Recovery and management of actual acid sulphate soils in Boyacá (Colombia)[1]

Recuperación y manejo de suelos sulfatados ácidos actuales en Boyacá (Colombia)[1]

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Summary: Acid sulphate soils (ASS), having very restricted use due to their extreme acidity, have been identified within the upper Chicamocha river basin, Boyacá (Colombia). This situation has led to increasing degradation of the land, rendering around 3,000 ha of land unproductive. Production alternatives are thus being sought for recovering these flat upland areas, currently suffering from ASS, as they do have agricultural potential. Soils were initially characterised and identified in a problem area so that possible management of such ASS could then be inferred from the initial study. Increasing doses of calcium hydroxide ($Ca(OH)_2$) (5 to 100 $t \cdot ha^{-1}$) were then evaluated and determined for neutralising extreme acid conditions in laboratory incubation assays (5-100 $t \cdot ha^{-1}$). Greenhouse and field tests (random block experimental design with 10 treatments and 4 repeats) were used for observing the response of *Avena sativa* as an indicator plant; just hen-dung (5-10 $t \cdot ha^{-1}$) and hen-dung mixed with lime (dry and wet matter) were also evaluated as amendment material. The experiments revealed the soils' chemical changes and reactions following these treatments: pH, Al, ECEC, % AL, % Ca, total S, Mn, Fe and P (i.e. after statistical correlations had been made). These studies led to the soils being recognised as non-coast actual ASS and classifying them as Typic Sulfaquept. The findings indicated that $Ca(OH)_2$ 12.5 $t \cdot ha^{-1}$ mixed with 10 $t \cdot ha^{-1}$ organic matter (hen-dung) represented the best treatment for obtaining the best *A. sativa* performance in terms of dry matter production, reflected in positive ASS chemical changes.

Additional key words: Actual acid sulphate soil (AASS), incubation test, calcium hydroxide, organic matter, iron sulphur.

Resumen: En el distrito de riego del Alto Chicamocha, ubicado en la parte central de Boyacá, se presenta degradación del suelo por condiciones sulfatadas ácidas (SSA) que afectan cerca de 3.000 ha, por lo que se buscan alternativas de producción que recuperen estas áreas planas con potencial agrícola. Inicialmente se caracterizaron e identificaron los suelos en un área problema modal para luego intervenir en su manejo. Para corregir las condiciones extremas de acidez se evaluaron y determinaron dosis de $Ca(OH)_2$ como enmienda a partir de pruebas de incubación en laboratorio. Mediante ensayos de invernadero y campo, a partir de un diseño experimental de bloques al azar con 10 tratamientos y cuatro réplicas, se observó la respuesta de *Avena sativa* a la aplicación de enmiendas: $Ca(OH)_2$ en dosis de 5 a 10 $t \cdot ha^{-1}$ y 10 $t \cdot ha^{-1}$ de gallinaza. A partir de la correlación estadística, se demostaron los cambios inducidos en la reacción y las condiciones químicas del suelo respecto de: pH, Al, CECE, %AL, %Ca, S total, Mn, Fe y P. Con ello se reconocen SSA actuales que se clasifican como Typic Sulfaquepts . Los resultados indican que el mejor tratamiento corresponde a la mezcla de 12,5 $t \cdot ha^{-1}$ de $Ca(OH)_2$ con 10 $t \cdot ha^{-1}$ de gallinaza, el cual dio mejores rendimientos de *A. sativa* expresados en una mayor producción de materia seca y en los cambios químicos positivos de los SSA.

Palabras clave adicionales: Suelos sulfatados ácidos actuales (SSAA), pruebas de incubación, hidróxido de calcio, gallinaza, sulfuros de hierro.

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Introduction

ACTUAL ACID SULPHATE SOIL (AASS) have developed throughout Colombia's continental areas, although they have only recently come to prominence in land-use planning, resulting from the detrimental environmental consequences that can result from such a disturbing process. In the upper Chicamocha river basin in Boyacá (Colombia) a large part of the agricultural lands formed by river flooding and lake sediment has been characterised as being actual non-coastal (Gómez and Castro, 2004).

Acid sulphate materials consist of saline soil or sediment containing a build up of iron sulphides (FeS) in the upper soil layer in flooded or anaerobic conditions. However, pyrite becomes oxidised to sulphuric acid. The sulphuric acid produced upon oxidation of pyrite lowers the pH in soil to extreme levels, at times being than 3.0 acidic. Soil becomes toxic, including increased aluminium, iron and (in some cases) manganese solubility; nutritional quality can become severely deficient (Bloomfield, 1972).

Poor development of most plants' roots caused by a reaction to ASS leads to loss of productivity. Such problems in Boyacá have arisen from drainage systems being made throughout the irrigation area. ASS conditions have frequently occurred in tropical marine areas and resulted from lake deposits or tailings from mining in flat coastal regions and continental areas in warm to cold climates (Dent and Dawson, 2000). ASSs in north-eastern Boyacá are derived from recent lake-fluvial sediment, the previous conditions forming ASS *in-situ*. Dear *et al.* (2002), Fitzpatrick (1996) and Dent's (1986) classification characterises these soils as being continental actual acid sulphate soil (AASS).

Non-coastal saline acid sulphate soil formation leads to the mobilization and accumulation of S and Fe, causing scalding discharge, which has now become a recognised phenomenon (Fitzpatrick, 1993, 1996). This phenomenon can occur in Colombia due to saline thermal-water directly present in the area (Castro and Gómez, 2003). Such non-coastal ASS conditions are now being sporadically reported in the Boyacá (GISSAT, 2004), Córdoba, and Valle del Cauca departments in Colombia (García, 1994). However, there has been limited identification of acid sulphate sediment soil in Colombia and there has been little research into their behaviour. ASS mainly occur in continental areas; non-coastal ASS conditions have not been adequately assessed in the region because of the poor state of knowledge regarding non-coastal ASS and their relationship to rising water table salinity and sodicity, reflecting dry and wet seasons.

This article reports research into continental ASS in Colombia, allowing more to be known about soil characteristics and their possible use and management in terms of farm productivity. This study was aimed at providing alternatives for recovering ASS and putting forward cultivation/production proposals for Boyacá's farmers located in the problem area. It was aimed at improving farmers' management of ASS by means of greater knowledge regarding their physical and chemical properties and applying lime and/or organic amendment. This research also attempted to provide alternatives for forage or organic (plant) fertilizer by using *Avena sativa* as a soil tolerance indicator plant.

The experiment was carried out in four stages. ASS were first located, identified and characterised in the problem area, starting from a study of the literature and analysing particular physical-chemical soil characteristics such as pH, Al, electrical conductivity (EC) and profile. Laboratory testing included applying lime to produce chemical changes in ASS reaction (pH). Lime and organic amendment were then assayed in greenhouse conditions, evaluating *A. sativa* as being a tolerant plant for extreme ASS conditions. Previous studies were corroborated by employing experimental field conditions. These research phases were then analysed, respective recommendations being carried out and discussed for the following stages, allowing research to focus on production problems and low fertility in these soils.

Materials and methods

A typical soil profile (Typic Sulfaquepts) was described for the Chicamocha Valley Irrigation Area; matrix colour was noted and samples were taken from representative areas along a straight line at fixed intervals and at depths of 0-25 cm, 25-50 cm and 50-75 cm below ASS surface. These horizon samples were then physically and chemically analysed. Laboratory methods employed for chemical soil analysis in all stages were as follows: pH was assessed using a glass electrode in soil, 1:1 water ratio, Walkley Black method for carbon, Bouyoucos hydrometer for texture after dispersion with sodium metaphosphate plus NaOH and electrical conductivity (EC) on saturated soil paste; exchangeable cation were extracted by unbuffered 0.5 M NH_4Cl solution (Truby

and Aldinger, 1985) and analysed by atomic absorption. Effective Cation Exchange Capacity (ECEC) was given as the sum of extracted cation; exchangeable acidity was assayed by Yuang's KCl (1 N) method and phosphorous by Bray II. Available Fe, Zn, Mn were assessed by EDTA extract and analysed by atomic absorption. Available sulphur was assayed by phosphate monocalcicum technique and analysed by colorimetric method.

pH (soil *in situ*) was measured (1:1 soil:water) as soon as samples had been taken in field condition; these were then analysed in the laboratory and compared for each horizon profile.

Incubation and lime were assayed for each horizon. Lime was evaluated with calcium hydroxide (existing source near to ASS) for neutralising extreme acidity; incubation was carried out with corrective growth 5, 10, 20, 40, 80 and 100 $t \cdot ha^{-1}$ doses. Curves were drawn for the chemical variables (S, Fe, Al, % Al, % Ca, pH) and statistically correlated.

Calcium hydroxide and dolomite were used as inorganic sources in 5, 10, 20, 40, 80, 100 $t \cdot ha^{-1}$ doses in green house conditions; hen-dung was applied as amendment in 5, 10, 20 and 30 $t \cdot ha^{-1}$ doses and compared with 10+5, 25+20, 50+30 $t \cdot ha^{-1}$ doses of lime hen organic fertilizer mixture. Changes concerning Al, pH and EC in ASS induced in soil and its effluent by treatment were evaluated and analysed using *A. sativa* as tolerant crop for evaluating dry and wet matter. A total random experimental design (Duncan-test) was employed; 22 treatments were applied using pots (kg capacity) plus four replications. The above variables were evaluated and analysed during the following 12 weeks, observing developments in ASS productivity.

The experimental field stage's object was recovery of adverse ASS conditions, the experimental phase's conclusions and recommendations thus providing farmers with production alternatives. *A. sativa* was used as a tolerant plant for evaluating dry matter during this stage. Calcium hydroxide and calcareous and organic matter were used as corrective measures. Treatment employed during this stage was 12.5, 25, 50 and 100 $t \cdot ha^{-1}$ lime and these doses mixed with 10 $t \cdot ha^{-1}$ hen-dung, using a random block experimental design (Duncan test) (0.05 p). ASS chemical changes and plant growth were analysed over a four-month period and statistically correlated. Technical recovery was attempted by implementing suitable drainage and using minimum tillage in ASS, allowing the best handling and productivity to be ascertained.

Results and discussion

Localization, identification and characterisation

ASS are located in flat river-basin areas resulting from recent lakes/fluvial areas in the Chicamocha river bed and former Quaternary deposits, these being directly influenced by hydrothermal saline water (Castro and Gómez, 2003).

Soil taxonomy (Soils Survey Staff, 2003) reflected site conditions and the associated pedological properties and processes characterising ASS (Dent and Ponds, 1995; Fitzpatrick, 1996). The parameters measured in the soil profile thus showed considerable variation (Table 1). Moisture was specified by water table.

The soils were classified as being a typical sapric, semiactive, isomesic Sulfaquept family, where the hydromorphic profile presented colours varying from black (A (0-25 cm) and Ab (50-75 cm) horizontal samples) to dark grey (Bj (25-50 cm) and Bgb (75 X) horizontal samples), contrasting with Bj horizontal samples' yellow redoxi-

Table 1. Initial ASS physical and chemical profile characteristics.

Taxonomical classification	25 cm depth horizon sample	Depth cm	Text. class	b.d g · cm^{-3}	pH	CO %	P mg · kg^{-1}	Al	Ca	Mg	K	Na	ECEC	Bases	Bases	Al	Ca	Salinity			S	Fe
								cmol(+) · kg^{-1}							Saturation (%)			Sat. Na %	EC	Class	mg · kg^{-1}	
Typic Sulfaquepts	A	0-25	F.L.	0.91	3.5	6.5	40.9	6.0	9.9	3.9	0.4	3.7	23.9	17.9	74.9	25.1	41.4	15.4	4.8	S_1Na	755	76
	Bj	25-50	F.L.	1.3	3.3	1.4	27.9	5.0	9.2	2.7	0.5	2.1	19.5	14.5	74.3	25.6	47.1	10.9	4.2	S_1	693	109
	Ab	50-75	F.L.	0.8	3.5	5.2	65.5	7.5	9.6	4.4	0.3	9.9	31.7	24.2	76.3	23.7	30.2	31.2	6.1	S_2Na	594	84
	Bgb	75-X	Ar.	1.4	4.8*	2.0	46.4	0.2	14.9	8.0	1.5	10.1	34.7	34.5	99.4	0.6	42.8	29.1	5.4	S_2Na	710	114

* pH evaluated in laboratory conditions for Bgb, in situ horizon sample was 6.8, close to neutrality.

morphic characteristics (jarosite). This formation represents a unique mixture of iron minerals that is indicative of a rapidly changing local environment and variation in Fe and S mineralisation rate (Bloomfield and Coulter, 1972; Dent, 1986; and Ludwig *et al.,* 1999).

The above matrix colours depended on redox concentration. A strong acid reaction was observed (A, Bj and Bgb presented a pH less than 3.5); the Bgb horizon presented a basic reaction accompanied by a high occurrence of organic material. High sulphur (800 mg $\cdot kg^{-1}$) and aluminium (10 cmol $\cdot kg^{-l}$) concentrations were observed; salinity (EC great than 5 dS $\cdot m^{-1}$), and sodicity (15%-32% sodium saturation) were analysed. These peculiar characteristics fit the inland (non-coastal) AASS category defined by Fitzpatrick (1993, 1996). The previous features accorded with extremely weatherable mineral soils, contributing towards increased salinity and sodicity, causing severe structural degradation of soil, water-logging and erosion, as well as poor quality water (pH dropped below 3.5 and EC was 8 dS $\cdot m^{-1}$). Surface expression developed into unsightly scalds, devoid of vegetation, and any part covered by *P. clandestinum* presented the poorest growing conditions, farming activity being completely lacking.

Physical properties

The characterised soil (Table 1) presented a mid texture, having bulk density ranging from 0.8 g $\cdot cm^{-3}$ (A-Ab, due to the accumulated influence of former organic material) to 1.3 g $\cdot cm^{-3}$ (former mineral and clay deposits). It presented a mass, sticky structure and cementation and compaction in all horizon samples. Fitzpatrick (1993) has reported that wetting leads to sulphuric conditions which destroy micro-aggregation (e.g. Bj horizon samples) by dissolving Fe and Al oxides; saline, low-strength soil develops, as does concentrated drying, whilst crystallisation of salt and iron minerals occurs on the soil surface by evaporation, producing a hard, impermeable soil layer and increased surface flow due to reduced infiltration.

Chemical properties

Table 1 gives the general information regarding these aspects. *In situ* pH showed that the soils were not extremely acid when they were waterlogged (Bgb horizon sample had a 6.8 pH), whilst A, Bj and Ab horizon samples were extremely acid. Acidification in oxidised biological and chemical conditions follows sulphuric acid formation; soil pH can drop below 4.0, depending on the season. This shows that an increase in exchangeable bases is directly correlated to depth and increased pH.

The carbon content denoted higher organic matter in A (124 g $\cdot kg^{-1}$ OM) and buried Ab horizontal samples (98,8 g $\cdot kg^{-1}$) and levels less than 50 g $\cdot kg^{-1}$ in other horizon samples (Bj, Bgb), due to high mineral content (Table 1). This figure was significant as it reflected low mineralisation. Brock *et al.,* (1987) have studied and shown the anaerobic conditions for organic matter breakdown lead, in turn, to sulphate becoming reduced to sulphite, resulting in sulphur fixation in an insoluble form, mainly as pyrite. The high concentration of total Fe and Al levels developed from sulphuric material during wet periods results in an extremely acid environment. Soil horizons presented weatherable mineral soil, presenting jarosite redoximorphic hydroxymetabasic characteristics (precipitated S, Fe and Al) (Bloomfield and Coulter, 1972; Dent, 1986; and Ludwig *et al.,* 1999).

The profile's very high electrical conductivity (EC) could have been due to the fact that this soil is influenced by hydrothermal water present in the area. Salinity (EC) and sodicity (% Na) increased with depths greater than 4 dS $\cdot m^{-1}$ and sodium saturation levels greater than 15%, respectively, in buried horizons (Ab and Bgb), indicating stagnant drainage due to the soil being localised in a flat geomorphological basin, as well as causing less infiltration and salt lixiviation in the wet season and salt evaporation and crystallisation on ASS surface during the dry season.

Incubation in laboratory test conditions

Table 2 presents incubation test results after applying lime. Lime was added at 100 t $\cdot ha^{-1}$ because of extreme acidity caused by sulphuric acid and high Al level in natural soil. Table 2 and Figure 1 show that the soil presented great buffering capacity so that, once the buffering capacity was exceeded, acid produced in the soil attacked the mineral clays, liberating up to 10 cmol $\cdot kg^{-1}$ Al, with a marked drop in pH to 3.5.

By contrast, aluminium became neutralised and precipitated around pH 4.8 when up to 30 t $\cdot ha^{-1}$ doses of lime were applied (probably due to precipitated gibbsite; Fink, 1972) and there was decreased toxic aluminium saturation (from 40% to 5%) and increased calcium saturation (from 40% to 80%). Figure 2 shows that increased concentration of other elements was sig-

Table 2. Chemical characteristics of Typic Sulfaquept horizon samples (0-25 cm) after applying doses of lime in laboratory incubation test conditions

$Ca(OH)_2$ t · ha^{-1}	pH	Ca	Mg	K	Na	Al	ECEC	Al	Ca	P	Mn	Fe	S	Zn
		cmol(+) · kg^{-1}						Saturation (%)			mg · kg^{-1}			
0	3.4	9.9	2.8	0.7	5.1	10.4	29.0	35.9	34.3	28.7	36.8	83	755	1.77
5	3.8	10.6	3.3	1.0	6.1	9.0	30.0	30.0	35.2	34.1	17.0	85	720	2.57
10	4.1	12.0	3.2	0.9	5.7	7.4	29.2	25.4	41.3	28.5	11.5	94	680	3.15
20	4.7	15.5	2.8	0.9	5.7	3.0	27.8	10.8	55.5	22.6	9.7	99	612	9.09
40	5.6	24.1	2.6	0.9	5.7	0.6	34.0	1.8	71.1	13.7	7.5	106	473	5.8
60	6.7	32.8	2.0	1.0	5.7	0.2	41.7	0.5	78.5	7.5	4.2	111	390	3.1
80	7.3	39.3	1.7	1.3	5.7	0.1	48.1	0.2	81.7	5.2	3.6	116	306	1.74
100	8.3	43.4	1.3	1.7	5.9	0.1	52.4	0.1	82.9	3.5	1.9	125	136	1.19

nificant for Fe and Cu and less pronounced for Mg and K or not significant (Na), whilst Mn, P and S decreased (from 755 mg · kg^{-1} to 135 mg · kg^{-1}). This probably indicates sulphate salt insolubilisation with Ca (i.e. gypsum, see Fortin and Beveridge's search for bacterial reduction in pyritic sediments, 1997).

ECEC increased with increased pH; this could be partly assigned to variable charge protonation and partly to silicate mineral incongruent or congruent dissolution (Dent, 1986); characteristics were thus dependent on pH in these soil charges. Previous tendencies in chemical properties after applying lime in greenhouse and field experiment conditions were observed here and thereby corroborated.

Greenhouse experiments

A sigmoid curve was obtained when analysing Al and pH, having an inflexion at pH 4.0, after the changes induced in soil due to the effects of calcareous and organic treatment were compared with exchangeable aluminium in greenhouse conditions (Figure 2). Exchangeable aluminium fell to zero at around pH 5.5 and

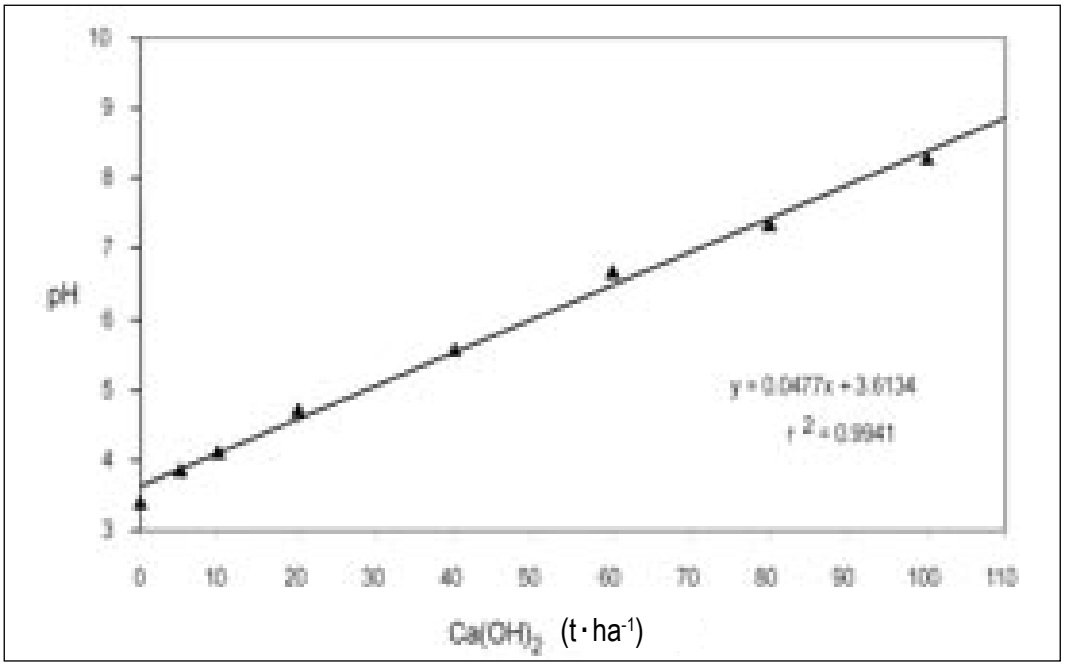

Figure 1. Relationship of pH in acid sulphate soil to doses of lime in laboratory incubation test conditions.

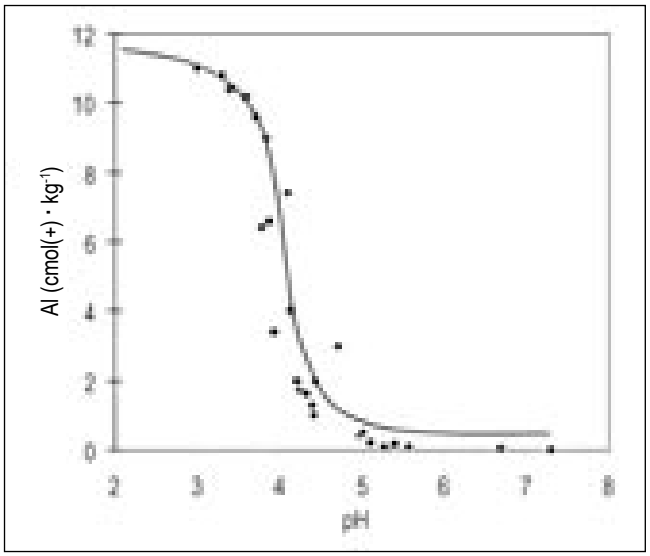

Figure 2. Relationship of interchangeable aluminium to ASS pH after applying calcareous treatment and organic amendments in experimental green-house conditions.

above. pH thus seemed to be pH buffered by mineral clays where a range of 2 to 8 cmol(+) · kg^{-1} exchangeable aluminium may be found. These results correlated with incubation test results. EC presented no significant change in all soil treatments; therefore, lime alone had no positive effect on desalinisation.

The best treatments regarding physical and chemical dynamics in acid sulphate soil (ASS) in terms of greenhouse *cf* control treatment (Table 3) were 25 and 50 t · ha^{-1} $Ca(OH_2)$ with 49.07 t · ha^{-1} and 54.83 t · ha^{-1} dry biomass, respectively (related to previous doses obtained in incubation tests regarding less aluminium toxic acidity) and 50 t · ha^{-1} dolomite lime and 25+20 and 50+30 t · ha^{-1} $Ca(OH_2)$+M.O mixture doses, indicating a positive response in dry biomass production (41.09 t · ha^{-1}, 48.03 t · ha^{-1} and 54.36 t · ha^{-1}). This data was reflected by increased pH and considerably decreased initial soil salt content and toxic Al.

Evaluating lime and organic amendments in field conditions

The chemical changes presented during this phase correlated to previous stages. The best treatment was 12.5 t · ha^{-1} $Ca(OH)_2$ mixed with 10 t · ha^{-1} organic matter, obtaining the best *A. sativa* production in dry matter (Table 4, Figure 3). This was reflected in ASS's positive chemical changes.

The amount of lime added was excessive because this treatment increased pH by 2 (3.5 to 5.5), pH ranging from 5.5-6.0 decreased salt and acid content and aluminium, manganese, and the sulphur concentration was fixed by the gypsum in the soil; there was greater P assimilation and nutritional equilibrium for the indicator plant grown and high sulphuric acid and Al production levels (10 cmol · kg^{-1}). Great buffering capacity was shown due to these soils' peculiar characteristics. Soil having doses greater than 50 t · ha^{-1} $Ca(OH)_2$ was seen to be over-limed (Figure 4). Over-limed soil, soil having just hen-dung (10 t · ha^{-1}) and the initial soil presented restricted development and recovery, indicating adverse conditions in ASS. Less plant productivity was observed in these cases (Table 4, Figure 4).

Table 3. Sources and doses of lime and organic amendment used when growing *A. sativa* in fresh matter in experimental greenhouse conditions (50 days after emergence).

Treatment No	Sources and mixtures	t · ha^{-1} dose	*A. sativa* grown in fresh matter *		Duncan test
			g/pot	t · ha^{-1}	
2	$Ca(OH)_2$	10	23.44	31,05	ef**
3	$Ca(OH)_2$	25	37.05	49,07	abc
4	$Ca(OH)_2$	50	41.40	54,83	ab
5	$Ca(OH)_2$	100	13.29	17,61	g
6	Dolomite lime	10	29.58	39,17	cdef
7	Dolomite lime	25	37.83	50,09	abc
8	Dolomite lime	50	31.02	41,09	cde
9	Dolomite lime	100	26.16	34,65	def
10	Organic matter (OM)	5	2.13	2,81	h
11	Organic matter (OM)	10	5.24	6,90	h
12	Organic matter (OM)	20	7.51	29,86	f
13	Organic matter (OM)	30	23.32	30,89	ef
14	$Ca(OH)_2$ + OM	10+5	24.25	32,12	def
15	$Ca(OH)_2$ + OM	10+10	29.62	39,23	cdef
16	$Ca(OH)_2$ + OM	25+20	36.26	48,03	abc
17	$Ca(OH)_2$ + OM	50+30	41.04	54,36	ab
18	Dolomite + OM	10+5	34.99	46,35	bc
19	Dolomite + OM	10+10	32.14	42,56	cd
20	Dolomite + OM	25+20	34.82	46,12	bc
21	Dolomite + OM	50+30	31.44	41,63	cde
22	Control	0	10.69	4,72	h

* Mean values.
** Different letters indicate significant differences at $P < 0.05$, CV = 12.2.

Table 4. Sources and doses of lime and organic amendment used when growing *A. sativa* in dry matter (t · ha^{-1}) in experimental field conditions.

Treatment No	Sources and mixtures	Dose t · ha^{-1}	*A. sativa* grown in dry matter *		Duncan test
			t · ha^{-1}	%	
1	$Ca(OH)_2$	12.5	3.62	40.5	fg**
2	$Ca(OH)_2$	25	5.06	56.5	e
3	$Ca(OH)_2$	50	6.21	69.46	d
4	$Ca(OH)_2$	100	4.87	54.5	e
5	$Ca(OH)_2$ + OM	12.5	8.94	100	a
6	$Ca(OH)_2$ + OM	25	7.75	86.6	b
7	$Ca(OH)_2$ + OM	50	7.29	81.5	bc
8	$Ca(OH)_2$ + OM	100	4.22	47.0	ef
9	Organic matter (OM)	10	6.87	76.8	cd
0	Control	0	2.99	33.5	g

* Mean values.
** Different letters indicate significant differences at $P < 0.05$, CV = 8.27.

Salinity may have played a part in the failure of most crops grown in ASS, but *A. sativa* presented great tolerance to these adverse conditions, presenting itself as an alternative for establishing forage or as a natural fertiliser. However, a major factor hampering productivity appeared to be severe acidity having pH values ranging from 3 to 3.5 and 5 to 10 cmol(+) · kg^{-1} Al as a result of sulphuric acid being produced on the surface due to pyrite biogeochemical oxidation.

High buffer capacity was observed by using increased doses of lime (calcium hydroxide) up to 100 t · ha^{-1} due to producing soluble acid, acid salt and high exchange Al concentration (10 cmol(+) · kg^{-1}). Applying lime and organic matter (OM) amendment generally led to positive performance regarding initial soil, mainly 12.5 t · ha^{-1} $Ca(OH)_2$ + 10 t · ha^{-1} doses of organic matter, where a considerable reduction in manganese, sulphur, exchangeable aluminium and sodium saturation were observed at pH 5-5.5, accompanied by greater assimilation of other essential elements in normal *A. sativa* development and growth.

The best technique for managing acid sulphate soil in this area lies in avoiding disturbing them or draining them; it is therefore important to know where ASS are likely to be found to avoid disturbing them. Detailed maps must thus be produced for this purpose and for later studies forming part of an unproductive ASS recovery programme. This research forms the basis for a first approach towards managing ASS in Colombia and further research regarding them, as current information in this country remains very limited.

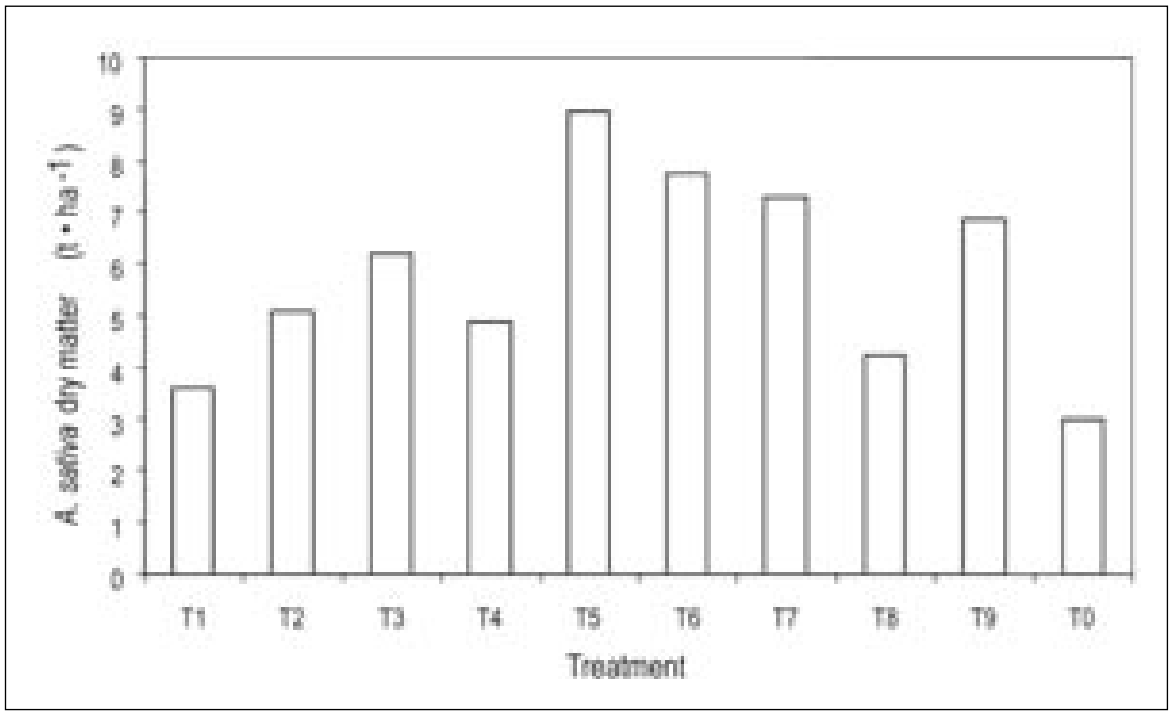

Figure 3. *Avena sativa* dry matter *cf* calcareous and organic treatments (Table 4) used in experimental field conditions at 90 days after emergence.

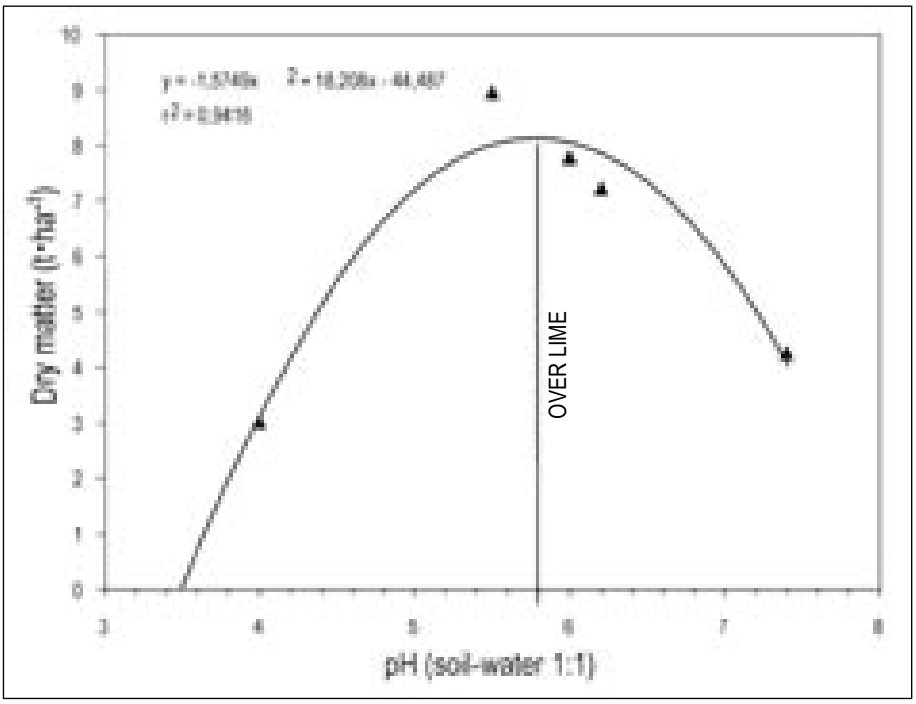

Figure 4. Over-lime in ASS, comparing *Avena sativa* dry matter ($t \cdot ha^{-1}$) to pH ASS after applying lime in experimental field conditions.

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