm 18.1	-	0.97
Pyrophosphate extractable SOC	88 \pm 0.4	53 \pm 10.6	-	0.60
Pyrophosphate extractable SOC/Total SOC (%)	73.3 \pm 0.7	46.6 \pm 11.7	-	-
K₂SO₄ extractable SOC	3.1 \pm 0.15	1.0 \pm 0.5	-	0.33
Dissolved SOC (mgL^{-1})	188 \pm 1.5	-	12 \pm 13.6	0.06

This implies that the greater part of the organic carbon in these soils appears as relatively stable organomineral complexes, as pointed out by several authors (Dahlgren et al., 1993, Powers and Schlesinger, 2002).

The general characteristics of the interrill erosion and runoff generation in these soils were described earlier. Figure 6 shows the annual evolution of sediment yield, generation of runoff (as a per cent of rainfall) and amount of rainfall per year.

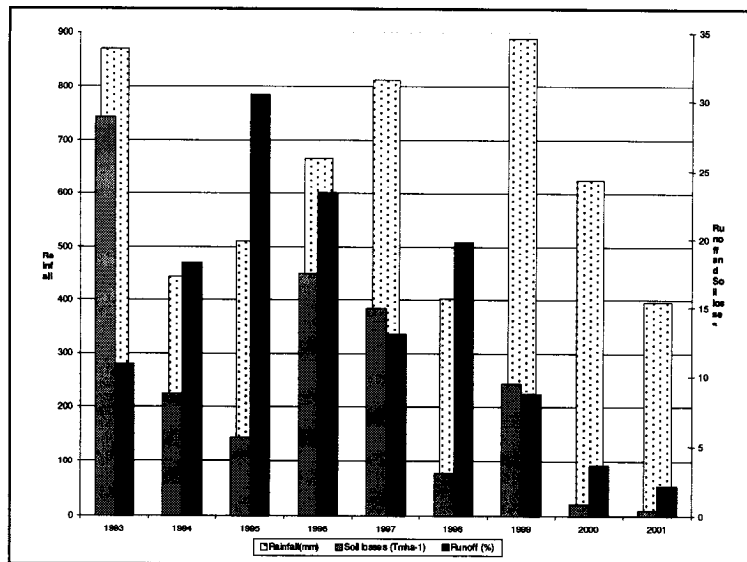


Figure 6. Soil losses, runoff and rainfall. Years 1993-2001

The results indicate that a high interannual variability exists in these parameters and clear relationships among them are lacking since the loss of soils is seemingly more closely related to the prior state of soil moisture, so that the largest rates of sediment yield and runoff were observed when the rains fell on dry soil.

An erosion mechanism of andic microaggregates of high hydrophobicity and low bulk density, having no apparent relationship with the rainfall or the amount of runoff, has been proposed for these soils by Rodríguez Rodríguez et al. (2002a,b) and also has been reported for the Andisols of Ecuador (Poulenard et al., 2001) and Costa Rica (Collinet et al., 1998).

It can be seen (Table 7) the loss of total organic carbon linked to the solid phase (sediments) and of the dissolved organic carbon in the runoff, as well as the sediment yields in the main events recorded between 1999 and 2002.

In the different events, the OC lost via erosion was mainly bonded to the solid phase, as stated above, since the dissolved organic carbon comprise only 0.1-3.5 per cent of the total OC eroded.

The content in total OC of the sediments ranges between 86 ± 3.5 and 145 ± 1.6 gkg^{-1} (116 ± 18.1 gkg^{-1}), involving erosion-induced losses of OC bonded to the solid phase that vary between 0.10 and 3.11 gm^{-2} , depending of the amount of sediments generated in each event (Table 7).

No relationship seems to exist between the amount of total OC lost and the sediments and the concentration of total OC they contain, taking into account that this depends more on the fractions eroded in the greatest amount in each event.

If we take into account that the measured erosion rates show an average yield of sediments of 0.96 $\text{kgm}^{-2}\text{yr}^{-1}$, the annual losses of OC caused by erosion and bonded to the solid phase are 111.4 $\text{gC m}^{-2}\text{yr}^{-1}$, similar to those found by Jacinte and Lal (2001) in cultivated soils (30 - 260 $\text{gC m}^{-2}\text{yr}^{-1}$), but much greater than those reported by other authors.

The values of the enrichment ratio in OC of the sediments are always close to the unit, pointing to the low selectivity of the erosion process in regard to organic carbon, no relationship being observed between this ratio (ER) and the amount of sediments produced ($R^2 = 0.0022$), or with the concentration of OC in the sediments ($R^2 = 0.0022$), or with the rainfall intensity ($R^2 = 0.006$).

The concentration of dissolved organic carbon in runoff also varies in the different events (2.0 ± 0.3 - 44.9 ± 4.3 mgL^{-1}), implying losses of dissolved OC oscillating between 0.8 y 18.0 mgm^{-2} (Table 7), depending on the runoff generated in each event and on its concentration.

The generation of runoff has an average value of 85.8 mmyr^{-1} , indicating losses of dissolved organic carbon of 1.03 $\text{gC m}^{-2}\text{yr}^{-1}$, much lower than the flows calculated by Moore (1998) for the

surficial horizon of a New Zealand forest soil ($80 \text{ gC m}^{-2}\text{yr}^{-1}$), but within the limits reported by other authors in a wide range of geographical locations ($1\text{-}10 \text{ gC m}^{-2}\text{yr}^{-1}$) (Hope et al., 1994).

Table 7. Eroded soil organic carbon

Events	Total OC Sediments Mean \pm SD (gkg^{-1})	OC Enrichment ratio	Sediments (gm^{-2})	Total OC Sediments (gm^{-2})	DOC Runoff Mean \pm SD (mgL^{-1})	DOC Runoff (mgm^{-2})
1-99	86 \pm 3.5	0.67	1.5	0.13	4.6 \pm 0.69	1.8
2-99	115 \pm 3.5	0.89	2.5	0.29	18.3 \pm 0.97	7.3
3-99	98 \pm 1.6	0.76	31.7	3.11	38.0 \pm 2.35	15.2
1-00	114 \pm 3.5	0.93	1.5	0.17	11.9 \pm 0.90	4.8
2-00	101 \pm 2.8	0.82	3.3	0.33	2.0 \pm 0.38	0.8
3-00	112 \pm 3.2	0.91	4.5	0.50	6.2 \pm 0.30	2.5
4-00	99 \pm 3.8	0.80	3.7	0.37	2.0 \pm 0.35	0.8
1-01	145 \pm 1.6	1.18	0.7	0.10	8.7 \pm 1.68	3.5
2-01	139 \pm 2.8	1.13	14.8	2.06	3.5 \pm 0.44	1.4
3-01	127 \pm 2.4	1.03	5.4	0.69	44.9 \pm 4.3	18.0
1-02	139 \pm 0.8	1.16	6.1	0.85	8.4 \pm 0.35	3.4
2-02	131 \pm 3.1	1.09	8.0	1.05	6.4 \pm 0.53	2.6
3-02	101 \pm 3.0	0.84	1.9	0.19	3.8 \pm 0.55	1.5
4-02	120 \pm 2.6	1.00	18.6	2.23	13.3 \pm 0.40	5.3

When the forms of OC present at the soil surface and in the eroded sediments are compared (Table 6) it is observed, however, that there exists in the sediments a significantly smaller proportion of pyrophosphate extractable OC than in the soil surface (46.6 ± 11.7 per cent versus 73.3 ± 0.7 per cent, Mann-Whitney test, $U = 0.000$, $p = 0.008$).

V. Conclusions

The studied andosols present a high capacity to accumulate carbon (up to $14.5 \pm 5.9 \text{ kgCm}^{-2}$, 113 gCkg^{-1}), a high percentage of which (57.2 per cent) is found in pyrophosphate extractable forms ($8.3 \pm 3 \text{ kgCm}^{-2}$), that is, complexed with the active forms of Fe and Al. The dissolved organic carbon in these soils is around $112.4 \pm 44.7 \text{ gL}^{-1}$.

Despite the high levels of organic C in andosols, among these soils, non-allophanic (organomineral) andosols tend to accumulate more organic C (with a prevalence of stable adsorbed forms), related to allophanic andosols (that have higher amounts of non-pyrophosphate extractable organic C). The existence of metal/carbon ratios higher than 0.12 indicates the occurrence of active Fe and Al forms, capable to form complexes with (and therefore to sequester) organic C.

Andosols generally show a strong resistance to water erosion and in this study we have tested the limited validity of the conventional estimation of erodibility (K-USLE) in andic soils where the sensitivity towards water erosion is mostly related to their content in organometallic compounds.

Raindrop impact seems to be the only important disaggregation mechanism in non allophanic andosols, although it is frequent in both types of soils and related to the content in pyrophosphate extractable organic carbon. The disaggregation due to aggregate humectation is absent from non allophanic andosols and is characteristic of allophanic andosols stabilized by allophane-humus complexes.

Important losses of organic carbon in these soils are caused by erosion ($114.4 \text{ gC m}^{-2}\text{yr}^{-1}$), which are fundamentally bonded to the solid phase since DOC losses in runoff water are negligible ($1.03 \text{ gC m}^{-2}\text{yr}^{-1}$).

Although complexed forms of organic carbon predominate at the soil surface as allophane-Al-humus or Al-humus complexes (73.3 per cent of total soil organic carbon), the predominating form in the sediments corresponds to non pyrophosphate extractable and non complexed forms of organic carbon (53.4 per cent).

The fact that the non pyrophosphate extractable forms constitute an important fraction of the eroded organic carbon, leads us to believe that in these soils mineralization of soil organic carbon removed from soils by sheet water erosion can be an important source of atmospheric CO_2 .

However, better knowledge is necessary of the susceptibility of the different forms of extractable organic carbon to microbial decomposition, when the eroded materials are redistributed along the landscape and deposited in other zones with different ecological characteristics from those in which they originated.

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References

- Bartoli, F., Burtin, G. and Herbillon, A.J., 1991. Disaggregation and clay dispersion of Oxisols: Na-resin, a recommended methodology. *Geoderma* 49: 301-317
- Beyer, L., Frund, R., Schleuss, U. and Wachendorf, C., 1993. Colluvisols under cultivation in Schleswig-Holstein. 2. Carbon distribution and soil organic matter composition. *Journal of Plant Nutrition and Soil Science*, 156: 213-217.
- Blakemore, L.C., Searle, P.L. and Daly, B.K., 1981. Soil Bureau Laboratory Methods. A: Methods for chemical analysis of soils. Newland Soil Bureau Scientific Report 10 A, CSIRO, Lower Hutt, New Zealand.
- Bower, C.A., Reitemeier, F.F. and Fireman, M., 1952. Exchangeable cation analysis of alkaline and saline soils. *J. Soil Sci.* 73, 251-261.
- Cheng, H.H. and Molina, J. A. E. 1995. In search of the bioreactive soil organic carbon: The fractionation approaches. In: R. Lal, J. Kimble, E. Levine and B.A. Stewart (Editors), *Soils and Global Change, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 343-350.
- Cihlar, J., Heimann, M. and Olson, R. 2002. Terrestrial carbon observations. The Frascati Report on in situ carbon data and information. Environment and Natural Resources Series n° 5, FAO, Roma.

- Collinet, J., Asseline, J., Jimenez, F., Bermudez, A.T. and Dromard, S. 1998.** Comportements hydrodynamiques et érosifs de sols volcaniques au Costa Rica. Rapport CATIE, Turrialba.
- Dahlgren, R., Shoji, S. and Nanzyo, M., 1993.** Mineralogical characteristics of volcanic ash soils. In: S. Shoji, M. Nanzyo and R.A. Dahlgren (Editors), *Volcanic ash soils: Genesis, properties and utilization*. Developments in Soil Science 21, Elsevier Science Publishers, Amsterdam, The Netherlands, pp. 101-143.
- Duchaufour, P. and Jacquin, F. 1966.** Nouvelles recherches sur l'extraction et le fractionnement des composés humiques. *Bulletin de l'Ecole National Supérieur de Nancy*, 8 (1) 1-24
- Egashira, K., Kaetsu, Y. and Takuma K. 1983.** Aggregate stability as an index of erodibility of Ando soils. *Soil Sci. Plant Nutr.*, 29:473-481
- El Swaify, S. and Dangler, E.W. 1977.** Erodibility of selected tropical soils in relation to structural and hydrological parameters. In: *Soil Erosion: Prediction and Control*. Soil Cons. Soc. of Am. Special Publ. N° 21. Ankeny (USA):105-114.
- Eswaran, H., Van der Berg, E., Reich, P. and Kimble, J., 1995.** Global soil carbon resources. In: R. Lal, J. Kimble, E. Levine and B.A. Stewart (Editors), *Soils and Global Change, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 27-43.
- Golchin, A., Baldock, J.A. and Oades, J.M., 1998.** A model linking organic matter decomposition, chemistry, and aggregate dynamics. In: R. Lal, J.M. Kimble, E. and R.F. Follet (Editors), *Soils Processes and the carbon cycle, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 245-266.
- Harden, J.W.; Sharpe, J.M.; Parton, W.J.; Ojima, D.S.; Fries, T.L.; Huntington, T.G. and Dabney, S.M., 1999.** Dynamic replacement and loss of soil carbon on eroding cropland. *Global Biogeochemistry Cycles*, 13: 885-901.
- Higashi, T., De Coninck, F. and Gelaude, F. 1981.** Characterization of some spodic horizons of the Campine (Belgium) with dithionite-citrate, pyrophosphate and sodium hydroxide tetraborate. *Geoderma*, 25:285-292.
- Hope, D., Billet, M.F. and Cresser, M.S. 1994.** A review of the export of carbon in river water: Fluxes and processes. *Environmental Pollution*, 84:301-324.
- Horwath, W.R. and Paul, E.A. 1994.** Microbial biomass. In: R.W. Weaver et al. Eds., *Methods of Soil Analysis. Part. 2: Microbiological and biochemical properties*, pp. 753-773, SSSA Book Series n° 5, Madison.
- Imeson, A. and Vis, M. 1984.** Assessing soil aggregate stability by water-drop impact and ultrasonic dispersion. *Geoderma* 34: 185-200.
- Inoue, K. and Higashi, T. 1988.** Al and Fe-humus complexes in Andisols. In: D.J. Kinloch et al (Editors) *Proc. of the 9th Int. Soil Classification Workshop, Japan, SMSS, Whashington*, 81-96.
- IPCC, 1996.** Revised IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual. Volume 3, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.
- Jacinte, P.A. and Lal, R., 2001.** A mass balance approach to assess carbon dioxide evolution during erosional events. *Land Degradation and Development*, 12: 329-339.
- Jacinte, P.A., Lal, R. and Kimble, J.M., 2001.** Assessing water erosion impacts on soil carbon pools and fluxes. In: R. Lal, J.M. Kimble, R.F. Follet and B.A. Stewart (Editors), *Assessment Methods for Soil Carbon, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, 427-449.
- Jastrow, J.D. and Miller, R.M., 1998.** Soil aggregate stabilization and carbon sequestration: Feedbacks through organomineral associations. In: R. Lal, J.M. Kimble, E. and R.F. Follet (Editors), *Soils Processes and the carbon cycle, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 207-223.
- Kay, B.D., 1998.** Soil structure and organic carbon: A review. In: R. Lal, J.M. Kimble, E. and R.F. Follet (Editors), *Soils Processes and the carbon cycle, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 169-197.
- Khamsouk B, De Noni G and Roose E., 2002.** New data concerning erosion processes and soil management on Andosols from Ecuador and Martinique. In *Proceedings of the 12th ISCO Conference*, Tsinghua University Press, Beijing, China, II: 73-79
- Kimble, J.M.; Ping, C.L.; Sumner, M.L. and Wilding, L.P., 2000.** Andisols. In: M.E. Sumner (Editor in Chief), *Handbook of Soil Science*, CRC Press, Boca Raton, FL, USA pp. E-209/E-224.
- Kubota T, Ishihara A, Taniyama I, Katou H, and Osozawa S., 1990.** Erodibility of Andosols in Japan. *Nat. Inst. of Agro-Environ. Sci. Ibaraki (Japan) (mimeo)*.

- Lal, R., 1995.** Global soil erosion by water and carbon dynamics. In: R. Lal, J. Kimble, E. Levine and B.A. Stewart (Editors), *Soils and Global Change, Advances in Soil Science*, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 131-142.
- Lal, R., 1988.** Erodibility and erosivity. In: R. Lal (Editor), *Soil Erosion Research Methods*. Soil and Water Conservation Society, Ankeny, Iowa, 141-160.
- Lal, R., 2001a.** Myths and facts about soils and the greenhouse effect. In: R. Lal (Editor), *Soil Carbon sequestration and the greenhouse effect*, SSSA Special Publication n° 57, Soil Science Society of America, Inc., Madison, WI, USA, pp. 9-26.
- Lal, R., 2001b.** Fate of eroded soil organic carbon: Emission or Sequestration. In: R. Lal (Editor), *Soil Carbon sequestration and the greenhouse effect*, SSSA Special Publication n° 57, Soil Science Society of America, Inc., Madison, WI, USA, pp. 173-182.
- Lal, R., Kimble, J.M. and Follet, R., 1998.** Knowledge gaps and researchable priorities. In: R. Lal, J.M. Kimble, E. and R.F. Follet (Editors), *Soils Processes and the carbon cycle*, Advances in Soil Science, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 595-604.
- McKeague, J.A., Brydon, J.E. and Miles, N.M. 1971.** Differentiation of forms of extractable iron and aluminium in soils. *Soil Sci. Soc. Amer. Proc.*, 35: 33-38
- Meurisse, R.T. 1985.** Properties of Andisols important to forestry. In: *Taxonomy and management of Andisols. Proceed. of Sixth Int. Soil Classif. Workshop. Soc. Chilena de la Ciencia del Suelo*:53-67.
- Mizota, C. and van Reeuwijk, L.P., 1989.** Clay mineralogy and chemistry of soils formed in volcanic material in diverse climatic regions. *Soil Monograph 2*, ISRIC, Wageningen.
- Moore, T. 1998.** Dissolved organic carbon: Sources, sinks, and fluxes and role in the soil carbon cycle. In: R. Lal, J.M. Kimble, E. and R.F. Follet (Editors), *Soils Processes and the carbon cycle*, Advances in Soil Science, CRC Lewis Publishers, Boca Raton, FL, USA, pp. 281-292.
- Nanzyo, M., Dahlgren, R. and Shoji, S., 1993.** Chemical characteristics of volcanic ash soils. In: S. Shoji, M. Nanzyo and R.A. Dahlgren (Editors), *Volcanic ash soils: Genesis, properties and utilization. Developments in Soil Science 21*, Elsevier Science Publishers, Amsterdam, The Netherlands, pp. 145-187.
- Nelson, D.W. and Sommers, L.E., 1982.** Total carbon, Organic carbon and Organic matter. In: A.L. Page et al. Eds., *Methods of Soil Analysis. Part. 2: Chemical and microbiological properties*, pp. 539-579, Agronomy Monograph n° 9, 2nd Edition, Madison.
- Oades, J.M., Gillman, G.P. and Uehara, G., 1989.** Interactions of soil organic matter and variable charge clays. In: D.C. Coleman, J.M. Oades and G. Uehara (Editors), *Dynamics of soil organic matter in tropical ecosystems*, Niftal, University of Hawaii, pp. 69-95.
- Parfitt, R.L. and Henmi, T. 1982.** Comparison of a oxalate extraction method and an infrared spectroscopic method for determining allophane in soils clays. *Soil Sci. Plant Nutr.* 28: 183-190.
- Parfitt, R.L. and Wilson, A.D., 1985.** Estimation of allophane and halloysite in three sequences of volcanic soils, New Zealand. In: E. Fernández-Caldas and D.H. Yaalon (Editors), *Volcanic Soils. Weathering and Landscape relationships of soils on tephra and basalt*. pp. 1-8, *Catena Supplement 7*, Catena Verlag. Giessen, West Germany
- Parfitt, R.L., Theng, B.K.G., Whitton, J.S. and Shepherd, T.G., 1997.** Effects of clay minerals and land use on organic matter pools. *Geoderma*, 75: 1-12.
- Pla I. 1992.** La erodabilidad de los Andisoles en Latinoamérica. *Suelos Ecuatoriales*, Vol. 22, no. 1: 33-43.
- Poulenard, J., Podwojewski, P., Janeau, J.L. and Collinet, J. 2001.** Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian Páramo: effect of tillage and burning. *Catena*, 45: 185-207.
- Powers, J.S. and Schlesinger, W.H. 2002.** Relationships among soil carbon distribution and biophysical factors at nested spatial scales in rain forest of northeastern Costa Rica. *Geoderma*, 109, 165-190.
- Quantin P. 1994.** The andosols. *Trans. 15th World Congr. of Soil Sci. Mexico*. Vol. 6^a: 848-859.
- Richards, L.A., 1980.** Diagnóstico y rehabilitación de suelos salinos y sódicos. Ed. Limusa. Ciudad de México
- Rivas-Martínez, S., Wildpret, W., Díaz, T.E., Pérez de Paz, P.L., Del Arco, M. and Rodríguez, O. 1993.** Outline vegetation of Tenerife Island (Canary Islands). *Itinera Geobotánica*, 7: 5-168.
- Rodríguez Rodríguez, A., Gorrín, S.P., Guerra, J.A., Arbelo, C.D. and Mora, J.L., 2002a.** Mechanisms of soil erosion in andic soils of the Canary Islands. In: J. Juren (Editor), *Sustainable utilization of Global Soils and Water Resources*, Tsinghua University Press, Beijing, Vol. I, 342-348

- Rodríguez Rodríguez, A., Guerra, J.A., Gorrín, S.P., Arbelo, C.D. and Mora, J.L., 2002b.** Aggregates stability and water erosion in Andosols of the Canary Islands. *Land Degradation and Development*, 13:515-523
- Roose, E., Khamsouk, B., Lassoudiere, A. and Dorel, M. 1999.** Origine du ruissellement et de l'érosion sur sols bruns à halloysite de Martinique. Premières observations sous bananiers. *Bull. Réseau Erosion*, 19:139-147
- Saggar, S., Tate, K.R., Feltham, C.W. Childs, C.W. and Parshotam, A., 1994.** Carbon turnover in a range of allophanic soils amended with ¹⁴C-labelled glucose. *Soil Biology and Biochemistry*, 26: 1263-1271.
- Schnitzer, M., 1978.** Humic substances: Chemistry and reactions. In: M. Schnitzer and S.U. Khan (Editors), *Soil Organic Matter*, Elsevier Publishing Co., Amsterdam, pp. 1-64.
- Shoji, S., Dahlgren, R. and Nanzyo, M. 1993.** Classification of volcanic ash soils. In: S. Shoji, M. Nanzyo and R.A. Dahlgren (Editors), *Volcanic ash soils: Genesis, properties and utilization. Developments in Soil Science 21*, Elsevier Science Publishers, Amsterdam, The Netherlands, pp. 73-100.
- Soil Survey Staff, 1999.** *Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys*, 2nd Edition, USDA-NRCS-US Gov. Printing Office, Washington, DC.
- Van Noordwijk, M., Cerri, C., Woomer, P.L., Nugroho, K. and Bernoux, M., 1997.** Soil carbon dynamics in the humid tropical forest zone. *Geoderma*, 79: 187-225.
- Van Reeuwijk, L.P. 1993.** *Procedures for soil analysis. Fourth Edition*, ISRIC Technical Paper n° 9, Wageningen
- Warkentin, B.P. and Maeda, T., 1980.** Physical and mechanical characteristics of Andisols. In: B.K.G. Theng (Editor), *Soils with variable charge*, New Zealand Society of Soil Science, Lower Hutt, New Zealand.
- Wischmeier, W.H., Johnson, C.B. and Cross, B.V., 1971.** A soil erodibility nomograph for farmland and construction sites. *Journal of Soil and Water Conservation*, 26 (5): 189-193.
- Wischmeier, W.H. and Smith, D.D., 1978.** *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook N° 537*, US Department of Agriculture, Washington DC.
- Yamamoto, T. and Anderson, H.W. 1973.** Splash erosion related to soil erodibility and other forest soil properties in Hawaii. *Water Resour. Res.*, 9: 336-345.

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