

# Liming Effects on the Stability and Erodibility of Some Brazilian Oxisols

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## ABSTRACT

The effects of liming on the aggregate stability and erodibility of three Oxisols in Parana State, southern Brazil, were studied. Two soils from Londrina, one in a 10-yr coffee (*Coffea* sp.) plantation (LC), and the other in a secondary mixed hardwood forest (LM), were compared with a third Oxisol from Cascavel, also under secondary mixed hardwood forest (CA), to give a range of surface organic-C contents in the order  $CA > LM > LC$ . Lime was applied to replicated field plots at each site to neutralize 0, 25, 50, 100, 200, and 400% of total exchangeable acidity. Acid was also added to the Londrina soils to reduce initial soil pH to that of the Cascavel soil. Changes in aggregate stability, soil splash, and water erosion were measured. Lime application decreased the weight percentage of 2.0 to 4.0-mm-diam. aggregates and mean weight diameter (MWD) of aggregates in Cascavel soil, but had no effect on the other two soils. Liming decreased the apparent clay content of all three soils, and increased water-dispersible clay on the LC soil. There were no significant effects of liming on soil splash, in part because of the high experimental variability of measurement. Soil erosion, measured on the field plots with a portable rainfall simulator, was in the order  $LC > LM > CA$ , a trend that corresponded to the decreasing organic-C contents of the soils. Liming significantly decreased erosion on the LC soil, and had no effect on the other two soils. The study suggests that, while there may be some short-term structural degradation caused by liming, the long-term effect is to reduce water erosion.

SOIL EROSION has become a major problem in southern Brazil because of large-scale deforestation and conversion of land to intensive cultivation for crop production. This is particularly true in the state of Parana, where forest cover has declined from the original level that was as high as 95% to the present level of <5% (Castro, 1988). Intensive cultivation of soybean, (*Glycine max* [L.] Merr.), coffee, and wheat, (*Triticum aestivum* L.) have resulted in severe declines in soil organic-matter contents, and use of large, heavy farm equipment has produced compacted soils with poor structure and infiltration that are susceptible to erosive rainfall. Use of structural measures such as large, broad-based terraces has failed to halt the soil degradation caused by water erosion.

The major soils in the crop-producing area of Parana are in the Third Plateau, and the soils of this region are primarily Hapludox (Red Latosols) (Castro, 1988). These are residual mineral soils formed in basalt, non-hydromorphic, with an Oxic B horizon. They are red-colored (10R to 5YR), very deep (3-10 m), very porous, friable, and well drained. They have high contents of Fe and Al sesquioxides, as well as Ti and Mn

oxides, and also contain kaolinite. Despite the high structural stability of the surface horizons of these soils, the subsurface horizons have a weaker, pulverized structure known as *coffee powder* (Empresa Brasileira de Pesquisa Agropecuaria, 1984). Erosion is a major hazard on these soils because of a rapid decline in organic-matter content with intensive cultivation following forest clearing, compaction and reduced structural stability, and the geomorphology, which is dominated by long, convex slopes (Castro, 1988).

The Oxisols are characterized by variable-charge soil constituents (Fe and Al oxides, kaolinite, and organic matter). They have PZC near pH 4, and natural soil pHs are typically near the PZC. Under these conditions, soil colloids are flocculated as a consequence of the high Al activities, interactions of positively charged Fe and Al oxides (PZC  $\approx 7-8$ ) with negatively charged kaolinite (PZC 3.5-5), and low net colloid particle charge (Uehara and Keng, 1975). The protonation of particle surfaces of these soils reduces interparticle cation bridging. Therefore, at low pH, aggregation is probably promoted only by organic matter through interactions with clay minerals, and by cementation with Fe and Al oxides.

As these soils are limed, a number of chemical, physical, and biological processes occur simultaneously. The effects of these processes can be to reduce or promote aggregate stability (Tama and El-Swaify, 1978). As soil pH is increased with liming to  $\approx 6$ , the net negative particle charge of these Oxisols (PZC of 4) will be increased, increasing interparticle repulsion. Charge interactions of kaolinite and gibbsite should also decrease. As lime is dissolved in these acid soils, and if fertilizer is also applied, there will be a short-term increase in soil solution ionic strength. This will result in increased particle charge as pHs are shifted away from the PZC (Sposito, 1984, p.217-224.), and will increase particle repulsion. At pHs closer to the PZC, increased electrolyte may increase flocculation (Miller and Baharuddin, 1986). On the other hand, liming will increase biological activity and the formation of polysaccharides, which promote aggregation (Emerson et al., 1986). High Ca concentrations and high ionic strength can also promote flocculation through cation bridging and reduction of double-layer thickness (Sposito, 1984, p. 217-224.).

These apparently conflicting effects of liming on the stability of soils of variable charge led us to study the effects of modifying soil pH and surface charge by liming on: (i) aggregate stability, (ii) soil splash (soil detachment by raindrop impact), and (iii) soil erodibility of some Oxisols of Parana.

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**Abbreviations:** LC, Londrina coffee plantation soil; LM, Londrina forest soil; CA, Cascavel forest soil; MWD, mean weight diameter; PZC, point of zero charge; IAPAR, Instituto Agronomico do Parana; CDB, citrate-dithionite-bicarbonate; PZSE, point of zero salt effect; GMD, geometric mean diameter; AS%, percent aggregate stability; EI, erosivity index; CEC, cation-exchange capacity; AS index, aggregate-stability index; WDC, water-dispersible clay.

## METHODS AND MATERIALS

Three experimental sites were selected at two locations in Parana State, Brazil. The Londrina site is on the grounds of the main experiment station of IAPAR. The LM site is in secondary mixed hardwood forest, a small portion of which was cleared in January 1986 for the experiment. The LC site is  $\approx 100$  m from the LM site, and is a coffee plantation in continuous production for about 10 yr. The Cascavel site (CA) is in a secondary bamboo (*Bambusa* spp.) forest 2 km north of the town of Cascavel, and the experimental area was established in January 1986. The soils at the three sites are classified as very fine, ferruginous, isothermic Rhodic Hapludox. A full description is given by Castro (1988).

### Soil Characterization

The soils were sampled by horizon from each site for characterization and for classification. In addition, bulk surface horizon samples were taken for some of the laboratory studies, as were samples from each of the lime-treatment plots. Characterization data are presented here for the surface 5 cm of unlimed areas. Texture was determined by pipette/sedimentation following ultrasonic dispersion in water (Gee and Bauder, 1982). Bulk density was determined on 100-cm<sup>3</sup> soil cores taken with a hand auger. Pore-size distribution was calculated from H<sub>2</sub>O desorption of undisturbed cores collected in 100-cm<sup>3</sup> cylinders and water saturated for 24 h. Moisture content was determined after equilibrium at 0.001, 0.01, 0.03, 0.1, 0.3, and 1.5 MPa. Micropores were based on H<sub>2</sub>O content at 0.01 MPa (calculated to be  $<14.7 \mu\text{m}$ ). Mineralogy of the clay-size fraction was determined by x-ray diffraction of K- and Mg-saturated samples for semiquantitative estimation of kaolinite and 2:1 phyllosilicates; gibbsite and kaolinite were also determined by differential scanning calorimetry (Dixon, 1966). Citrate-dithionite-bicarbonate-extractable Fe was determined by the method of Mehra and Jackson (1960). Soil pH was determined in 0.02 M CaCl<sub>2</sub> (1:2.5 soil/solution). Exchangeable cations were extracted with 1 M KCl; Ca and Mg were determined by atomic-absorption spectroscopy, and Al was determined colorimetrically by the modified ferron method (Kubota et al., 1986). Potential acidity was determined by extraction with 0.5 M Ca(OAc)<sub>2</sub> (pH 7; 1:10 soil/extractant) for 15 min, the suspension was allowed to stand overnight, and then it was titrated to a phenolphthalein end point (Vettori, 1948). Organic C was determined by wet oxidation (Walkley, 1947). Point of zero salt effect was measured by acid and base titration in NaCl and CaCl<sub>2</sub> at ionic strengths of 0.001, 0.01, 0.1, and 1.0 mol/L. Regression analysis (Castro, 1988) was used to fit the titration data. The regression equations were also used to calculate particle charge from pH and ionic-strength measurements in the soil-splash studies (see below).

### Field Liming Study

Field plots (1 m<sup>2</sup>, four replicates in a randomized block design) were laid out at each site. Dolomitic limestone (0.25 mm or  $<60$  mesh, 32.62% CaO, 18.33% MgO, 104% CaCO<sub>3</sub> equivalent, 98% total neutralizing power) was applied at rates to neutralize 0, 25, 50, 100, 200, and 400% of total exchangeable acidity. Soil samples were equilibrated at these lime rates in the laboratory for 60 d, at which time soil pH was determined. From regression of soil pH vs. lime addition, field lime rates were selected to achieve soil pHs of 3.5, 4.5, 5.5, 6.5, and 7.5. In addition, acid (0.2 M HCl) was added to one set of plots on the Londrina soils to lower pH to that of the unlimed Cascavel soil, which had a lower natural pH. Reagents were added by hand and mixed with a hand trowel to a depth of 20 cm. The plots were then left unattended prior to sampling except for periodic hand weeding to remove emergent vegetation. Soils were not sampled

for aggregate-stability and soil-splash measurements until about 6 mo after lime application.

### Aggregate Stability

Aggregate stability was determined by the wet-sieving method of Yoder (1936). Field samples were screened to collect the  $<4$ -mm fraction, which was then air dried. Samples were placed on a set of nested sieves of 4- to 2-, 2- to 1-, 1 to 0.5-, 0.5- to 0.25-, and  $<0.25$ -mm pore size and wet by capillary rise for 15 min. They were then shaken for 10 min and the soil on each sieve was collected, oven dried, and weighed. Data were used to calculate MWD, GMD and AS% (Kemper, 1965; Kemper and Chepil, 1965).

### Soil Splash

Soil detachment by raindrop impact (here described as soil splash) was measured by means of a falling-drop tower (Al-Durrah and Bradford, 1981) constructed at IAPAR. A drop former, built to specifications of Mutchler and Moldenhauer (1963), was used to produce drops of 5.2-mm diam. at a terminal velocity of 9.0 m/s. Details of the falling-drop tower are given in Castro (1988). Soil samples were taken from the 0 to 5-cm depth of each lime or acid treatment plot, and additional samples were taken from areas between plots. Splash was measured as the total mass of soil (oven-dry weight) detached by 10 water drops and expressed as mg/drop. Deionized double-distilled water was used for the splash experiments.

Two studies on splash were conducted. In the first, unground soil samples from each lime and acid field plot treatment were screened to recover the  $<2$  mm fraction; 120-g samples were placed in metal retaining cylinders without compaction and water saturated by wetting from the bottom; the cores were then placed on a tension table at  $-10$  kPa until they reached equilibrium. This resulted in average bulk densities of 1.07, 1.00, and 0.99 g/cm<sup>3</sup>, and moisture contents of 12, 20, and 21% (by weight) for the LC, LM, and CA soils, respectively. Particle-size distribution and WDC were also determined on these field samples in conjunction with the splash study. Samples for particle-size distribution were dispersed by addition of 2 M NaOH (20 g of soil, 145 mL of H<sub>2</sub>O, 5 mL of 2 M NaOH; shaken for 2 h with 10 g sand  $>0.5$ -mm diam.) (Camargo et al., 1986), compared with the original site characterization, performed in the Ohio State University Soil Characterization Laboratory, in which the samples were dispersed only by ultrasonic vibration. Ultrasonic dispersion tended to break down fine aggregates more than the NaOH treatment. Water-dispersible clay was determined by shaking in water as discussed above, except that NaOH was excluded (Camargo et al., 1986). Extracted soil solution was analyzed for electrical conductivity in order to estimate equilibrium ionic strength. Surface charge was calculated from the PZSE titration curve regression equations.

In the second study, effects of pH and ionic strength on splash were investigated on soil samples from untreated areas between the lime and acid plots. Target soil pHs of  $\approx 2$ , 4, and 7 were established by addition of HCl or NaOH at ionic strengths of 0.001, 0.01, and 0.2 mol/L as NaCl. Screened soil samples were placed in metal cylinders (100 cm<sup>3</sup>) with cheesecloth on either end. The cylinders were immersed in solutions to produce the desired pHs and ionic strengths for 3 d, and then they were placed on a suction table at  $-4$  kPa until they reached equilibrium. Under suction, there was some subsidence of the soil in the cylinders, resulting in a final bulk density of 1.36 g/cm<sup>3</sup> and a moisture content of 40% by weight. A second set of cylinders was prepared by packing the cylinder with dry soil to a bulk density of 0.96 g/cm<sup>3</sup>, followed by immersion in the solutions and placement on the suction table. The final moisture content was 35% by weight.

### Soil Erosion

The lime and acid field plots were subjected to simulated rainfall by use of a portable rainfall simulator based on the design of Roth et al. (1985). A metal frame 0.5 by 0.5 m was placed in the center of each plot. Treated well water for drinking was used with the rainulator at Londrina, and untreated well water at Cascavel. Rainfall was applied to an area 0.68 by 0.68 m. Two rains were applied, the first at an intensity of 63 mm/h, and the second at 127 mm/h. The first rain was applied until there was complete soil saturation, as evidenced by the onset of runoff. The second rain was then applied for 20 min. The EI value for the second rain was 1373 (MJ mm/ha h) (Foster et al., 1981). Soil loss was calculated as kilogram dry solids per hectare obtained by oven drying and weighing the runoff samples.

## RESULTS AND DISCUSSION

### Soil Characterization

The Londrina soils contained 25 to 28% CDB-extractable Fe, 6 to 9% gibbsite, 62 to 65% kaolinite, and 2 to 4% Al-interlayered vermiculite. There were no differences in mineralogy between the coffee and forest sites. In contrast, the Cascavel soil contained half as much kaolinite (28–30%), a similar quantity of CDB-extractable Fe (28–31%), and four to five times as much gibbsite (30–31%). This soil also contained more Al-interlayered vermiculite (6–12%) than the Londrina soils. Hematite was the dominant Fe oxide in both soils; goethite was more abundant in the Cascavel soil, although hematite was still the dominant Fe mineral. Similar mineralogies have been reported by Fasolo (1978) and Pavan et al. (1985).

Physical properties of the three soils by horizon are given in Table 1. The high clay contents and low bulk densities of these soils are typical of Oxisols (El-Swaify, 1980; van Wambeke et al., 1983). Likewise, the high total porosity and high content of micropores have been reported by others (El-Swaify, 1980; van Wambeke et al., 1983; Kemper and Derpsch, 1981). There were few differences in physical properties between the three soils except for slightly less total clay in CA than in LC or LM.

Chemical properties of the study-site soils are given in Table 1. Organic-C content was in the order CA > LM > LC. Soil pH on all three sites was in a narrow range between 3.8 and 4.8. The highest pH was on the coffee site (LC). Lowest pH was on the CA soil. Cation-exchange capacity was highly correlated with total organic-C content on all three soils ( $R^2 = 0.81$ – $0.98$ ).

Exchangeable acidity dominated the CEC of all three soils and was predominantly  $H^+$ . Exchangeable acidity

was primarily a function of CEC and pH. Exchangeable Al was low in the LC soil, while exchangeable Ca and Mg were greater in this soil than in the two forested soils, probably as a result of coffee fertilization.

The PZSE values for the three soils were quite similar and in the range reported for other Brazilian Oxisols (van Raij and Peech, 1972; Morelli and Ferreira, 1987). The PZSE values in  $CaCl_2$  for LC, LM, and CA were 3.53, 3.45, and 3.75, respectively; the corresponding values in NaCl were 3.30, 3.20, and 3.70. The PZSE value was lower than the pH in the Londrina soils and was the same as the pH in CA. Oxisols in their natural condition tend to have pHs near their PZCs (van Wambeke et al., 1983), and in this condition have little WDC (Uehara and Keng, 1975).

### Aggregate Stability

Aggregate distribution by size class is presented in Table 2 for the lime and acid field plot treatments. Overall, there was a greater mass of small (<0.25-mm)

Table 2. Changes in aggregate-size distribution with soil pH for the Londrina and Cascavel sites (mean of four replicates).

Soil type	pH	Soil retained by sieve class				
		<0.25 mm	0.25–0.5 mm	0.5–1.0 mm	1.0–2.0 mm	2.0–4.0 mm
		%				
Londrina coffee plantation	3.38	25.67	20.82	26.35	14.40	12.76
	4.38	19.41	20.11	27.57	16.12	16.79
	4.60	18.55	18.49	26.38	18.25	18.32
	4.98	16.48	16.87	27.52	19.75	19.38
	5.38	19.72	19.08	28.14	17.06	15.99
	5.50	18.44	17.39	27.41	18.82	17.93
	5.77	20.85	18.85	26.93	16.90	16.48
<i>F</i> test	6.05	19.15	17.17	26.78	18.46	18.45
		2.9*	2.5*	1.1NS	5.8**	2.0NS
Londrina mixed forest	3.10	13.63	19.43	29.71	18.75	18.49
	4.23	9.32	17.87	34.60	21.34	16.87
	4.33	10.92	17.57	31.57	20.87	19.08
	5.15	9.86	17.37	32.69	20.88	19.20
	5.33	8.60	18.86	37.34	19.90	15.31
	5.48	4.37	17.13	41.82	19.43	17.24
	5.55	12.02	14.75	32.19	21.33	19.71
<i>F</i> test	5.95	10.97	15.30	34.59	21.90	17.24
		2.0NS	1.0NS	4.7**	1.7NS	0.5NS
Cascavel mixed forest	3.60	19.52	15.08	21.31	17.69	26.40
	3.93	16.33	18.79	23.56	18.17	23.15
	4.88	18.50	18.38	22.81	17.29	23.01
	5.00	18.21	18.54	22.19	16.34	24.72
	5.45	21.06	18.45	21.85	16.70	21.95
	5.90	21.01	19.57	27.17	17.25	15.00
	5.98	25.31	17.35	24.08	16.78	16.48
<i>F</i> test		2.6NS	1.8NS	1.9NS	0.3NS	10.9**

\*, \*\*, NS Significant at the 0.05, 0.01 probability levels, and nonsignificant, respectively.

Table 1. Selected physical and chemical properties of the surface 5 cm of the Londrina and Cascavel soils, Parana, Brazil.

Soil type				Bulk density	Porosity			pH	C	KCl extractable				
	Sand	Silt	Clay		Total	Macro (>14.7 μm)	Micro (<14.7 μm)			CEC†	H+Al	Al	Ca	Mg
	% (w/w)				g/cm³	g/kg								cmol <sub>c</sub> /kg
Londrina coffee plantation	3.2	12.0	85.0	0.99	65.4	24.7	40.7	4.4	15.9	9.56	5.21	0.10	2.52	1.23
Londrina mixed forest	5.0	11.0	84.0	0.85	68.2	30.3	37.9	4.2	25.9	13.75	8.52	0.53	4.02	0.86
Cascavel mixed forest	6.2	14.5	79.3	0.78	71.9	34.4	37.5	3.7	45.4	16.52	13.93	1.94	1.87	0.45

† Cation-exchange capacity.

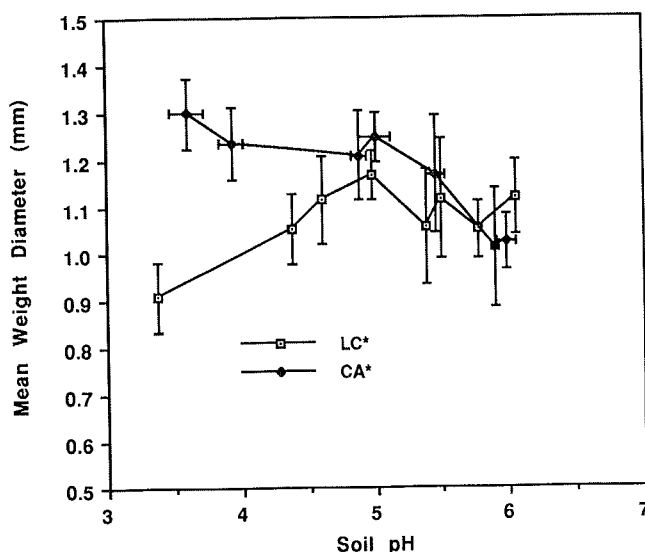


Fig. 1. Effect of liming on mean weight diameter (MWD) of aggregates in Londrina Cafe and Cascavel soils.

aggregates and less of the 0.5 to 1.0-mm aggregates in the cultivated Londrina soil compared with the same soil in forest. This effect is expected as a result of lower organic C (Table 1) and greater soil disturbance in the cultivated soil. The Cascavel soil had a greater mass of large (2.0–4.0-mm) aggregates than either of the Londrina soils.

Increased pH increased the 1.0 to 2.0-mm size aggregates and decreased those in the 0.25 to 0.5- and <0.25-mm classes of LC soil (Table 2). Most of this effect was associated with the lowest pH treatment, which was achieved by acid addition. This relatively harsh treatment may have resulted in degradation of the larger aggregates (the 2.0–4.0-mm aggregates were also decreased, but not significantly). In the LM soil,

increased pH also increased the 0.5 to 1.0-mm aggregates; again, the effect was primarily associated with acid addition at the lowest pH (Table 2). When the acid treatments were omitted from analysis of the data for the Londrina soils, there was no effect of pH on aggregate-size distribution. In the CA soil, where acid was not added, there was a significant and regular decrease in the 2.0 to 4.0-mm aggregates. This decrease was associated with nonsignificant increases in the other aggregate classes.

There were significant effects of liming on MWD in the LC and CA soils, but no significant effect on LM. The results for the LC and CA soils are presented in Fig. 1. The significantly lower MWD at the lowest soil pH on the LC soil was due to the acid addition required to produce this pH, as discussed above. Liming decreased MWD on the CA soil as a result of the decreased percentage of aggregates in the 2.0 to 4.0-mm range. The results for the GMD parameter were identical in trend and in significance to those for MWD (data not shown). Whereas MWD reflects the proportion of large aggregates, GMD reflects the dominant aggregate-size class. The data in Table 2 shows that the 2.0 to 4.0-mm aggregate-size class was dominant in the CA soil. There were no significant effects of liming on AS index (data not shown), except for a reduction with acid addition on the LC soil. The AS index is an indication of overall aggregation.

The results for the Cascavel soil suggest that liming has resulted in breakdown of the large (2.0–4.0-mm) aggregates that dominate this forested soil. Disturbance of the soil by lime addition can be discounted as an effect on aggregate breakdown because care was taken to equalize soil mixing in all plots. It is not clear from these results if the effect of liming on aggregate stability is chemical or biological. Liming may increase dispersion by increasing surface charge and interparticle repulsion. Likewise, a pH increase would decrease

Table 3. Effects of liming on particle-size distribution, water-dispersible clay, and soil splash for the Londrina and Cascavel soils.

Soil type	pH	Net charge cmol/kg	Sand	Silt	Clay	Water- dispersible clay	Soil splash
							mg/drop
Londrina coffee plantation	3.65	−0.4	13.75	12.50	73.75	46.0	1.68 (1.9)†
	4.53	−3.6	12.50	14.50	73.00	49.7	0.38 (0.3)
	5.55	−6.1	13.00	17.25	69.75	50.9	2.18 (0.7)
	5.80	−6.7	12.75	18.25	69.00	53.3	0.55 (0.5)
	5.98	−7.1	13.50	19.25	67.25	53.7	0.54 (0.5)
	5.93	−7.0	12.50	18.25	69.25	51.1	0.52 (0.4)
	5.98	−7.1	12.50	19.75	67.25	49.4	0.60 (0.5)
<i>F</i> test			NS	11.32*	7.54*	3.14*	NS
Londrina mixed forest	3.38	+0.9	12.50	12.00	75.50	39.0	1.81 (0.6)
	4.05	−1.6	13.25	14.75	72.00	40.9	0.83 (0.2)
	4.58	−3.4	13.50	14.25	72.25	44.6	1.07 (0.8)
	5.80	−7.2	12.25	17.00	70.75	46.6	0.54 (0.6)
	5.83	−7.3	13.50	15.25	71.25	44.0	1.75 (1.2)
	5.98	−7.8	15.50	15.00	69.50	47.3	0.15 (0.0)
	5.95	−7.7	15.75	16.25	68.00	45.3	1.07 (0.6)
<i>F</i> test			NS	NS	3.21*	NS	3.21*
Cascavel mixed forest	3.83	+0.5	20.00	18.25	61.75	33.3	0.46 (0.5)
	4.50	−1.4	18.25	19.75	62.00	34.5	1.27 (1.2)
	5.85	−4.3	20.75	21.25	58.00	39.3	1.10 (0.2)
	5.95	−4.6	22.00	21.75	56.25	38.7	0.24 (0.1)
	5.68	−3.9	21.75	21.25	57.00	34.6	0.41 (0.2)
	6.13	−5.1	24.25	19.75	56.00	36.4	0.64 (0.7)
	6.08	−5.0	31.50	18.50	50.00	28.7	1.15 (0.6)
<i>F</i> test			10.69*	5.68*	13.17*	NS	NS

\*NS Significant at the 0.05 probability level and nonsignificant, respectively.

† Standard deviation.

the positive charge on gibbsite and reduce kaolinite-gibbsite charge attraction. On the other hand, Ca addition and increase in pH could increase interactions of organic matter with soil clays and promote cation bridging. This would increase both flocculation and aggregation. It is also possible that the effect of liming the Cascavel soil on large-aggregate breakdown is due to increased biological activity and organic-matter decomposition. Soil samples from this site incubated in the laboratory gave increased  $\text{CO}_2$  evolution with lime addition (data not shown). The degradation in organic matter with liming may have more than offset the production of polysaccharides by increased microbiological activity, or the precipitation of  $\text{Al}(\text{OH})_3$  polymers that would be expected to occur in the pH range attained in the limed plots.

### Soil Splash

Effects of soil pH and surface charge of the field plots on particle-size distribution, WDC, and soil splash are summarized in Table 3. There was a systematic decrease in clay content and a corresponding increase in sand or silt content of the surface soil compared with the original characterization (Table 1). This difference is attributed to differences in sample dispersion prior to sedimentation, as previously described. There were significant effects of pH on all parameters in one or more of the soils. Increasing pH significantly decreased clay content ( $R^2 = 0.90$ ) and increased silt content of the LC soil ( $R^2 = 0.96$ ). Water-dispersible clay was also significantly increased with increasing pH ( $R^2 = 0.64$ ). There was no effect on sand content, and a non-significant trend for decreasing splash with increasing pH. There was a significant decrease in clay content in the LM soil ( $R^2 = 0.77$ ) with increasing pH, and a significant but nonsystematic effect on soil splash. Clay content of the CA soil was significantly decreased with increasing pH ( $R^2 = 0.64$ ), with corresponding significant increases in silt ( $R^2 = 0.24$ ) and sand ( $R^2 = 0.34$ ).

The results of this phase of the study confirm that, for the LC soil with the lowest organic-C content of the three studied, increasing pH above that of the PZSE increases WDC, as suggested by Uehara and Keng (1975). On the other hand, there was a consistent decrease in total clay content with increasing pH and net negative charge for all three soils. This suggests that liming has increased flocculation or aggregation,

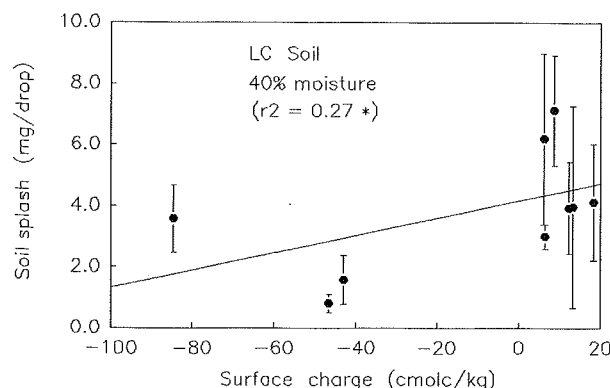


Fig. 2. Effect of surface particle charge on soil splash for the Londrina Cafe soil at 40% volumetric soil moisture.

or both. Since WDC increased with liming, at least in one of the soils, flocculation would not appear to be responsible for particle agglomeration.

In the study on LC soil, increasing pH and net negative surface charge (as a function of varying ionic strength) decreased soil splash in the LC soil at 40% (v/v)  $\text{H}_2\text{O}$  contents (Fig. 2). There was no significant effect of pH and surface charge on soil splash at the lower moisture content. The range of surface charge was greater at the higher than the lower moisture content, as a result of the wider pH range that was obtained. As discussed above, the soil pH range was selected according to the PZSE curves, but actual values differed between the two sets of samples. At the 35%  $\text{H}_2\text{O}$  content, pH ranged from 3.9 to 7.2. At 40%  $\text{H}_2\text{O}$  content, pH varied from 1.8 to 10.9.

The inverse relationship between splash and both soil pH and net negative charge suggests that soil stability, as measured by soil splash, is not affected by the repulsive forces that should occur with increasing particle charge. A similar conclusion was reached by Norton (1986), who found, in a study of Paleudults and a Paleudalf from the USA, that soil wash and WDC were greatest when net particle charge was closest to zero. Soil splash, however, was inversely related to wash and WDC. This led Norton (1986) to suggest that the mechanisms affecting soil splash were not related to particle charge.

Aggregating factors, such as cation bridging, should be important in reducing soil splash, and these should increase with increasing pH. Aggregate stability of the LC soil, however, was not affected by liming (Table 2) but was reduced by acid addition. We cannot, therefore, discount the possibility that acid addition in the splash study caused aggregate breakdown and contributed to the higher splash observed at the lower pH values.

### Soil Erosion

Soil loss decreased significantly with increasing pH on the LC soil only (Fig. 3). While there was a trend

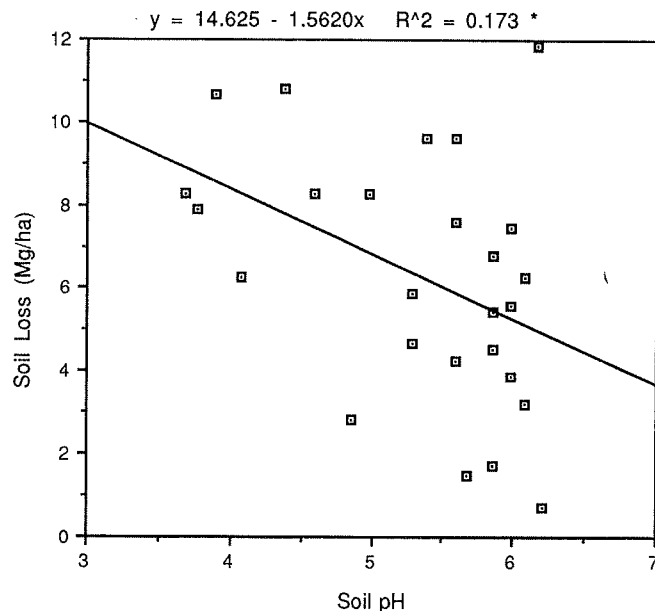


Fig. 3. Effect of soil pH on soil erosion on Londrina Cafe soil.

for decreased soil loss with increasing pH on the LM soil (data not shown), the relationship was not significant. Measured soil loss ranged from 732 to 8691 kg/ha. There was no statistically significant relationship between soil loss and liming on the CA soil. Soil loss ranged from 0 to 8118 kg/ha, and 30% of the plots had no measurable soil loss.

The results were highly variable, which could be due to inherent field variability and to the experimental methodology used, but also confirms that erosion is a function of factors other than soil pH. Examination of the data for the three soils indicates that erosion was in the order: LC  $\gg$  LM > CA. This corresponds generally to organic-C contents of these three soils, and suggests that organic-matter content is more important to aggregate stability and soil erodibility of these Oxisols than soil pH effects. The significant negative relationship observed between erosion and pH for the low-organic-matter, cultivated LC soil (Fig. 3) suggests, however, the liming to pHs near 5.5 to 6.0 may aid in stabilizing soil against water erosion on cultivated soils.

## DISCUSSION

This study suggests that liming Oxisols has differential effects on flocculation and aggregation, and that these effects combine in conflicting ways to determine the observed effects on erosion. The results also reflect the dominant effects of organic-matter content on soil structure. Whereas liming decreased the percentage of 2 to 4-mm aggregates in CA soil, it had little effect on aggregate stability of the other two soils. The CA soil had the highest organic-C content and the highest content of 2 to 4-mm aggregates. Tama and El-Swaify (1978) reported an increase in aggregate breakdown as pH increased from 4.5 to 6 in a Typic Torrox. El-Swaify (1980) explained this phenomenon as a reduction of kaolinite-sesquioxide interactions, which occur at more acid pHs in Oxisols. Roth et al. (1986) found that, 2 yr after liming an Oxisol in Parana, aggregate stability increased with increased pH. Interestingly, they also found a negative relationship between aggregate stability and soil organic-C content. This is consistent with the results of our study, in which aggregation decreased on the Cascavel soil, which had the highest organic-C content.

Water-dispersible clay increased with liming on the LC soil. Water-dispersible clay was greatest on the LC soil, which had the lowest content of organic C, and the increase in WDC on this soil may suggest that this may be a problem only on more cultivated soils with lower organic-matter contents. Roth et al. (1986) found that, while laboratory incubations of a similar soil from Londrina showed increased clay dispersion and lower water infiltration with liming in the pH range from 5 to 7, field measurements 2 yr after lime application showed increased infiltration with liming.

Soil splash was highly variable, and liming had no significant effect on splash on field samples. In laboratory-equilibrated samples, liming and increased ionic strength slightly reduced soil splash in one experiment at 40% volumetric H<sub>2</sub>O content, and no effect in another experiment at 35% H<sub>2</sub>O content. The lack of treatment effects was probably due to the high experimental variation and to the relatively narrow

range of soil pH values achieved. Soil-splash values reported here (0.15–2.18 mg/drop) are much lower than those reported by Al-Durrah and Bradford (1981), which ranged from a low of about 0.2 mg/drop to as high as 23 mg/drop for an Ida silt loam (fine-silty, mixed (calcareous), mesic Typic Udorthent). The apparatus used in our study was modeled on that used by Al-Durrah and Bradford (1981).

Soil erosion was significantly decreased with liming on the low-organic-matter LC soil only. This soil had maximum erosion rates that were 50 to 200% higher than the other two soils, which clearly indicates that the effect of liming on erosion is minor compared with the effect of organic matter. Miller and Baharuddin (1986) found that soil loss on 15 Ultisols and Alfisols was positively correlated with clay dispersibility. They attributed this correlation to decreased infiltration with increasing clay dispersibility. In our study, liming increased WDC but decreased soil loss. Infiltration was not significantly affected by liming. This may suggest that, on the generally well-aggregated Oxisols, the effect of clay dispersion on infiltration may not be as significant a factor on erosion of Oxisols as on other soils.

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## DIVISION S-7—FOREST & RANGE SOILS

### Forest Soil Sampling Efficiency: Matching Laboratory Analyses and Field Sampling Procedures

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#### ABSTRACT

Soil characteristics can be extremely variable, both spatially and temporally, and the cost of sampling to achieve high levels of precision may be prohibitive. Researchers are often faced with the need to obtain the best possible precision within a fixed budget. We present methods of determining the optimal number of field composite samples, the number of field samples per composite, and the number of laboratory analyses per composite. Example problems illustrate methods of obtaining both a desired precision at a minimum cost and the greatest possible precision at a given cost. Calculations to compare and select among alternative laboratory procedures are also illustrated. Often, less precise but inexpensive laboratory procedures may result in greater overall precision than highly precise but expensive procedures.

ACCURATE ASSESSMENT of forest soil properties is often difficult because of high variability. Temporal variation in soil nutrient levels has been well documented (Anderson and Tiedemann, 1970; Gupta and Rorison, 1975; Davy and Taylor, 1974). Such variation is usually controlled by either timing sampling to coincide with climatic or phenological events or by increasing sampling frequency. Spatial variability is also well documented with fairly large differences in variability among individual nutrients even when samples are stratified by horizon. For example, Usher (1970) found that small volumes of soil with high nutrient content or *concentration aggregations* existed in

forest soils such that N was extremely variable over short distances while P was relatively homogeneous. Similarly, Mollitor et al. (1980) working on a flood-plain soil found that while <10 samples were needed to characterized bulk density and reaction, >1000 samples were necessary to estimate K levels within 10% of the mean, 95% of the time.

Because of this high variability, it is often an economic impossibility to collect enough samples to account for differences between soils and treatments. Petersen and Calvin (1986) presented a method, based on Cochran's (1953) work, by which a number of different sampling schemes can be compared when using simple random sampling. They described soil sampling as a two-stage procedure. The first stage is the collection of field samples and the second is the laboratory analysis of these samples. The variance among replicate laboratory analyses can often be minimized at a specified cost through adjusting quality-control procedures to improve precision. Dealing with spatial variability in the field is more difficult and more costly because it dictates that more samples must be taken and analyzed. Thus, if more samples are taken, both field and laboratory costs increase. Composite field samples (where several random samples are combined in equal amounts to form one sample) from which lab samples are taken have been used to reduce field variability. The technique described by Petersen and Calvin (1986) can be used to evaluate the number of laboratory, field, and composite samples needed to achieve a desired level of precision when variability and costs are known or can be estimated.

There are usually wide discrepancies among variances and costs for field, composite, and laboratory

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