SOME FACTORS AFFECTING THE MINERALIZATION OF ORGANIC MATTER IN VOLCANIC ASH SOILS

by

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INTRODUCTION

In many areas of volcanic ash soils, the use of fertilizer nitrogen (N) is limited by economics. In those soils where fertilizer N is not applied, the biological processes of N mineralization and dinitrogen fixation constitute the main source of plant available N.

Soils derived from volcanic ash, which often contain significant amounts of amorphous alumino-silicates in the clay fraction, cover about 20% of the total area of Colombia. In addition, similar soils are found in large areas of Central and South America, western United States, Hawaii, Japan, and New Zealand (Dudal, 1964; Wright, 1964).

A prominent characteristic of volcanic ash soils is their high organic matter content. In spite of this fact, N deficiency symptoms are frequently observed in crops that do not receive fertilizer N. Crop responses to fertilizer N have been demonstrated in these soils. These observations are often associated with lower rates of organic matter mineralization found in volcanic ash soils as compared with other types of soils (Broadbent, Jackman and McNicoll, 1964; Jackman, 1964b).

A number of hypotheses have been suggested to explain the stability of organic matter in volcanic ash soils. It is widely believed that the lack of carbon (C) for energy and microbial growth is the causative factor for

the low N mineralization rates (Jackman, 1960; Urbina, San Martin, and Schaefer, 1969). On the other hand, the fact that volcanic ash soils have strikingly high phosphorus (P) sorption capacities, suggests that low P availability for microbial growth might be a rate limiting factor for organic matter mineralization.

The present research was undertaken with the following major objectives:

1. To determine the effect of the addition of readily available C on both soil C and N mineralization
2. To study the effect of P on the mineralization of C and N
3. To evaluate the effect of P on the utilization of readily available C added to the soil
4. To observe the effect of combined additions of P, inorganic N and readily available C on soil C and N mineralization
5. To compare the rates of organic matter mineralization in soils differing in the content of amorphous alumino-silicates.

REVIEW OF LITERATURE

Content and Rate of Mineralization of Organic Matter in Volcanic Ash Soils

Soils derived from volcanic ash and having significant amounts of amorphous hydrous alumino-silicates (allophane and related minerals) have exceptionally high contents of organic matter (Greenland, 1971; Jackman, 1964a). This characteristic has also been found in soils of non-volcanic origin containing allophane-like minerals (Jackman, 1964b). Although climatic conditions, especially temperature and precipitation are considered to be important factors affecting the organic matter content in soils (Jenny, Gessel, and Bingham, 1949), volcanic ash soils have been found to have high organic matter contents, irrespectively of the climatic conditions as compared to nonvolcanic ash soils (Aomine, 1972; Jackman, 1964b). This may indicate that some nonclimatic factor common to volcanic ash soils determines their high organic matter contents. In fact, Jenny (1950) concluded that the relationship he had established between temperature and organic matter content in soils from the temperate regions was not applicable to soils from Colombia and Costa Rica. Later, it has been found that most of the soils studied by Jenny (1950) in these two countries were derived from volcanic ash.

High organic matter and total N contents in volcanic ash soils have been reported recently in Colombia. Luna (1968) found organic C values ranging from 3.74 to 14.5% for the surface horizon of eight Andepts from the Department of Antioquia. The organic N content of these soils varied from 0.31 to 1.42%. The Andepts from Nariño studied by Calhoun, Carlisle and Luna (1972) and Luna (1973) had organic C contents in the surface horizon between 4.2 and 9.4%. Three Andepts from the Central Cordillera of Colombia had organic matter contents between 4.9 and 10.9% and C:N ratios between 16 and 24 (Cortes and Franzmeier, 1972). Volcanic ash soils from the Bogota high plateau have been reported to have organic C contents between 5.0 and 8.9% and organic N between 0.68 and 0.83 in the surface horizon (Mejia, L. 1967. Principales caracteristicas fisicas, quimicas, mineralogicas y micromorfologicas de los suelos de la cuenca alta del rio Bogota. Instituto Geografico Agustin Codazzi. Bogota. Unpublished report).

It has been generally accepted that the organic matter in volcanic ash soils is mineralized at lower rates than organic matter in soils without amorphous aluminosilicates (Jackman, 1964b). Broadbent et al. (1964) compared the mineralization of C and N in allophanic and nonallophanic soils from New Zealand and found that both C and N were mineralized at significantly lower rates in soils where allophane was the dominant clay mineral than

in nonallophanic soils. Based on parabolic functions they calculated annual losses of C which were 4.19 and 6.30% of the total C per year for two allophanic soils and 9.82 and 10.7% for two nonallophanic soils. The amounts of N mineralized after 54 days of incubation were 1.82 and 2.20 mg per g of C for the two allophanic soils and 3.59 mg per g of C for a nonallophanic soil.

Tejeda and Gogan (1970) found that Chilean soils derived from volcanic ash had lower rates of N mineralization than other types of soils. Bornemisza and Pineda (1969) reported an inverse relationship between allophane content and N mineralization in volcanic ash soils from Costa Rica. Furthermore, they considered that when the allophane content of a soil is higher than 15%, low rates of N mineralization can be expected.

Nitrogen Availability in Volcanic Ash Soils

Despite the high content of organic N generally found in volcanic ash soils, N availability for plant growth is frequently low (Aomine, 1972; Fox, 1969; and Tejeda and Gogan, 1970). Nitrogen deficiencies and responses to fertilizer N in volcanic ash soils have been observed in several places and for a large number of plant species. A significant yield increase due to N fertilization of wheat (*Triticum aestivum* L.) in Chilean volcanic ash soils has been reported by Aomine (1972). Fox (1969) found that sugar

cane (Saccharum officinarum L.) growing in Andepts in Hawaii requires applications of 300-400 kg N/ha per two year growing season in order to obtain optimum yields. Severe N deficiencies in pastures in the same soils were also reported by Fox (1969).

Twelve field trials conducted in Nariño, Colombia, showed that the fertilizer N requirements for barley (Hordeum vulgare L.) are between 30 and 60 kg N/ha (Muños, Wieczoreck, and Leon, 1973). The fertilizer N requirements of potatoes (Solanum tuberosum L.) determined after 19 field trials in Narino were considered to be between 50 and 100 kg N/ha (Wieczoreck and Baird, 1959). Significant increases in the yield of pastures and potatoes due to N fertilization have been reported in volcanic ash soils from Meseta de Popayan - Colombia (Michelin, 1970; Silva, 1962).

Responses to fertilizer N were found for eight vegetable crops, potatoes, corn (Zea mays L.) and several grasses in Andepts from Antioquia, Colombia. Optimum levels of fertilizer N for these crops were established between 50 and 100 kg N/ha (Rodriguez, 1973).

Several techniques have been used to establish laboratory methods for predicting fertilizer N requirements in soils derived from volcanic ash. Tejeda and Gogan (1970) conducted a comparative study of eight laboratory methods for determining N availability in Chilean soils in which they included volcanic ash soils.

The N uptake by ryegrass (Lolium perenne L.) was taken as evaluation criterion. Significant correlation coefficients for the volcanic ash soils were found between N uptake and the following parameters: mineralized N determined by the aerobic and anaerobic techniques of Keeney and Bremner (1966) and Waring and Bremner (1964) respectively, N extracted by hot water (Keeney and Bremner, 1966), total N (Thun, Hermann, and Nickmann, 1955), C:N ratio, and NO_3-N displaced by 300 ml of distilled water added to 200 g of soil. The aerobic incubation method gave the highest correlation coefficient. With the exception of the method of extraction of NO_3-N with distilled water, there were no significant differences between the correlation coefficients for volcanic ash soils and those for other soils.

Hypotheses Proposed to Explain the Accumulation of Organic Matter in Volcanic Ash Soils

Adsorption of Organic Matter by Amorphous Alumino-silicates

Amorphous alumino-silicates have a relatively high adsorption capacity for organic matter constituents of the soil, compared with other soil clay minerals (Greenland, 1965a; 1965b). The capacity of allophane and montmorillonite to adsorb organic compounds produced in the process of plant tissue decomposition was studied by Wada and Inoue (1967). The adsorption maximum that they found for

allophane was very high as compared to that of montmorillonite and halloysite. Later, Inoue and Wada (1968) concluded that the differences in adsorption maxima for allophane, montmorillonite and halloysite were not affected by changing the exchange complex from Ca to Al saturation, nor by the presence of extractable iron oxides. When adsorption studies were conducted using soils of similar clay content and nutrient levels, instead of pure clays, allophanic soils were found to adsorb twice as much C as montmorillonitic soils (Wada and Inoue, 1967). The rate of mineralization of the adsorbed organic compounds was strikingly lower in allophanic soils. These results allowed Wada and Inoue (1967) to conclude that the combination of a greater adsorption capacity and a lower rate of mineralization of the adsorbed organic matter in allophanic soils might produce significant differences in the accumulation of organic matter in allophanic and montmorillonitic soils.

Level of Available Carbon and Energy Sources for Microbial Growth

Jackman (1960) and Urbina et al. (1969) hypothesized that the soil organic C in volcanic ash soils adsorbed by the amorphous clay minerals is not readily available for energy and synthesis of cellular constituents of soil microorganisms. Therefore, an increase in organic matter mineralization could be expected due to the addition of

readily available C sources to volcanic ash soils. Increased CO_2 evolution after the addition of readily available C sources like sucrose and sodium pyruvate were observed but it was not determined whether the increased CO_2 evolution came from the soil organic matter or if it was just the product of the metabolism of the added C.

Mineralization of soil N in volcanic ash soils from Hawaii was reduced by additions of C sources. Sucrose increased the immobilization of native as well as added N more than a slowly available C source such as sugar cane bagasse (Agarwal, Singh, and Kanehiro, 1972a).

Effects of Amorphous Alumino-silicates on Enzymatic Activity in the Soil

It has been clearly established that the presence of clay minerals affects enzymatic activity in the soil (Aomine and Kobayashi, 1964a; Stotzky and Rem, 1966). The addition of increasing concentrations of allophane to protease-haemoglobin mixtures was found to reduce the enzyme activity. A similar effect was found with halloysite and montmorillonite. However, allophane caused a greater inhibition of protease activity than montmorillonite and halloysite (Aomine and Kobayashi, 1964b). Allophane has also been found to decrease the activity of alpha- and beta-amylase and cellulase (Aomine and Kobayashi, 1964a). The activity of beta-amylase was reduced by additions of allophane and montmorillonite to enzyme-starch

mixtures. However, the effect of montmorillonite was stronger than that of allophane (Aomine and Kobayashi, 1966). These results may suggest that the relative effect of different clay minerals on enzymatic activity varies depending upon the enzyme.

Experiments have been conducted in order to establish whether the reduction in enzymatic activity caused by clays is due to enzyme adsorption. Aomine and Kobayashi (1964b) found that the enzymatic activity of protease adsorbed by allophane and montmorillonite was reduced as compared to the activity of the enzyme in a free state. The adsorption of protease by halloysite did not change the activity of the adsorbed enzyme in comparison to the enzyme in a free state. When protease was adsorbed by allophane, the activity of the enzyme was one-fourth of the activity of the enzyme in a free state. Adsorption of protease by montmorillonite reduced the enzyme activity to one-half of the activity of the enzyme in a free state.

Kinetic studies have been conducted in order to elucidate the type of enzyme inhibition caused by allophane. Kobayashi and Aomine (1967) studied the effect of allophane and montmorillonite on the Michaelis constant (K_M) and the maximum initial velocity (V_{max}) of protease when incubated in mixtures of clay and carbobenzoxy-L glutamyl-L tyrosine as substrate. Both the K_M and V_{max} were reduced in the presence of allophane and montmorillonite. The decrease

in the K_M was interpreted as an increase in the rate of formation of the enzyme-substrate complex in the presence of the clay. Another explanation was that the adsorption of the enzyme by the clay may exert some influence in the configuration of the enzyme molecule which could facilitate the formation of the enzyme-substrate complex. The decrease in V_{max} indicated a retardation of the hydrolysis of the substrate and that effect was attributed to the adsorption of the enzyme by the clay. Similar effects on K_M and V_{max} were observed for alpha- and beta-amylase and clay mineral systems.

The adsorption of enzymes by clay minerals has been found to cause different effects on K_M and V_{max}, depending upon the nature of the enzyme and the clay. From kinetic studies, it was concluded that allophane may be regarded as partially competitive and partially non-competitive inhibitor (Kobayashi and Aomine, 1967).

Allophane and montmorillonite are inhibitors of enzymatic activity but the relative effect of the two types of clays seems to vary for different enzymes. Sometimes montmorillonite is a stronger inhibitor of enzymatic activity than allophane. For this reason, it is difficult to explain the larger accumulation of organic matter in allophanic soils than in montmorillonitic soils under similar climatic conditions entirely on enzyme adsorption phenomena. Therefore, it may be concluded that the

inhibition of enzymatic activity by adsorption of enzymes on allophane is not the only factor contributing to the low rates of organic matter mineralization observed in volcanic ash soils.

Aluminum Content and Soil Acidity

Soil acidity and the Al content of the soil (either exchangeable or extractable) have been considered to be factors determining accumulation of organic matter in volcanic ash soils (Mutatkar and Pritchett, 1966).

It has been hypothesized that Al could influence the rate of organic matter decomposition in soils through two mechanisms: (1) a strong adsorption of Al on the organic matter, forming microbiologically stable organo-aluminum complexes or (2) through toxic effects of Al on microbial activity (Mutatkar and Pritchett, 1966).

Silva and Schaefer (1971) considered that the formation of "chelates" of fulvic acids with Al is a mechanism of accumulation of organic matter in volcanic ash soils. They found that a large proportion of the Al in volcanic ash soils was associated with the fulvic fraction of the organic matter. This fraction was considered to be highly stable to acid hydrolysis. It was inferred that the fulvic acid-Al "chelates" may have a slow rate of biodegradation.

The effect that Al has on microbial activity and survival varies among microbial species, even in the case

of microorganisms closely related to each other from the taxonomic standpoint. Matsuda and Nagata (1957) concluded that poor microbial activity of acid soils seemed to be due to the "active" Al as well as to the acid reaction.

The Al concentration required to obtain toxic effects was different for Aspergillus niger, Penicillium sp., Torula sp., Acetobacter sp., and Saccharomyces sp. Azotobacter chroococcum was found to survive at pH 4.0 and its survival rate decreased with increasing Al concentration in the medium, whereas Azotobacter indicum (Beijerinckia indica) was more resistant to acidity and Al (Katznelson, 1940). Beijerinckia spp. have been found to be more tolerant to Al than Azotobacter spp. (Becking, 1961). On the other hand, Zwarun, Bloomfield and Thomas (1971) found that increasing acidity from pH 6.6 to 4.5 greatly reduced the survival of a Bacillus sp. When 80 ppm of Al were added to the medium at pH 4.5, there was no further detrimental effect upon the growth and survival of the organism. Exchangeable Al in the form of Al-saturated Wyoming bentonite caused a decrease in the survival of the organism as compared with Ca-saturated Wyoming bentonite. Mutatkar and Pritchett (1966) concluded that fungi may be more tolerant to Al than bacteria and later Mutatkar and Pritchett (1967) concluded that soil microorganisms may be more tolerant to Al than higher plants.

An Al ion extracted with water from a Hawaiian volcanic ash soil by Ko and Hora (1972) was found to be a fungitoxin for ascospores of Neurospora tetrasperma.

Some microbial processes in the soil have been found to be affected by acidity and Al content. It was found that microbial activity in a mixture of fine sand and muck, as measured by CO_2 evolution and NO_3 production increased with decreasing H-ion concentration (Mutatkar and Pritchett, 1967). Aluminum additions to this mixture had little effect on CO_2 evolution and an inconsistent effect on NO_3 production. However, additions of Al to a mixture of a tropical latosol and muck when the pH was below 4.5 caused a decrease in CO_2 production. In this same study, urease activity and the processes of ammonification did not appear to be affected by either H or Al ion concentrations in the fine sand-muck mixture. The decrease in CO_2 evolution with additions of Al was thought to be due to Al since much more CO_2 evolution occurred in a Ca-muck than in an Al-muck even though both treatments were adjusted to pH 4.

It is generally accepted that soil acidity has a greater effect on the transformations of NH_4 to NO_3 (nitrification) than on the production of NH_4 from organic N forms (ammonification) (Harmsen and Van Schreven, 1955). Urbina et al. (1969) found that additions of Al to a volcanic ash soil from Chile did not influence the

ammonification process but did restrict nitrification. Similar results were reported by Mutatkar and Pritchett (1967) for a fine sand-muck mixture.

Tejeda (1970) working with 19 volcanic ash soils from Chile found that N mineralization as determined by an aerobic incubation technique decreased as the extractable Al increased. In addition, he found a highly significant correlation for these two variables. The correlation coefficient for extractable Al and N mineralization in 18 nonvolcanic ash soils was not significant. The content of extractable Al of volcanic ash soils was almost ten-fold that of nonvolcanic ash soils.

According to Benavides (1972), liming some volcanic ash soils from Colombia increased N mineralization, as determined by the anaerobic incubation technique of Waring and Bremner (1964). The increases in NH_4-N were considered not to be of economic significance. Broadbent et al. (1964) concluded that the increase in organic matter decomposition due to liming was not greater in allophanic as compared to nonallophanic soils.

Ino and Monsi (1964) studied the effect of raising the pH of a humic allophane soil on CO_2 evolution. They found that a soil maintained at pH 6.5 by a NaOH solution evolved more CO_2 than the same soil at the original pH of 4.5 and that maintained at pH 5.5. No difference in CO_2 evolution was recognized between the treatments at

pH 5.5 and 4.5. When the pH was raised to 6.5 by adding $CaCO_3$ the rates of CO_2 evolution increased more than in the case when NaOH had been added. It was concluded that the effect of $CaCO_3$ was due not only to the change in pH but also to the effect of Ca. Agarwal, Singh, and Kanehiro (1972b) thought that the effect of liming on soil N mineralization may be attributable in some instances to the accompanying cations and anions, in addition to the change in pH brought about by the chemical per se. Jackman (1960) found that raising the pH of a volcanic ash soil (derived from ryolitic pumice) by adding NaOH or $Ca(OH)_2$ caused an increase in microbial respiration. It was inferred that raising the pH released C into an available form which determined the increase in respiration. NaOH produced a larger effect on respiration than $Ca(OH)_2$ which is opposite to the results of Ino and Monsi (1964).

Some volcanic ash soils as the Eutrandepts are slightly acid and have low Al saturation. These soils also have high organic matter contents. Therefore, the effects of Al and soil acidity on the processes of organic matter mineralization do not explain the accumulation of organic matter in Andepts of high base status.

Effect of Nutrient Elements on Carbon and Nitrogen Mineralization

Phosphorus

Phosphorus availability is low in volcanic ash soils, especially in those which are highly weathered (Fox, 1969). The presence of amorphous alumino-silicates in these soils gives rise to a very high P fixation capacity (Rajan, 1973). This fact has been confirmed for Andepts from Colombia (Leon, 1964; Luna, 1973).

Soil microorganisms may utilize either organic or inorganic P to synthesize their own cell material (Chang, 1940; Jackman, 1955a; and Taylor, 1946).

In some instances the level of soil P has been found to be limiting for microbial growth (Stotzky and Norman, 1961). On the other hand, volcanic ash soils have low rates of P mineralization, probably due to the presence of amorphous alumino-silicates (Fuentes, Igue, and Bornemisza, 1972; Jackman, 1955b).

A positive correlation may exist between soil test P and N mineralization as inferred by the data presented by Benavides (1972) for volcanic ash soils from Colombia. Tejeda (1970) found a highly significant positive correlation between available P and N mineralization in volcanic ash soils from Chile. However, it was also found that available P was significantly correlated with total N and

the logarithm of extractable Al. Thus, Tejeda (1970) concluded that the correlation between available P and N mineralization was due to the fact that both N mineralization and available P were correlated with extractable Al.

Additions of 4000 and 16,000 ppm P as KH_2PO_4 to volcanic ash soils produced increases in CO_2 evolution as well as in the dehydrogenase activity (Urbina et al., 1969). In this same study it was also found that N mineralization was increased by additions of 16,000 ppm P but decreased by 400 and 4000 ppm P. Jackman (1960) found increases in the microbial respiration of a volcanic ash soil from New Zealand after the addition of 11.64 mg P per 50 g of soil but this effect was attributed to the rise in pH that was caused by that treatment.

Ino and Monsi (1964) working with a humic allophane soil from Japan found that additions of $NH_4H_2PO_4$ at the rates of 1.3, 2.6, and 5.2 mg P per g of soil were fairly efficient in accelerating the CO_2 evolution. They also found that H_3PO_4 increased CO_2 evolution and that NH_4Cl did not change the pH nor did it affect the evolution of CO_2. Changing the pH with NaOH or $CaCO_3$ to the same level as $NH_4H_2PO_4$ did increase microbial respiration. It was concluded that P had an effect by itself on CO_2 evolution. These results may indicate the difficulty in separating the effect of P from that of pH on microbial activity in cases when the source of P added causes a change in pH.

Nitrogen

The N transformations in soils are governed to a large extent by the C:N ratio in the soil as well as in the materials added (Winsor, 1958). It is recognized that the supply of mineral N may affect the mineralization of N causing either a depression or a stimulation of this process (Megasur, 1968). Very high concentrations of soluble inorganic N in the soil reduce the process of N mineralization. This reduction is thought to be due either to a high concentration of electrolites or to a stimulation of the process of immobilization of inorganic N which gives the impression of a reduced mineralization. On the other hand, additions of fertilizer N to soils exhibiting low N mineralization have been noted to stimulate the process of N mineralization (Harmsen and Kolenbrander, 1965).

Studies on the effect of additions of inorganic N on N mineralization in volcanic ash soils are rather scarce. Agarwal et al. (1972a) reported that 24 and 56% of the 200 ppm NH_4-N added to two Andepts from Hawaii were immobilized after 23 days of incubation.

Inorganic N added to volcanic ash soils has been shown to have depressing effects on microbial respiration. Jackman (1960) reported decreases in respiration due to the addition of NH_4NO_3 at the rate of 100 mg per 50 g of

soil. Addition of 700 ppm N as NH_4NO_3 to a volcanic ash soil from Chile decreased CO_2 evolution (Urbina et al., 1969). Ammonium chloride did not have any effect on CO_2 evolution from a volcanic ash soil (Ino and Monsi, 1964). However, Agarwal et al. (1972a) found that the addition of 200 ppm N as $(NH_4)_2SO_4$ to a Typic Hydrandept from Hawaii increased the CO_2 evolution. The same treatment did not cause any noticeable increase in the CO_2 evolution from an Ustollic Eutrandept included in the same study.

Calcium

Some authors have concluded that Ca itself has a stimulating effect on soil C and N mineralization. Ino and Monsi (1964) found that raising the pH of a volcanic ash soil from Japan with $CaCO_3$ caused a larger increase in CO_2 evolution than raising the pH to the same level with NaOH. Thus, they concluded that Ca had an effect on C mineralization.

The addition of $Ca(OH)_2$ to an Andept from Hawaii increased CO_2 evolution whereas $CaCl_2 \cdot H_2O$ caused a decrease in this process. The former result was thought to be due to the raise in the Ca level and the latter to an increase in the osmotic pressure (Agarwal et al., 1972b). Jackman (1960) found increases in microbial respiration of volcanic ash soils after addition of $Ca(OH)_2$ but he attributed this result to the change in pH that was brought about by

$Ca(OH)_2$. These results indicate the difficulty in separating the effect of Ca on biological activity in the soil from that of the pH, the accompanying anion or the osmotic pressure effect.

Effect of Nutrient Salts on Nitrogen Release

Some explanations suggested to account for the stimulating effect of inorganic fertilizer N on the mineralization of soil organic N were examined by Broadbent (1965). Exchange between fixed and exchangeable NH_4 and between exchangeable NH_4 and amino-N was ruled out. Rates of exchange resulting from biological activity were increased as a consequence of increasing the level of fertilizer N applied. The osmotic effects were thought to be a contributing factor.

Increases in osmotic pressure in the soil solution have been found to cause a decrease in CO_2 evolution from soil (Johnson and Guenzi, 1963). Singh, Agarwal, and Kanehiro (1969) studied the effect of the osmotic pressure of chloride salts on the release of inorganic N and microbial activity as determined by CO_2 evolution in a Typic Hydrandept from Hawaii. The addition of chloride salts of Na, K, Ca, Mg, Al, and Fe caused a decrease in CO_2 evolution with respect to the control. CO_2 evolution declined with successive increments of salts. Despite this decrease in microbial activity, NH_4 release was increased

by salts and this effect was attributed to a nonbiological process, namely a cellular breakdown due to the osmotic pressure. In general, chloride salts of divalent cations had a greater effect on NH_4 release than chloride salts of monovalent cations. Calcium brought about a greater NH_4 release than Mg did. Trivalent cations at low concentrations had a greater effect on NH_4 release than monovalent and divalent cations but at high concentrations the effect was reversed. Similar results were found for a Tropeptic Eutrorthox which had a lower organic matter content than the Typic Hydrandept. The fact that the relative effect of the different salts added was dependent upon the type of cation led Singh et al. (1969) to believe that in addition to the osmotic effect, certain chemical reaction was also involved in the release of N. They hypothesized that an exchange may occur between NH_4 from organo-inorganic complexes in the soil and cations in the soil solution. In a further step, Agarwal, Singh, and Kanehiro (1971) concluded that sulfate salts caused the same effects as chloride salts, except for a stimulating effect on CO_2 evolution caused by low concentrations of sulfate. Chlorides were more effective than sulfates in affecting NH_4 release in the soil. The capacity of the cations to release NH_4 was found to decrease in the order $Ca > K > Na$ for the chloride series.

The contribution of osmotic effects to the mineralization of organic N in the soil was confirmed by Broadbent and Nakashima (1971) working with California soils. Furthermore, they concluded that the effect is due at least in part to the extraction of organic N by the salt solution and that the organic N rendered soluble is then readily mineralized.

MATERIALS AND METHODS

Soil Samples

The soils included in this study are the surface horizon of four Inceptisols from the Departments of Cundinamarca and Antioquia, Colombia. Data related to the location and climate of the sampling sites are included in Table 1. The sampling sites are located in tropical areas at relatively high elevations where the mean annual temperature varies less than 5 C.

The soil samples were collected from exposed profiles which were cleaned before sampling. La Ceja and San Jorge soil profiles were located at the border of grass fields, Tibaitata profile was at the border of an alfalfa (Medicago sativa L.) field and Facatativa profile was bordering a potato field. Samples were collected between the 13th and the 24th of May 1973. The morphology, parent material and classification of the soils is summarized in Table 2.

Preparation and Storage of the Soil Samples

After collection the samples were sent to Raleigh, North Carolina. Regulations of the United States Department of Agriculture required the samples to be submitted to a quarantine in Miami, Florida, which included fumigation with methyl bromide. Colony counts by the dilution plate technique before and after the fumigation indicated

Table 1. Location and climatic data of the sampling sites

Soil Name	Location			Elevation (m)	Mean Annual Temp. (°C)	Annual Rainfall (mm)
	Coordinates	Town	Department			
La Ceja[a]	N.A.[b]	Medellin	Antioquia	2500	14	2500
Tibaitata[c]	4° 44' N 74° 16' W	Madrid	Cundinamarca	2570	14	800 ± 200
Facatativa[c]	4° 52' N 74° 18' W	Facatativa	Cundinamarca	2800	10	950
San Jorge[d]	N.A.	Soacha	Cundinamarca	3150	8	800-1000

[a]Luna (1968).

[b]Not available.

[c]Mejia, L. 1967. Principales caracteristicas fisicas, quimicas, mineralogicas y micromorfologicas de los suelos de la cuenca alta del rio Bogota. Instituto Geografico Agustin Codazzi. Bogota. Unpublished report.

[d]Mejia, L. Soil chemist. Instituto Geografico Agustin Codazzi. Bogota, Colombia; personal communication.

Table 2. Morphology, parent material and classification of the soils

Soil	Horizon	Depth (cm)	Field Texture	Color (Moist)	Structure	Parent Material	Classification of Soil Profile
La Ceja[a]	A1	0-10	Sandy loam	Black 10 YR 2/1	Weak fine angular blocky	Volcanic ash and metamorphic rocks	Typic Dystrandept
Tibaitata[b]	A11	0-18	Loam	v. dk. gray brown 10 YR 3/2	Moderate fine granular	Volcanic ash 1-1.5 m thick	Andic Aquic Eutropept
Facatativa[b]	A12	3-20	Silt loam	Black 10 YR 2/1	Massive to weak fine crumb	Volcanic ash over sandstone	Typic Placandept
San Jorge[c]	A1	0-23	Sandy loam	Black 5 YR 2/1	Moderate fine granular	Volcanic ash over sandstone	Dystrandept?

[a]Luna (1968).

[b]Mejia, L. 1967. Principales caracteristicas fisicas, quimicas, mineralogicas y micromorfologicas de los suelos de la cuanca alta del rio Bogota. Instituto Geografico Agustin Codazzi. Bogota. Unpublished report.

[c]Mejia, L. Soil chemist. Instituto Geografico Agustin Codazzi. Bogota, Colombia; personal communication.

a severe reduction in the microbial population of the samples. To overcome this problem the samples were inoculated at the beginning of each experiment. This change in the natural microbial population of the soils was not considered to be a limiting factor for the objectives of this study since some evidences have been shown by Broadbent et al. (1964) indicating that the low organic matter mineralization rates in volcanic ash soils are not due to the composition of the microbial population.

The soil samples were ground to pass a 2 mm sieve and stored moist in plastic bags in a cold room at 5 C.

Physical and Chemical Analyses of the Soils

Bulk Density

Air-dry clods were weighed and then coated with paraffin. The volume of the coated clods was determined measuring the volume of water that they displaced after being submerged in a graduated cylinder. The volume of the paraffin coat was discounted. Paraffin density was assumed to be 0.9 g/cm^3 (Blake, 1965).

Soil pH

Soil pH was determined by glass electrode in water and 1 N KCl, with a soil:solution ratio of 1:1.

Fluoride Test for Amorphous Materials

The presence of amorphous materials was qualitatively tested by measuring the pH of the soil in 1 N NaF, 1:50 soil:solution ratio at 2 and 60 min after the addition of the solution (Fieldes and Perrot, 1966).

Exchangeable Bases

Exchangeable Ca, Mg, K, and Na were extracted with 1 N NH_4OAc at pH 7.0. Calcium and Mg were determined using a Perkins-Elmer model 403 atomic absorption spectrophotometer. Potassium and Na were determined using an Instrumentation Laboratory model 143 flame photometer.

Exchangeable Acidity

The exchangeable acidity was extracted with unbuffered 1 N KCl. The leachate was titrated with 0.1 N NaOH to a phenolphthalein end point. Ten ml of NaF solution (40 g per liter) were added to the titrated leachate and then it was titrated again with 0.1 N HCl to determine exchangeable Al. Exchangeable H was calculated by the difference between exchangeable acidity and exchangeable Al (McLean, 1965).

Cation-exchange Capacity

The cation-exchange capacity was determined by extracting 10 g soil samples with 1 N NH_4OAc at pH 7.0. The NH_4 saturated soil was washed with 95% ethanol and

the retained NH_4 was displaced with acidified 10% NaCl solution. The NH_4 retained by the soil was determined by semimicro-Kjeldahl distillation and titrated with standard acid (Soil Conservation Service, 1972).

Effective Cation-exchange Capacity

Effective cation-exchange capacity was calculated adding the sum of bases extracted with 1 N pH 7.0 NH_4OAc plus the exchangeable acidity, extracted with unbuffered 1 N KCl.

Organic Carbon

One hundred mg air-dry samples were used to determine organic C by the Walkley-Black method as described by Allison (1965).

Organic Nitrogen

Organic N was determined by a semimicro-Kjeldahl procedure. Ten ml of concentrated H_2SO_4 were added to 200 mg of air-dry soil and digested. The digest was heated for one hour after it had cleared. The digestion accelerator used was a mixture of $CuSO_4$ and K_2SO_4 in a 1:20 ratio. Three Hengar selenized granules were added to each digestion flask. The digest was diluted with 10 ml of distilled water and then connected to the distillation apparatus. Forty ml of 50% NaOH were added and this mixture distilled until 35 ml of distillate had been

collected in 4% boric acid. The ammonia was determined by titration with standard H_2SO_4 using a mixture of bromocresol green and methyl red as indicator.

Inorganic Forms of Nitrogen

Exchangeable NH_4, NO_3, and NO_2-N were extracted by shaking the soil sample with 10 ml of 1 N KCl per g of soil for one hour. The soil-KCl suspension was filtered using Whatman 42 paper and stored in a freezer at -2 C until the analyses were performed.

Determination of NH_4-N: Method A. Ten ml aliquots of the KCl extract were used to determine NH_4-N by the steam distillation method described by Bremner and Keeney (1966).

Determination of NH_4-N: Method B. The NH_4-N in the KCl extracts was determined using a model 95-10 Orion ammonia electrode connected to a model 520 Fisher Accumet digital pH/ion meter. Ten ml of the extract were placed into a plastic beaker and 0.4 ml of 2.5 N NaOH were added immediately before immersing the electrode. This extract-NaOH mixture had a pH about 13. Standard curves were constructed with solutions of different concentrations of NH_4Cl in 1 N KCl.

It was found that the Method B determination for NH_4 was faster than Method A. Since both methods have been found to have the same degree of accuracy (Banwart,

Tabatabai, and Bremner, 1972), Method B was used in the latter parts of the investigation.

Determination of NO_3 and NO_2-N: Method A. Nitrate and NO_2-N in the KCl extracts were determined by the steam distillation method described by Bremner and Keeney (1966).

Determination of NO_3 and NO_2-N: Method B. Nitrate plus NO_2-N were determined using a Beckman Acta III spectrophotometer. Extracts were scanned from 220 to 275 mm. Standard curves were constructed by scanning standard KNO_3 solutions. Interference due to dissolved organic matter was subtracted from the values for the soil extracts.

Mineralogical Analyses

Removal of organic matter was done by adding 35 ml of 30% H_2O_2 in small increments to 5 g of soil maintained in water bath at 80 C for 24 hours. Dispersion was done by adding 10 ml of 10% sodium hexamethaphosphate (Calgon) solution and shaking for 20 min in a reciprocal shaker. The wet sieving procedure described by Jackson (1956) was used to separate the fraction greater than 50 μ. The suspension with the particles less than 50 μ was transferred to a one-liter cylinder and brought to volume with distilled water, shaken and allowed to settle for 24 hours. The fraction less than 2 μ was separated by decantation. The clay was floculated with 1 N $MgCl_2 \cdot 6H_2O$ and then

saturated with Mg following the procedure described by Jackson (1956).

X-ray diffraction patterns were obtained for the Mg saturated clays for which oriented slides were prepared by evaporating aliquots of suspensions containing about 50 mg of clay on 75x25 mm glass slides. A general Electric XRD-5 X-ray diffractometer was used with Cu-Kα radiation (λ = 1.54415 Å), a nickel filter and a scanning rate of 2° 2θ per minute.

Differential thermal analysis of the Mg-saturated clays was done taking 20 mg of freeze-dry samples and equilibrating them in a desiccator with a slurry of $Mg(NO_3)_2$. The samples were packed in platinum capsules and heated at a rate of 20 C per minute in a N_2 atmosphere. A Dupont 200 differential thermal analyzer with Pt vs Pt-Rh thermocouples was used.

Phosphorus Fixation Curves

Phosphorus fixation curves were obtained by adding P to the soils in increments ranging from 0 to 2400 ppm P. A 5 ml aliquot of KH_2PO_4 solution of the appropriate concentration was added to a 10 g soil sample and stirred with a glass rod. After 14 days of incubation at room temperature P was extracted with 50 ml of Bray II solution (0.03 N NH_4F and 0.1 N HCl) and determined by the molybdate-blue method using a model B Beckman spectrophotometer.

Incubation Studies

The samples for incubation studies were the amount of moist soil required to have an equivalent of 10 g of soil on oven-dry basis per flask. Samples were placed in Erlenmeyer flasks and the treatment solutions were added in the volume required to bring the moisture content to 50% of the moisture holding capacity of the soil. The treatment solutions were made by dissolving the amount of substance required according to each particular experiment and treatment in a soil extract used as inoculum. The inoculum was made by shaking a suspension of soil in sterile distilled water in a 1:10 ratio for 30 minutes. The soil used was the surface horizon of the Cecil soil (Typic Hapludult) collected from a corn field near Raleigh, North Carolina. Counts of bacterial and fungal colonies for this soil using the dilution plate technique are presented in Appendix Table 1.

After inoculation the flasks were incubated at a temperature maintained between 28 and 30 C. The flasks were weighed every five days and sterile distilled water was added as required to maintain the moisture level at 50% of the moisture holding capacity. Three replications were included in the incubation studies.

Carbon Dioxide Evolution

The evolution of CO_2 was followed using a continuous air-flow respirometer. CO_2-free air was forced through the

flasks containing the soil samples. The air-flow rate was periodically adjusted to approximately 25 ml/min. The air was purified using the scrubber system described by Stotzky (1965). The CO_2 was collected in 10 ml of 0.1 N NaOH with a specific conductance of 20.79 mmhos cm^{-1} contained in test tubes 1.5 cm in diameter and 15 cm long. The amount of CO_2 absorbed by the alkali solution was determined by a modification of the conductimetric technique proposed by Wollum and Gomez (1970). The modification consisted of using a 0.1 N NaOH solution instead of 0.5 N NaOH in order to increase the sensitivity of the technique. Test tubes were removed from the respirometer at the desired time intervals, replaced by tubes containing fresh alkali and allowed to stand for one hour in a water bath at 25 C. The specific conductance of the alkali solutions was measured using a Beckman G-2 conductivity cell connected to a model RC16B Industrial Instruments conductivity bridge. The amount of CO_2 in solution was calculated using the equation

$$CO_2 = (20.7311 - S.C.)/0.5919$$

where S.C. is the specific conductance in mmhos cm^{-1} and CO_2 is expressed in mg per 10 ml of solution. This equation is plotted in Appendix Figure 1 and was experimentally determined following the procedure outlined by Wollum and Gomez (1970).

Nitrogen Mineralization

In order to study the changes in inorganic N content throughout the different experiments, samples treated as previously described were incubated in 125 ml Erlenmeyer flasks capped with aluminum foil with several openings to assure air exchange. Inorganic N was extracted and determined, using the methods already described, at the beginning and after the desired incubation time was completed. The difference in inorganic N content at these two times was considered to be the mineralized N.

RESULTS AND DISCUSSION

Soil Properties

Chemical Analyses

Some of the chemical properties of the soils used in this investigation are summarized in Table 3. The soil reaction as measured in H_2O was slightly acid for Tibaitata soil and strongly acid for the other three soils. The pH in KCl was always lower than the pH in water which indicates that the soil colloids have a net negative charge.

Exchangeable Al was not detectable in Tibaitata soil whereas the other soils have relatively high levels of this cation. Exchangeable H was generally low for all soils.

The cation-exchange capacity (C.E.C.) for all soils was relatively high. Tibaitata soil has the lowest C.E.C. and conversely the highest percent base saturation (P.B.S.) in comparison to the other soils. While C.E.C. was similar for all soils the P.B.S. differed greatly among soils. La Ceja soil has very low P.B.S. as do the Facatativa and San Jorge soils. Birrel (1964) and Swindale (1969) pointed out that the C.E.C. determined by the conventional methods is subject to pH-dependent charge effects when amorphous colloids are present in the soil. Therefore, they calculated the cation-exchange capacity of those soils by summation of the exchangeable acidity and bases

Table 3. pH, exchangeable bases, exchangeable acidity, cation-exchange capacity and percent base saturation

Soil	pH (1:1)		meq/100 g Soil									% Base Saturation	
			Exchangeable Bases				Sum of Bases	Exch. Acidity		ECEC[a]	CEC[b]	Based on ECEC	Based on CEC
	H_2O	KCl	Ca	Mg	K	Na		Al	H				
La Ceja	5.0	4.3	0.18	0.13	0.29	0.35	0.95	2.47	0.17	3.59	68.0	26.5	1.4
Tibaitata	6.1	5.1	20.31	7.14	1.53	1.88	30.86	0.00	0.10	30.96	46.6	99.7	66.2
Facatativa	5.2	4.4	2.98	1.09	0.70	0.14	4.91	1.46	0.15	6.52	59.4	76.5	8.3
San Jorge	5.1	4.2	0.99	4.75	2.02	0.22	7.98	2.57	0.24	10.79	60.2	74.0	13.3

[a]ECEC: effective cation-exchange capacity (exchangeable bases plus exchangeable acidity).

[b]CEC: cation exchange capacity by NH_4OAc.

and considered this value to be the effective cation-exchange capacity (E.C.E.C.). These observations also apply to the calculation of P.B.S. A large difference was found between the E.C.E.C. and the C.E.C. as determined by 1 N pH 7.0 NH_4OAc in all of the soils studied. The E.C.E.C. was the highest for Tibaitata soil and the lowest for La Ceja soil. Large differences were also found between the two methods of calculating P.B.S.

Exchangeable K was high for all of the soils although La Ceja soil has an exchangeable K level which is much lower than that of the other soils.

Generally, the Tibaitata soil was the least acidic and had the highest base content whereas La Ceja soil was the most acidic and depleted of bases. In the latter soil exchangeable Al constituted 69% of the E.C.E.C. With respect to acidity and base content, the Facatativa and San Jorge soils were intermediate between La Ceja and Tibaitata soils.

Results of the analyses of C and N are presented in Table 4. The organic C content is high for all of the soils and it is in the range generally found for many volcanic ash soils (Swindale, 1969). In comparison to the rest of the soils, Tibaitata has a lower organic C content. The organic N content follows C content and it is very high in comparison to most agricultural soils but not to other volcanic ash soils (Swindale, 1969). The C:N ratios

of the soils studied are similar to those found for other volcanic ash soils from Colombia (Blasco, 1969; Luna, 1969) and they are considered to be higher than the C:N ratios generally found in other types of soils (Birrell, 1964). The C:N ratios reported here were calculated using the organic N content instead of total N as suggested by Jones (1958).

Table 4. Organic C and N, C:N ratio and inorganic forms of N

Soil	% Organic C	% Organic N	C:N[a]	Inorganic Forms of N ppm N			
				NH_4	NO_3	NO_2	Total
La Ceja	16.87	1.017	16.59	122.5	51.0	9.4	182.9
Tibaitata	7.99	0.702	11.38	74.1	45.7	--	119.8
Facatativa	14.32	1.154	12.41	103.1	34.3	1.9	139.3
San Jorge	16.17	1.047	15.44	48.4	30.4	26.9	105.7

[a]C:N = Organic C divided by organic N.

The inorganic N content was predominantly in the form of NH_4. Nitrites were negligible except for San Jorge soil.

Bulk Density

Low bulk density is a general property of volcanic ash soils (Forsythe, Gavande, and Gonzalez, 1969). The results for bulk density reported in Table 5 are, in fact,

low as compared to the bulk density of other types of soils but they may be thought to be high for volcanic ash soils. This may be attributed to the method used for this particular determination (paraffin coated clods). Tisdall (1951) found that coated clod methods usually give higher bulk density values than other methods. Bulk density values determined by the core method were 0.5 and 0.8 g/cm^3 for Facatativa and Tibaitata soils respectively (Mejia, L. 1967. Principales caracteristicas fisicas, quimicas, mineralogicas y micromorfologicas de los suelos de la cuenca alta del rio Bogota. Instituto Geografico Agustin Codazzi. Bogota. Unpublished report.).

Table 5. Bulk density and fluoride test for amorphous materials

Soil	Bulk Density g/cm^3	pH (1:50) NaF	
		2 min	60 min
La Ceja	1.03	11.6	11.8
Tibaitata	1.18	9.6	10.2
Facatativa	0.93	11.6	11.8
San Jorge	0.97	11.6	11.8

Mineralogical Analyses

The fluoride test for amorphous alumino-silicates (allophane) indicated their presence in all of the soils (Table 5). A pH value greater than 9.4 obtained two

minutes after the addition of NaF is indicative of the predominance of allophane in the clay fraction of the soil (Fieldes and Perrot, 1966). Based on the smaller change of pH after the addition of NaF, the Tibaitata soil seems to have less allophane than the other three soils. Differences in allophane content between the soils that apparently have higher amounts of these clay minerals could not be detected probably because a buffer system is created and the pH does not increase above a certain level (Bracewell, Campbell and Mitchell, 1970). In addition, the results of the fluoride test must be cautiously interpreted because they may indicate the presence of allophane when none is present (De Villers, 1971; Luna, 1968). However, X-ray diffraction patterns of the clay fraction ($< 2\mu$) constitute an indirect evidence of the predominance of amorphous clay minerals in the soils studied. The diffractograms (Figure 1) show a high diffraction background and a very low diffraction peak intensity. There were not sharp X-ray diffraction maxima in the clay fraction of the soils studied. Some low intensity maxima seem to indicate the presence of crystalline minerals in very low amounts. In La Ceja and Facatativa soils, the low intensity peak at 4.07 Å may indicate traces of cristobalite. Tibaitata soil may contain trace amounts of quartz as indicated by the low intensity peaks at 3.36 and 4.22 Å. Very small quantities

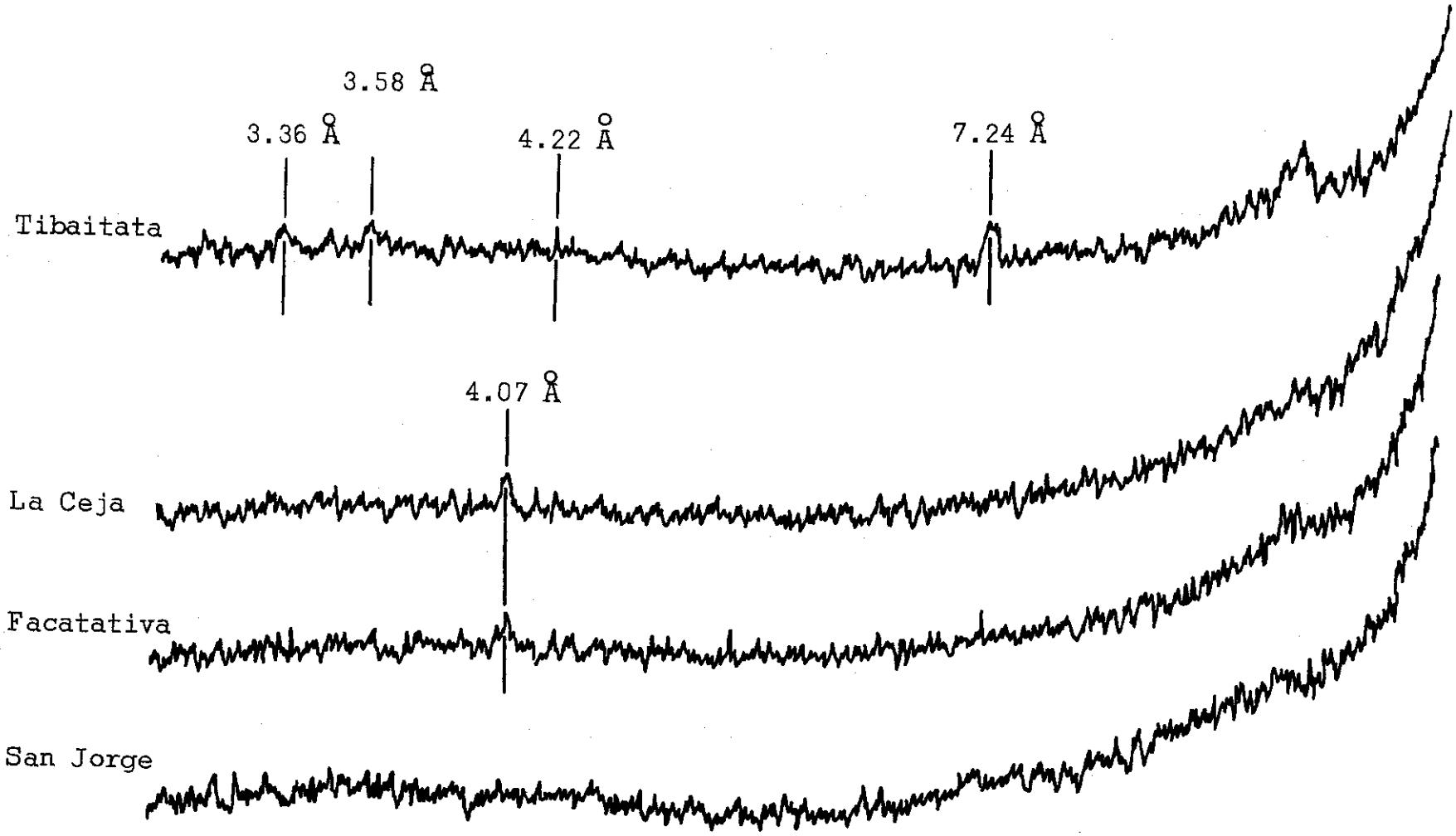

Figure 1. X-ray diffraction patterns of the clay fraction (< 2μ) of the soils

of kaolinite and halloysite may also be present in this soil as indicated by the weak peaks at 3.58 and 7.24 Å, respectively.

The differential thermal analysis (D.T.A.) patterns confirm the presence of large quantities of amorphous clay minerals in the soils studied (Figure 2), as indicated by the strong and broad endothermic peak at low temperatures (21-260 C) found for all of the soils (Holdridge and Vaughan, 1957). A difference in the height of these endothermic peaks is noticeable and may be used to compare the relative content of amorphous minerals in the clay fraction of the soils (Jackson, 1956). Tibaitata soil seems to have a lower content of amorphous clay minerals than the other soils, which is in agreement with the results of the fluoride test. These results also suggest that the San Jorge soil has the largest content of amorphous clay minerals, while La Ceja and Facatativa amorphous clay mineral content is intermediate between San Jorge and Tibaitata. Another distinct feature of the D.T.A. pattern for the clay fraction of Tibaitata soil is the endothermic effect between 450 and 530 C (with a maximum at 491 C) and an exothermic peak between 800 and 933 C, with a maximum at 914 C. These features may indicate the presence of kaolinite in this soil (Barshad, 1965). The endothermic effect with maximum around 290 C found for San Jorge, La Ceja and Facatativa soils may

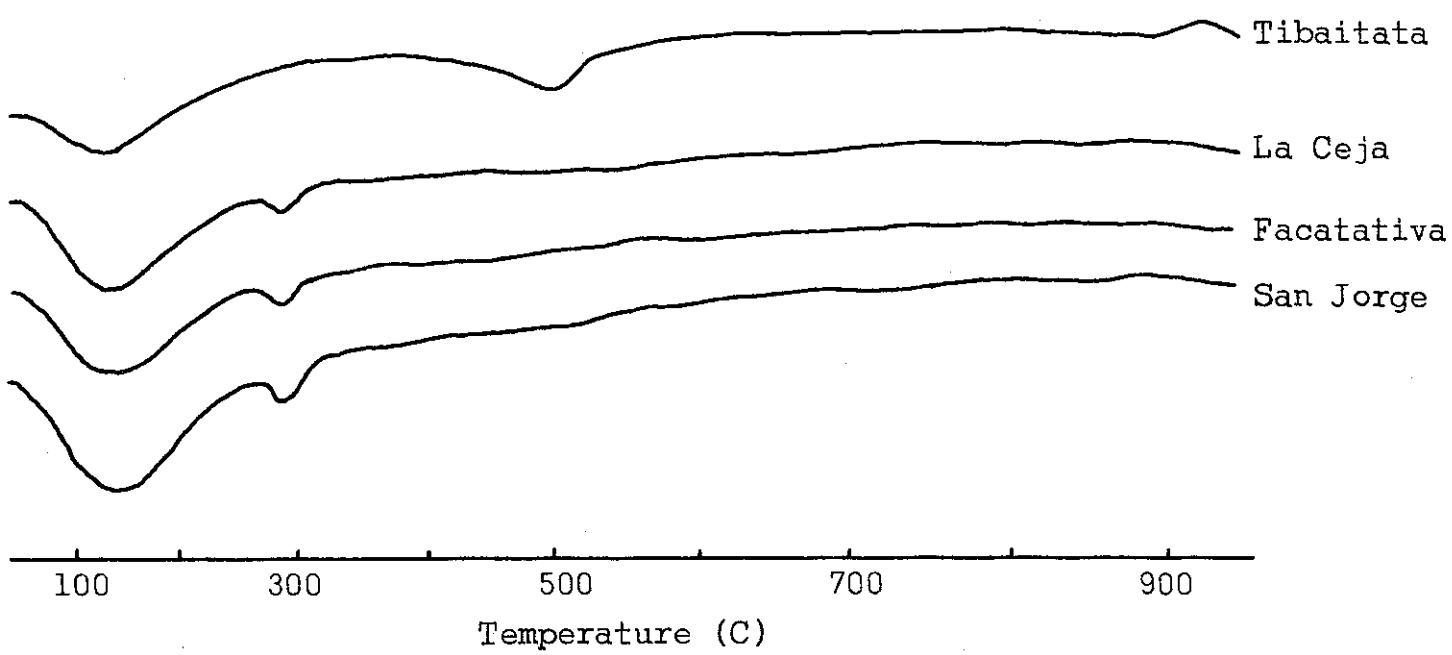

Figure 2. Curves of differential thermal analysis of the clay fraction of the soils

indicate small amounts of gibbsite (Bracewell et al., 1970). Mackenzie (1957) pointed out that small amounts of gibbsite are difficult to detect with X-ray diffraction but they give sharp thermic effects. The latter endothermic effect was not found for Tibaitata soil. The mineralogical data for Tibaitata and Facatativa soils closely agree with that of Mejia, who used four diagnostic techniques to characterize the mineralogy of these soils (Mejia, L. 1967. Principales caracteristicas fisicas, quimicas, mineralogicas y micromorfologicas de los suelos de la cuenca alta del rio Bogota. Instituto Geografico Agustin Codazzi. Bogota. Unpublished report). The results for La Ceja soil agree with those of Luna (1968).

Phosphorus Fixation Curves

Facatativa, La Ceja and San Jorge soils showed a very high P fixation capacity (Figure 3). Tibaitata soil has a lower fixation capacity than the other soils used in this study. These results seem to be related with the relative content of amorphous clay minerals which was appreciably lower for Tibaitata soil. However, San Jorge soil which seems to have a higher content of amorphous materials than Facatativa and La Ceja soils, has a lower P fixation capacity than the latter soils. The initial available P level is very low for all of the soils, although it is higher for Tibaitata soil in comparison

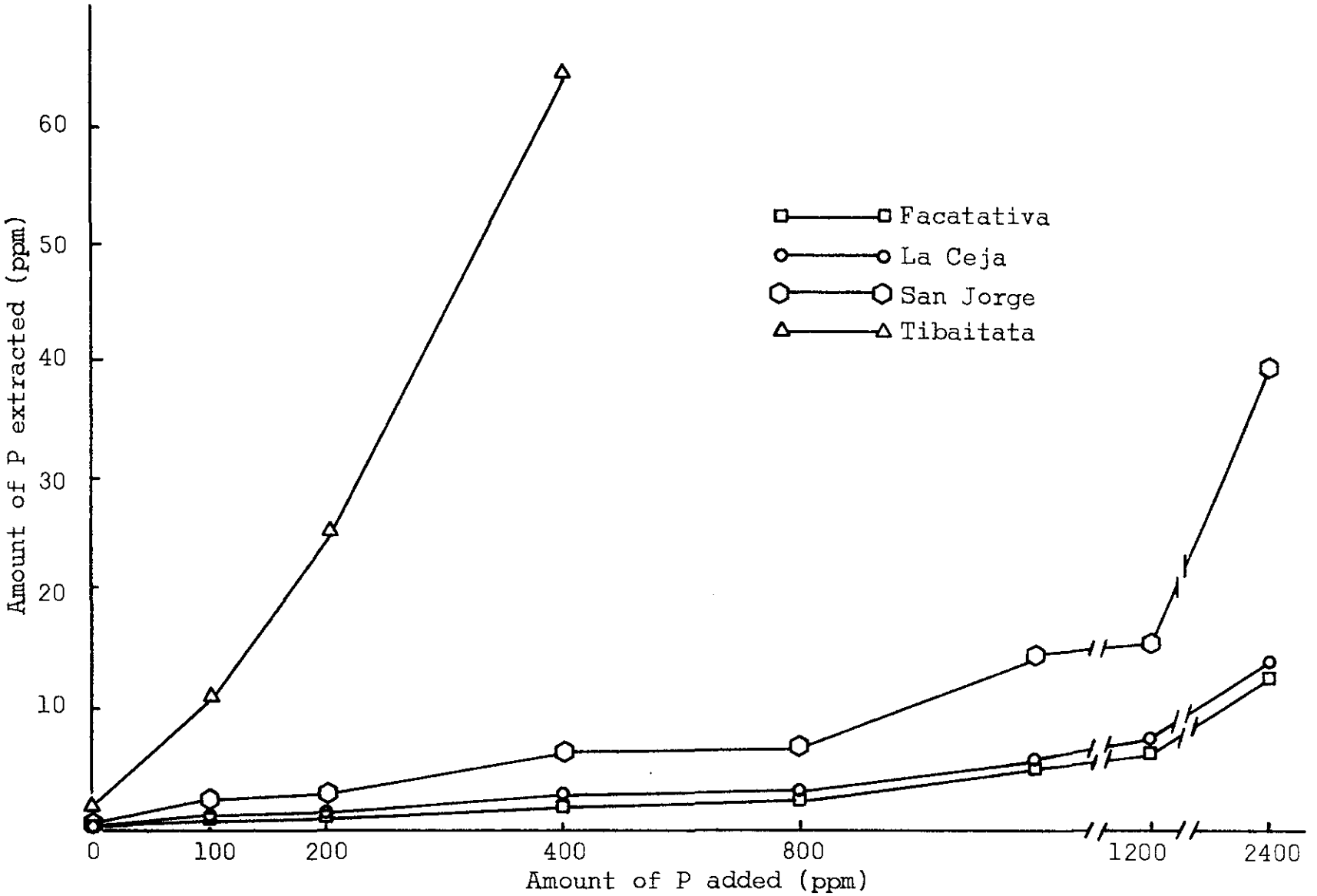

Figure 3. Phosphorus adsorption curves for the soils studied

to the other soils. The complete data of P extracted for constructing the fixation curves are presented in Appendix Table 2.

Effect of Readily Available Carbon on the Mineralization of Carbon and Nitrogen

The validity of the hypothesis proposed by Jackman (1960) and Urbina et al. (1969) which suggests that the stability of organic matter in volcanic ash soils is due to the lack of C for energy and microbial growth was tested. Readily available C was added to La Ceja soil at four levels (0, 30, 300, 3000 ppm of glucose on oven dry soil basis) and CO_2 evolution was monitored. Inorganic N was also determined after different incubation periods by Method A.

Curves for cumulative CO_2 evolution are shown in Figure 4. It was found that the differences in CO_2 evolution from the control and the 30 ppm treatments were not statistically significant except for the values at 42 hours. The 300 ppm treatment was significantly greater than the control and the 30 ppm treatment only at 19 and 42 hours. The 3000 ppm treatment was significantly different from all of the other treatments from 19 until 251 hours.

To determine when the treatment effect disappeared, analyses of variance were calculated for the CO_2 evolved during each time interval. The treatment effect seemed to disappear around 152 hours as indicated by the leveling

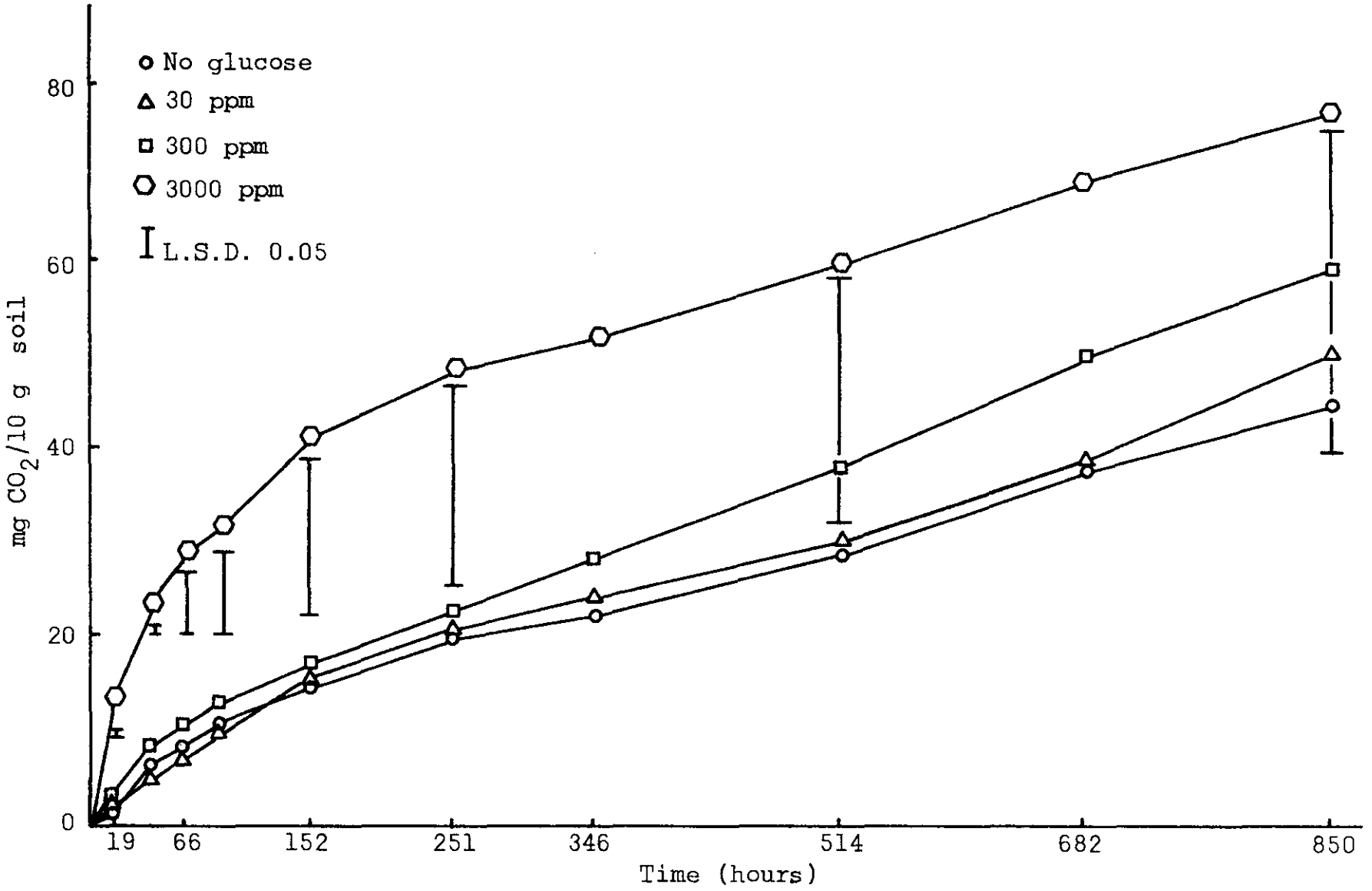

Figure 4. Cumulative CO_2 evolution from La Ceja soil amended with the indicated rates of glucose

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off in the evolution curves. In fact, the differences among treatments in the amount of CO_2 evolved from 91 to 152 hours were not significant. This probably indicates that most of the glucose had been utilized by that time.

According to Stotzky (1965), 60-80% of the organic C metabolized by soil microorganisms is released as CO_2. The total CO_2 evolved at 850 hours from the soil treated with 3000 ppm glucose minus the total CO_2 evolved at the same time from the untreated soil corresponded to 71.2% of the C added as glucose. Therefore, the increases in respiration were probably due to the added glucose and not to a priming effect of glucose on soil C respiration.

The changes in inorganic N content during the course of the experiment are presented in Figure 5. The additions of 3000 ppm of glucose caused a large net immobilization of inorganic N after one and two weeks of incubation. During the subsequent time intervals, the total inorganic N content for the soils receiving 3000 ppm glucose was larger than at the beginning of the incubation but the amount of N mineralized was significantly less in comparison to the unamended soil. The 300 ppm treatment caused an increase in N mineralization after one week of incubation but this effect disappeared one week later. These results probably indicate that soil inorganic N was utilized to fulfill the growth requirements of the microbial population. This is an effect that has been observed

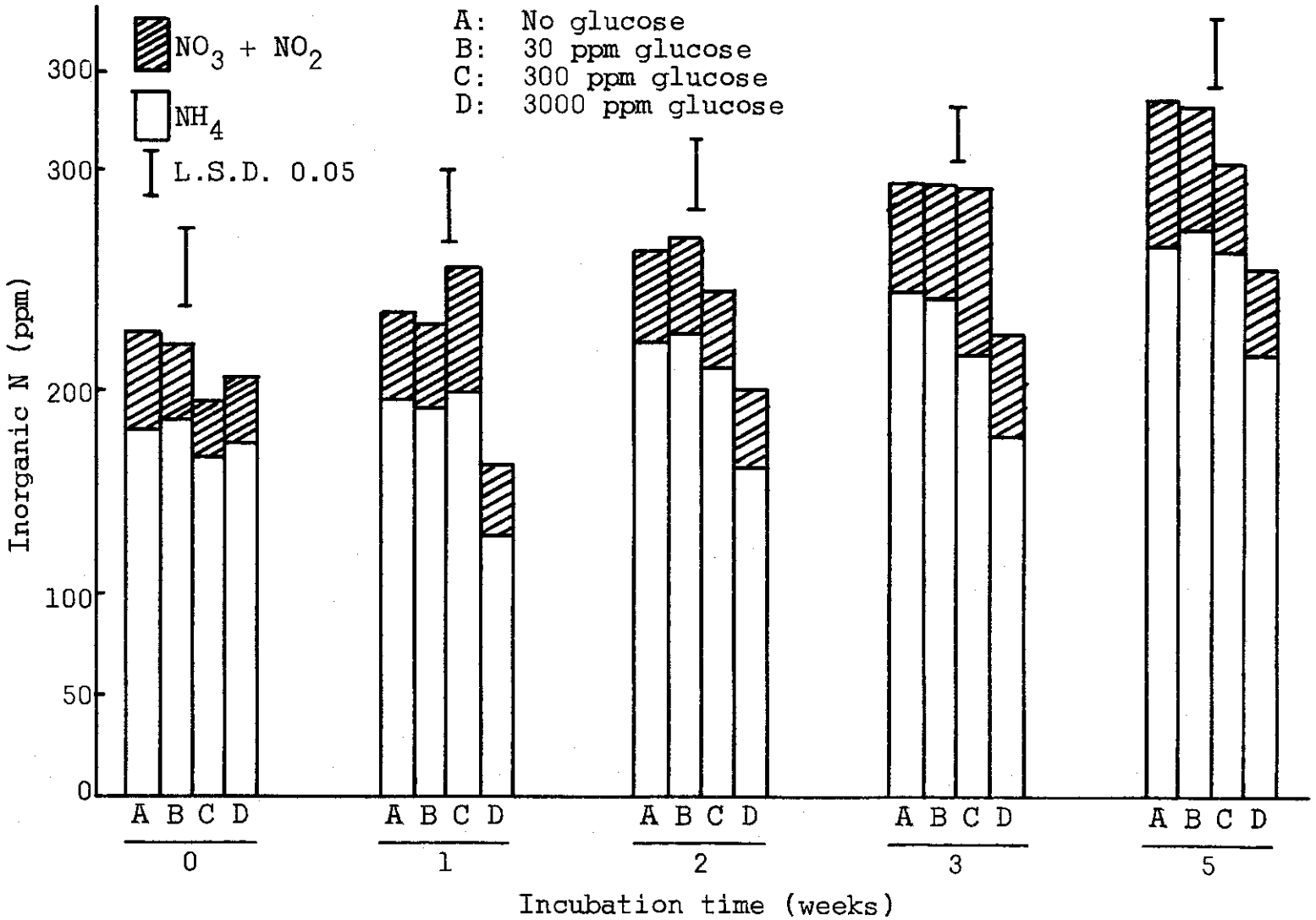

Figure 5. Change in inorganic N content in La Ceja soil after incubation with the indicated rates of glucose

frequently after additions of readily available C have been made to soils without adding a N source (Bartholomew, 1965).

There were no significant differences in mineralized N at any time due to the addition of 30 ppm glucose nor with the addition of 300 ppm glucose after two weeks of incubation.

The analyses of variance for NH_4 and mineralized NH_4 showed the same type of significant differences as those for total inorganic N and total mineralized N (mineralized $NH_4 + NO_3 + NO_2$), respectively.

The differences in NO_3 and NO_2 content of the treated and untreated soils were not statistically significant at any time. Ammonium constituted most of the inorganic N at any time.

These results show that additions of readily available C to this soil do not stimulate the mineralization of N. Rather, they caused decreases in the inorganic N content probably due to the processes of N immobilization. Based on these results and the CO_2 data it seemed difficult to accept the hypothesis that the lack of available C is limiting the degradation of organic matter in the soil studied.

To verify this conclusion, it was decided to observe the effect of readily available C on the mineralization of C and N in other soils and also to use a wider range of available C. Carbon was added to La Ceja, Tibaitata and

Facatativa soils at the rates of 0, 100, 1000 and 10,000 ppm of glucose. The soils were incubated for 30 days and CO_2 evolution was determined at different time intervals. The inorganic N content was determined at the beginning of the incubation and 20 and 30 days later. Method A was used for these N determinations.

The values of cumulative CO_2 evolution for the control and 10,000 ppm glucose treatments are plotted in Figure 6. The data for all of the treatments are presented in Appendix Table 3. The differences in cumulative CO_2 evolution among the glucose levels and soils are statistically significant at the 0.01 level. The largest CO_2 evolution from the unamended soils was obtained for Facatativa soil, followed by La Ceja soil. Tibaitata soil evolved the least CO_2. The latter soil has a considerably lower organic C content than the other two soils (Table 4) which explains the lower CO_2 evolution from this soil. Although La Ceja soil has higher organic C content than Facatativa soil, the latter evolved significantly more CO_2 than the former. This may be related to the higher acidity and lower level of exchangeable bases in La Ceja soil in comparison to Facatativa soil (Table 3). These factors may be responsible for the Facatativa soil having a lower microbial activity than La Ceja soil.

The differences in CO_2 evolution between the treatments receiving glucose and the untreated soils never

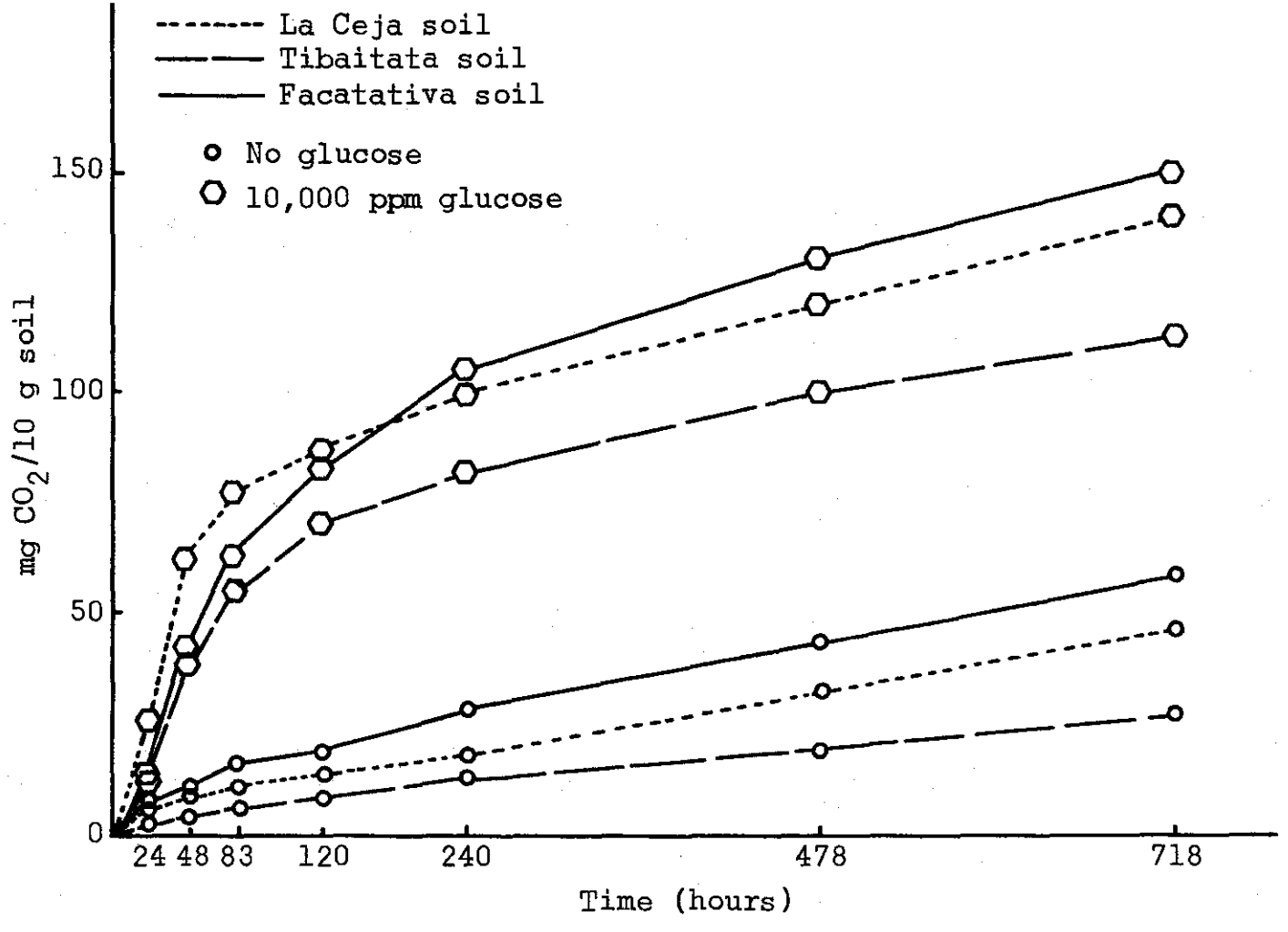

Figure 6. Cumulative CO_2 evolution from three soils incubated with and without glucose

accounted for more than 63% of the added C. These results support the finding of the previous experiment, namely that the addition of readily available C to these soils did not seem to have a priming effect on soil C respiration.

The changes in total inorganic N ($NH_4 + NO_3 + NO_2$) were statistically significant at the 0.05 level for soils and glucose levels as well as for the soil-glucose interaction (Figures 7, 8, and 9).

There was net mineralization of N for all of the unamended soils (controls) after 30 days of incubation. The amount of N mineralized was greater in Facatativa soil than in the other two soils. Addition of successive levels of glucose caused decrease in net N mineralization with respect to the controls, with the exception of the 100 ppm glucose treatment in Tibaitata soil which resulted in an increase in N mineralization. The 10,000 ppm glucose level caused net immobilization of N in La Ceja and Facatativa soils. Net N mineralization in Tibaitata soil treated with 10,000 ppm glucose was very low.

Very small changes in inorganic N content occurred in La Ceja and Facatativa soils between 20 and 30 days of incubation. The mineralization-immobilization processes may have reached a steady-state by that time. A small increase in N mineralization obtained at 20 days with 100 ppm glucose in Facatativa soil disappeared at 30 days. Some changes in inorganic N between 20 and 30

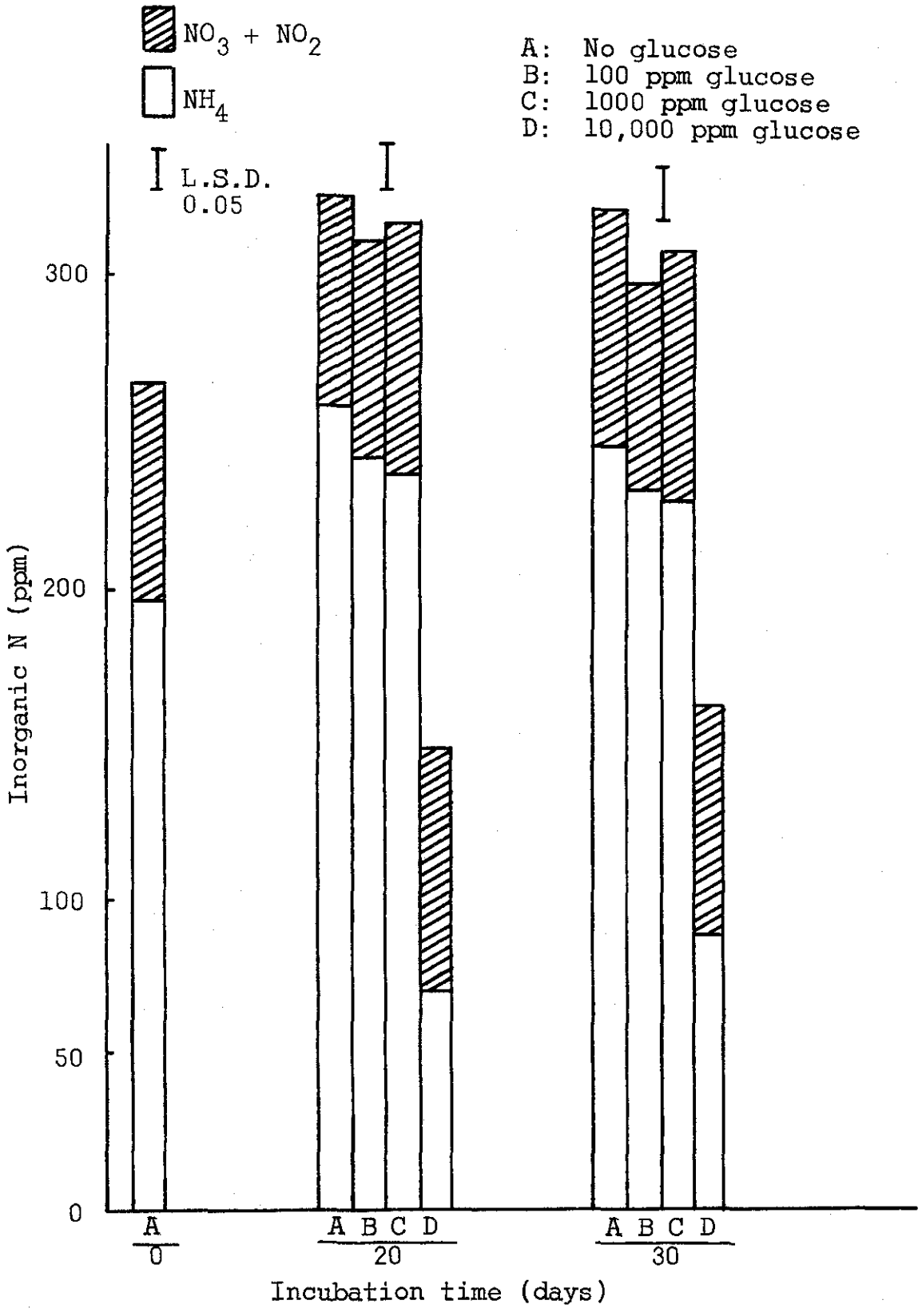

Figure 7. Change in inorganic N content of La Ceja soil after incubation with the indicated rates of glucose

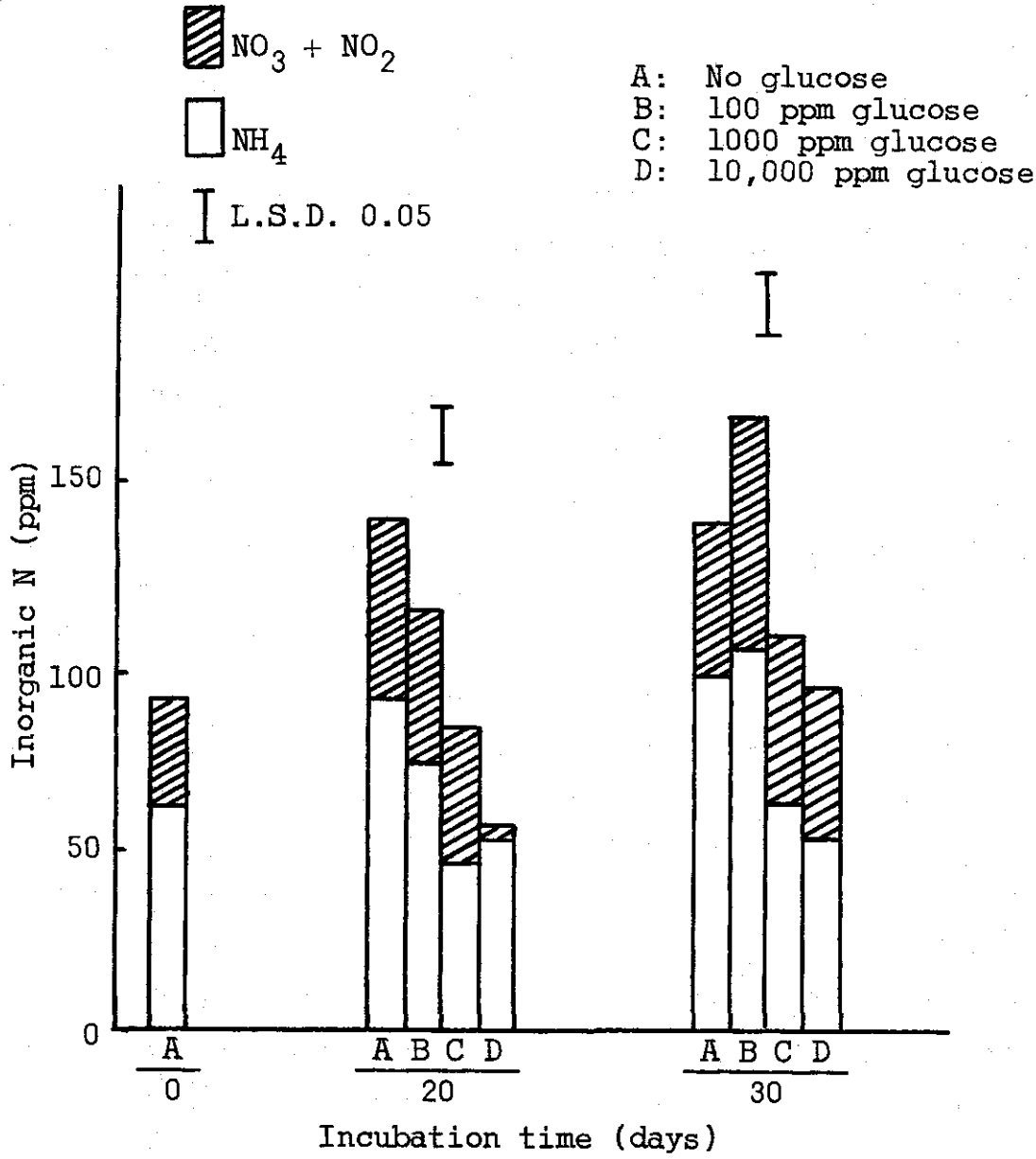

Figure 8. Change in inorganic N content of Tibaitata soil after incubation with the indicated rates of glucose

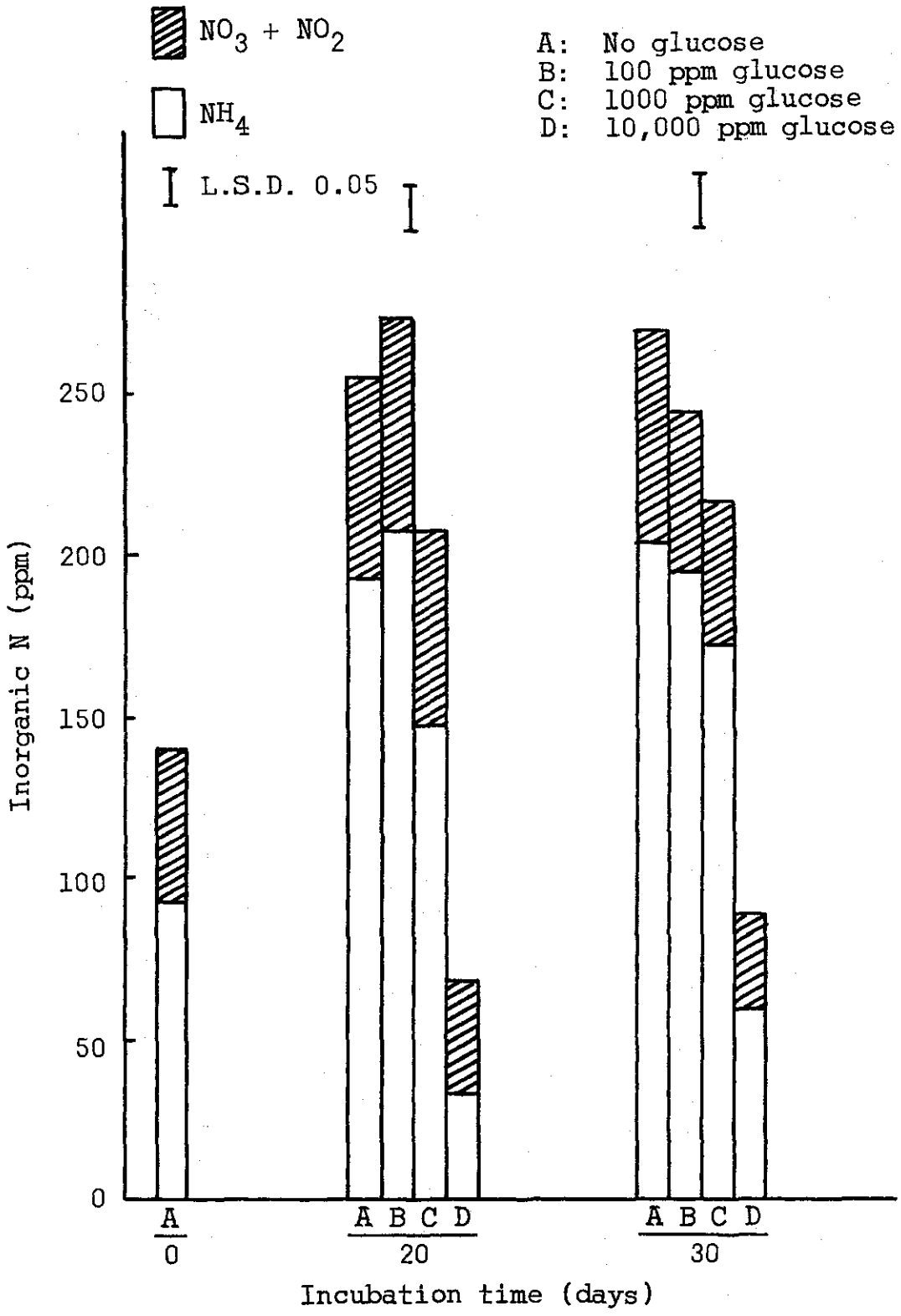

Figure 9. Change in inorganic N content of Facatativa soil after incubation with the indicated rates of glucose

days of incubation were observed in Tibaitata soil. The 100 ppm glucose treatment caused a decrease in net mineralization at 20 days but at 30 days the effect of the same treatment was to increase net mineralization. The 1000 and 10,000 ppm glucose levels caused net immobilization of N at 20 days but net mineralization of N at 30 days.

Analysis of variance for the variable mineralized N was computed. Similar conclusions as those obtained from the total inorganic N data were obtained analyzing this variable (Appendix Table 4). However, the differences in mineralized N between the controls and the 100 ppm glucose level are not statistically significant when calculated in this way.

In this experiment most of the inorganic N was in the form of NH_4. Consequently, analyses of variance for the variables NH_4 content and mineralized NH_4 showed similar tendencies as those for total inorganic N and mineralized N respectively.

These results would appear to contradict the hypothesis of Jackman (1960) and Urbina et al. (1969) concerning the relationship between lack of available C and N mineralization in soils derived from volcanic ash.

Effect of Calcium Phosphate on Mineralization of Carbon and Nitrogen

A hypothesis was formulated suggesting that the level of P available for microbial growth was the rate limiting factor for organic matter mineralization in volcanic ash soils. This hypothesis was based on the following observations: (1) the low levels of available P along with the high P fixation capacity found in volcanic ash soils, (2) the increased C mineralization due to additions of P observed by Ino and Monsi (1964) and Urbina et al. (1969) and (3) the apparent correlation between soil test P and mineralized N observed in the data presented by Benavides (1971) and Tejeda (1970).

This hypothesis was tested in an experiment where rates of $Ca(H_2PO_4)_2 \cdot H_2O$ equivalent to 0, 400, 800 and 1200 ppm P were added to Facatativa and San Jorge soils.

The moisted soils were preincubated for 14 days without P amendment; subsequently the P treatments were added. Carbon dioxide evolution was followed both during preincubation and for 44 days after the additions of P.

In this and all subsequent experiments inorganic N was determined by Method B, at the beginning and end of the preincubation and 14 and 44 days after the addition of P.

Carbon Mineralization

During the first 14 days of incubation without P additions, significantly more CO_2 was evolved from Facatativa than from San Jorge soil (Table 6). The CO_2 evolution per gram of soil C for the unamended soils was also significantly higher for Facatativa than for San Jorge soil (Table 7). The lower rate of organic matter mineralization as indicated by CO_2 evolution for the San Jorge soil may be related to its greater amorphous clay content (Bornemisza and Pineda, 1969; Broadbent et al., 1964).

Rates of CO_2 evolution per day are presented in Figures 10 and 11. Increases in the rate of CO_2 evolution were observed immediately after the addition of P. The control treatment (without P added) also showed an increase in the rate of CO_2 evolution. To keep experimental conditions comparable, a volume of water equal to that of the volume of P solutions added was also added to the controls. The addition of water caused a flush in C mineralization which may be similar to that observed after rewetting a soil (Birch, 1958). This may indicate that, although the moisture content of the soils was maintained at about 50% of the moisture holding capacity by periodic additions of water, the moisture level was not optimum for C mineralization under these experimental conditions.

Table 6. Cumulative CO_2 evolution (mg CO_2/10 g soil) from Facatativa and San Jorge soils incubated during 14 days without any amendment

Time (Days)	Soil		L.S.D. 0.01
	Facatativa	San Jorge	
0.5	2.64	1.40	0.34
1.0	4.74	2.66	0.39
2.0	8.10	4.26	0.87
3.0	11.13	5.85	1.27
5.0	16.34	8.80	2.40
11.4	28.91	17.74	3.13
14.0	33.56	21.14	3.66

Table 7. Cumulative CO_2 evolution (mg CO_2/g soil C) from Facatativa and San Jorge soils incubated during 14 days without any amendment

Time (Days)	Soil		L.S.D. 0.01
	Facatativa	San Jorge	
0.5	1.84	0.87	0.24
1.0	3.31	1.64	0.26
2.0	5.66	2.63	0.59
3.0	7.77	3.62	0.84
5.0	11.41	5.44	1.60
11.4	20.19	10.97	2.06
14.0	23.44	13.07	2.44

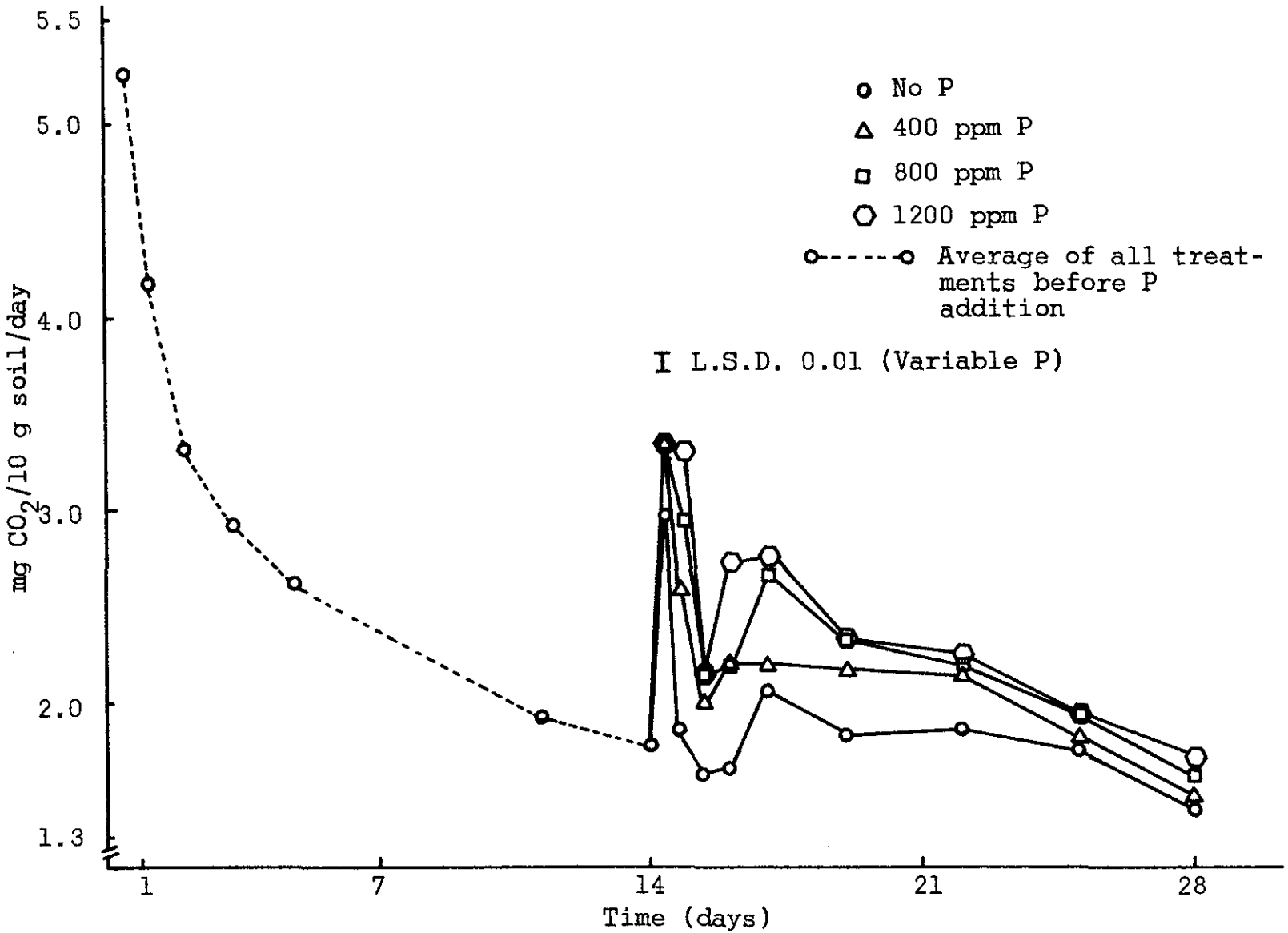

Figure 10. Rate of CO_2 evolution from Facatativa soil incubated with the indicated levels of P

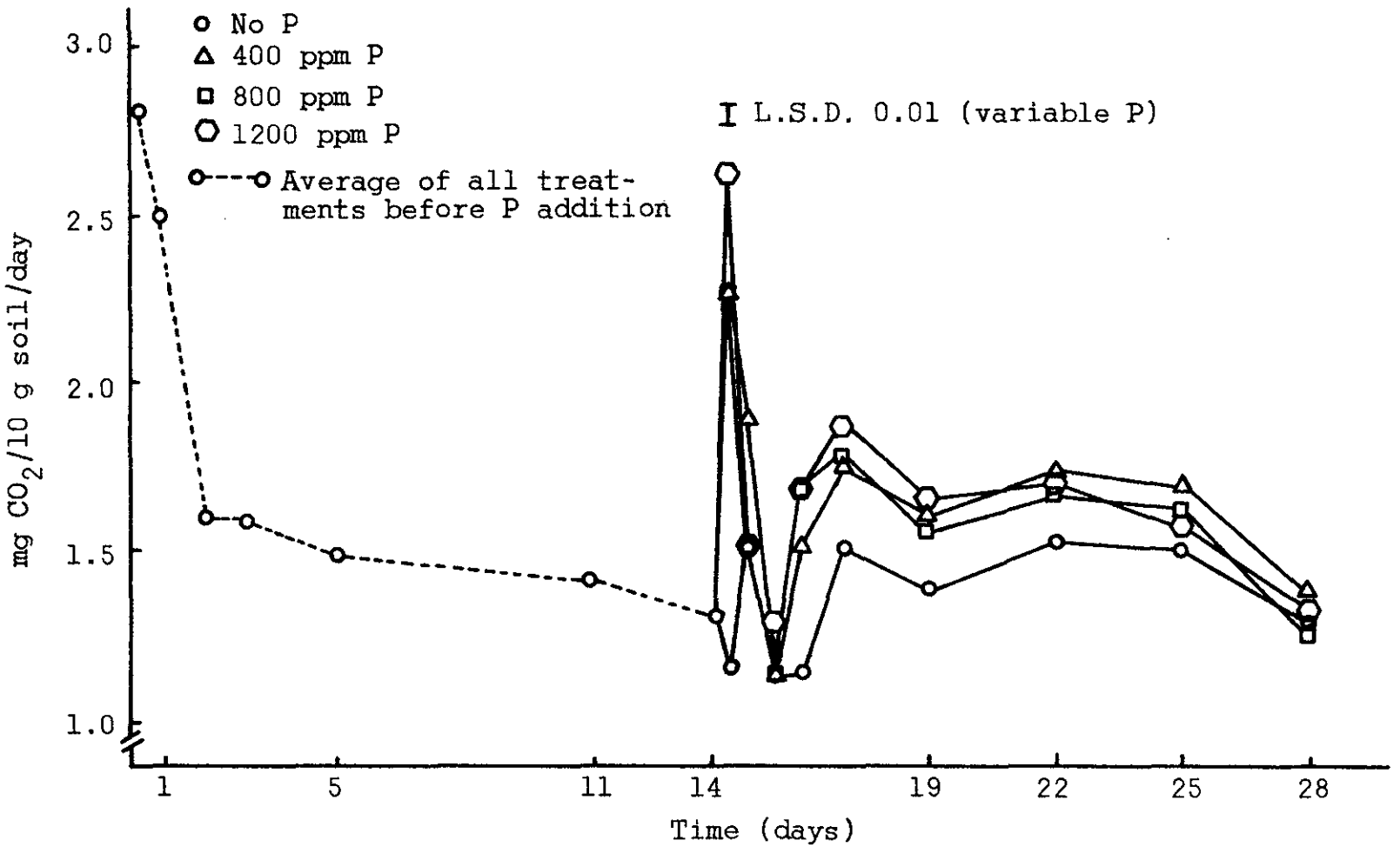

Figure 11. Rate of CO_2 evolution from San Jorge soil incubated with the indicated levels of P

Although a portion of the increase in rates of CO_2 evolution might have been due to a moistening effect, the soils treated with P significantly respired more CO_2 than the untreated soils which might be attributed to the treatment per se. The moistening effect on the rate of CO_2 evolution was lower in San Jorge soil and it was observable at 16 hours after the addition of the treatment solutions, whereas for Facatativa soil this effect occurred 8 hours after the soils had been treated. Rates of CO_2 evolution were significantly different at the 0.01 level for soils and P levels. CO_2 evolution maxima were attained 8 hours after the addition of P. The maximum rate of CO_2 evolution for Facatativa soil with the addition of 400, 800 and 1200 ppm of P was significantly greater than the CO_2 rate for the control. However, the rates of CO_2 evolution were not significantly different among the three P treatments. The mean rate of CO_2 evolution (the average of the CO_2 evolution rates at the different time intervals) was significantly larger in both soils for all of the treatments that received P as compared to the control.

The CO_2 evolution rates for San Jorge soil were significantly lower than those for Facatativa soil, but here again 400, 800 and 1200 ppm P as $Ca(H_2PO_4)_2 \cdot H_2O$ had a significant effect increasing this parameter. The difference in CO_2 evolution rates between the 400 and 800 ppm

P levels was not significant. The rate for the 1200 ppm P level was significantly higher than that of the 400 and 800 ppm P level.

These results indicate that P added as $Ca(H_2PO_4)_2 \cdot H_2O$ had a significant positive effect on the utilization of soil C by microorganisms.

Nitrogen Mineralization

The addition of $Ca(H_2PO_4)_2 \cdot H_2O$ caused statistically significant differences in N mineralization in both soils. The mineralized N at 14 days after the addition of P was significantly greater for the 1200 ppm P treatment than the mineralized N in the control for both soils. The 800 ppm P level caused a significant decrease in mineralized N at this time interval in San Jorge soil but this effect disappeared 44 days later.

The amount of N mineralized 44 days after the addition of P (58 days of incubation) was significantly greater for the 800 and 1200 ppm P levels than for the control in both soils. In Facatativa soil the 400 ppm P level also caused a significant increase in mineralized N (Figure 12).

The amount of N mineralized in the unamended soils was greater for Facatativa than for San Jorge soil. The N mineralized as a percentage of soil organic N was 1.45% for Facatativa and 0.88% for San Jorge soil. It was previously shown that C mineralization was also greater in Facatativa than in San Jorge soil.

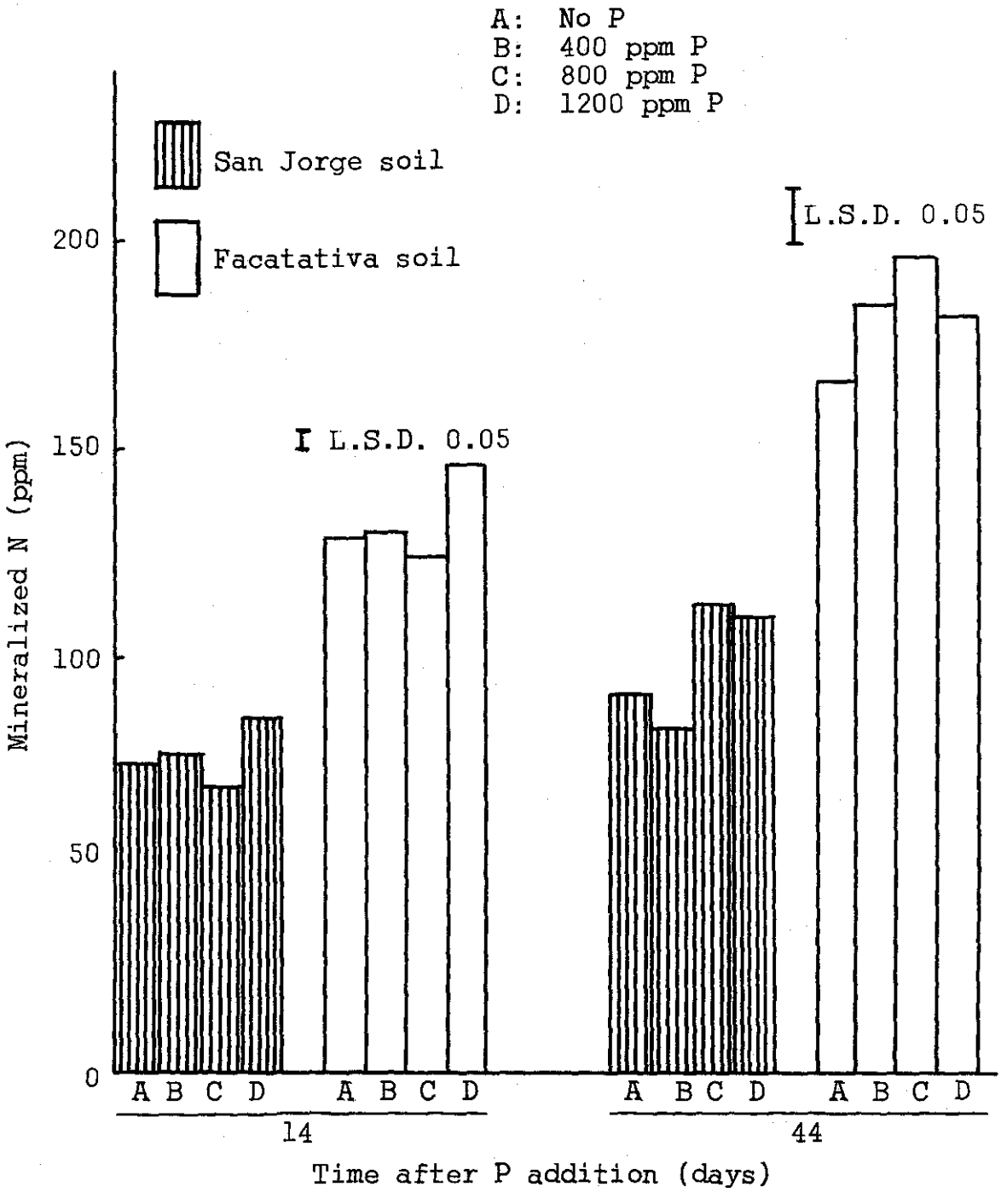

Figure 12. N mineralized in two soils incubated with the indicated levels of P as $Ca(H_2PO_4)_2$

Effect of Calcium Phosphate on the Utilization of Readily Available Carbon Added to the Soils

As another approach to study the effect of available P on microbial activity in these soils, glucose and $Ca(H_2PO_4)_2 \cdot H_2O$ were added to Facatativa and San Jorge soils and the evolution of CO_2 was determined.

The moistened soils were preincubated for 14 days and then the $Ca(H_2PO_4)_2 \cdot H_2O$ was added at the rates equivalent to 0 and 1200 ppm P. Fourteen days later glucose was added at the rates of 0 and 1000 ppm to have a factorial arrangement of the P and glucose treatments. Carbon dioxide evolution was measured at different time intervals throughout a total of 60 days of incubation.

Statistically significant differences in cumulative CO_2 evolution were obtained between the unamended soils (controls) and the treatments receiving 1200 ppm P (Figure 13). The increase in cumulative CO_2 evolution after the addition of glucose was significantly greater for the treatments which had previously been amended with 1200 ppm P than for those without added P.

The effect previously mentioned was confirmed by the rates of CO_2 evolution which were higher for the treatments receiving P than for those without it (Figure 14). An increase in the rate of CO_2 evolution was obtained 8 hours after the addition of P with respect to the control treatments.

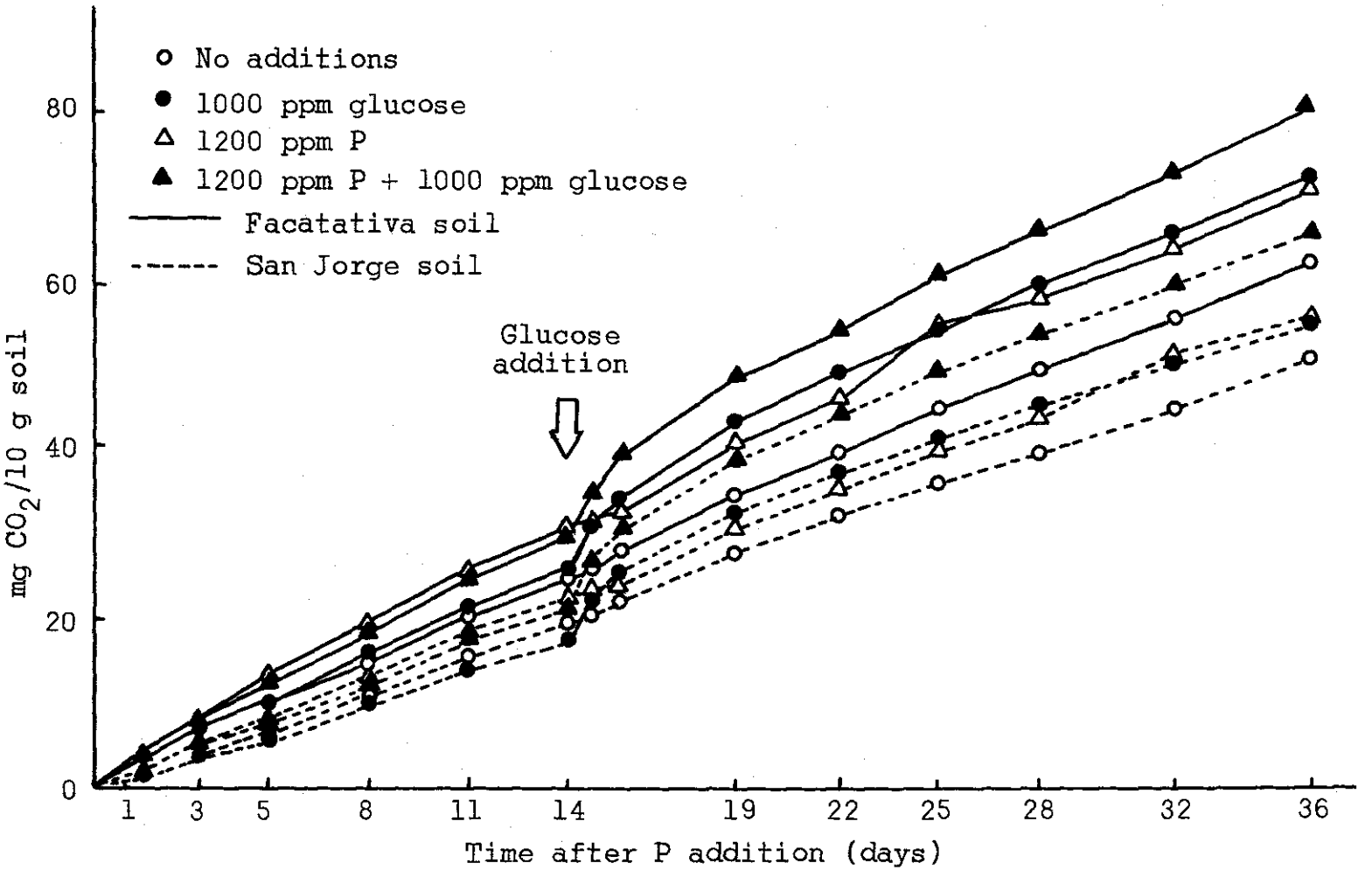

Figure 13. Cumulative CO_2 evolution from two soils incubated with different levels of glucose and P[2]

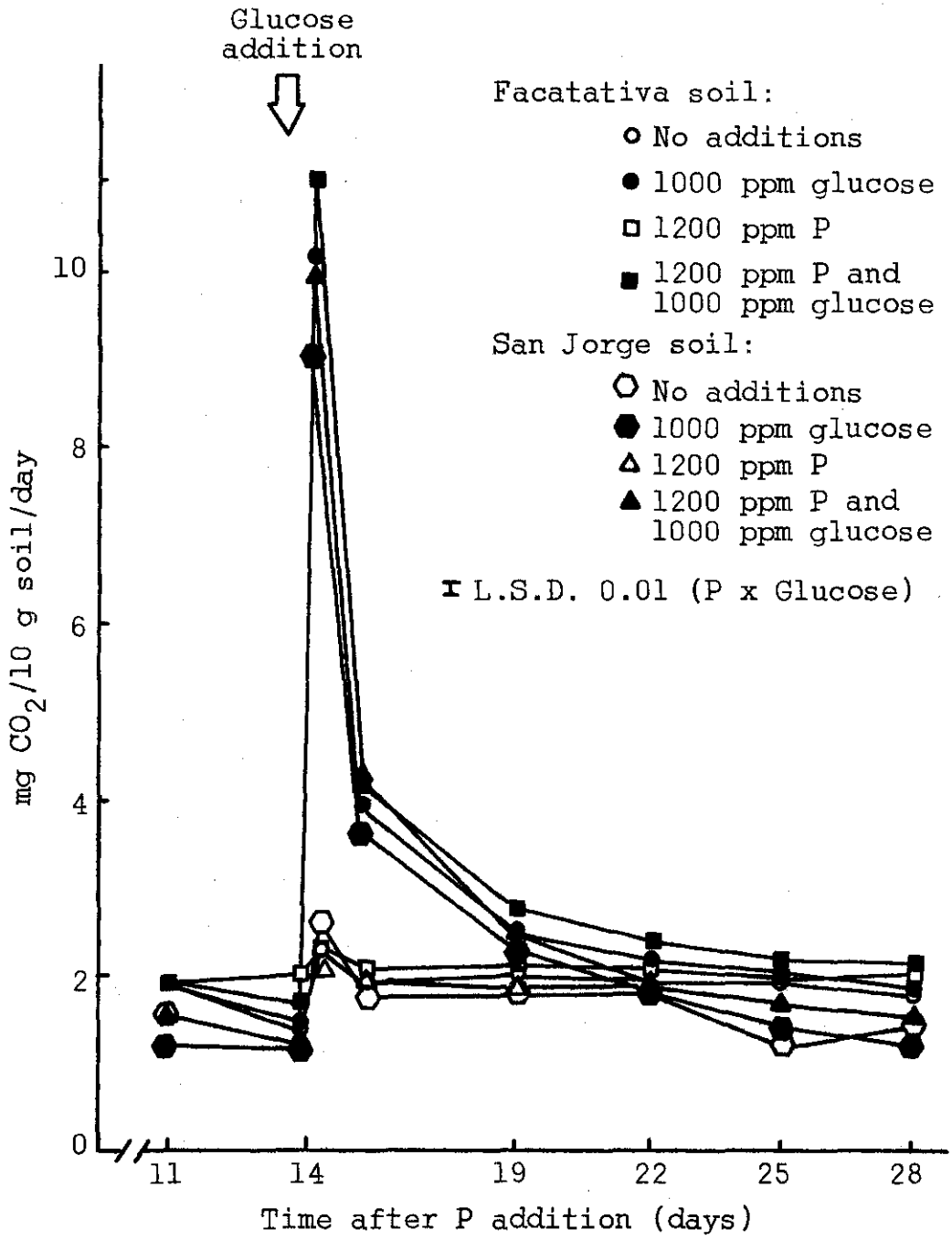

Figure 14. Rates of CO_2 evolution from two soils incubated with different rates of glucose and P

Glucose added to the soils was rapidly utilized as indicated by the almost immediate increase in the rate of CO_2 evolution. This increase was significantly greater for the treatments that had received P. The effect of the P treatments was still evident 46 days after the treatments had been initiated.

Combined Effect of Inorganic Nitrogen, Calcium Phosphate and Readily Available Carbon on Carbon and Nitrogen Mineralization

In order to study the effect of inorganic N, P and readily available C added simultaneously to the soil on C and N mineralization, a factorial experiment was conducted in which 0, 80 and 200 ppm N as NH_4NO_3; 0, 1200 and 2400 ppm P as $Ca(H_2PO_4)_2 \cdot H_2O$ and 0 and 1000 ppm glucose were added to San Jorge soil. The treated soil samples were incubated for 30 days during which CO_2 evolution was measured at different time intervals using two replications. The initial inorganic N content used to calculate mineralized N was that determined immediately after the addition of the treatment solutions with which the N added was taken into account. One additional level of N (20 ppm) and three replications were included in the N study.

Carbon Mineralization

The values of CO_2 evolution after 30 days of incubation are presented in Table 8. Additions of N did not have

any significant effect on cumulative CO_2 evolution. However, additions of P as $Ca(H_2PO_4)_2 \cdot H_2O$ caused a significant increase in CO_2 evolution both with or without added glucose. At 2400 ppm P, CO_2 increased at all N levels when no glucose was added and at the 0 and 80 ppm N levels when glucose was added. In the presence of glucose and 200 ppm N the increase in CO_2 evolution due to 2400 ppm P was not significant. The effect of 1200 ppm P in the absence of glucose was significantly greater than the control only at 80 ppm N. In the presence of glucose, 1200 ppm P caused a significant increase in CO_2 evolution in the absence of N added only.

Table 8. Carbon dioxide evolved during 30 days of incubation of San Jorge soil with the indicated treatments

P (ppm)	mg CO_2/10 g Soil		
	0 ppm N	80 ppm N	200 ppm N
	No Glucose Added		
0	41.91	37.87	40.84
1200	41.73	42.36	38.04
2400	46.82	44.00	44.35
	1000 ppm Glucose Added		
0	47.35	48.07	51.20
1200	51.52	50.29	50.38
2400	53.73	52.02	52.40

L.S.D. 0.05: 3.00
0.01: 4.11

Significant differences were also found in the rates of CO_2 evolution (Appendix Table 5). The 1200 and 2400 ppm P treatments caused a significant increase in the rate of CO_2 evolution either in the presence or absence of glucose. In the absence of glucose and P, the 80 and 200 ppm N levels caused significant decreases in the rate of CO_2 evolution with respect to the control at most of the time intervals. The level of 200 ppm N in the absence of glucose also caused a decrease in the rate of CO_2 evolution at the 2400 ppm P level as compared to the treatment receiving 2400 ppm P and no N or glucose. The addition of 200 ppm N in the presence of glucose significantly increased the rate of CO_2 evolution when no P was added. However, in the presence of 2400 ppm P and glucose the 200 ppm N level caused a decrease in the rate of CO_2 evolution with respect to the rest of the N and P treatments. This difference might be due to the fact that C assimilation for microbial cell synthesis is apparently increased when the levels of available nutrients is raised (Stotzky and Norman, 1961).

Nitrogen Mineralization

Statistically significant differences were found in mineralized N due to additions of $Ca(H_2PO_4)_2 \cdot H_2O$, N and C. The P x N interaction was also significant (Figure 15). Calcium phosphate increased the amount of N mineralized

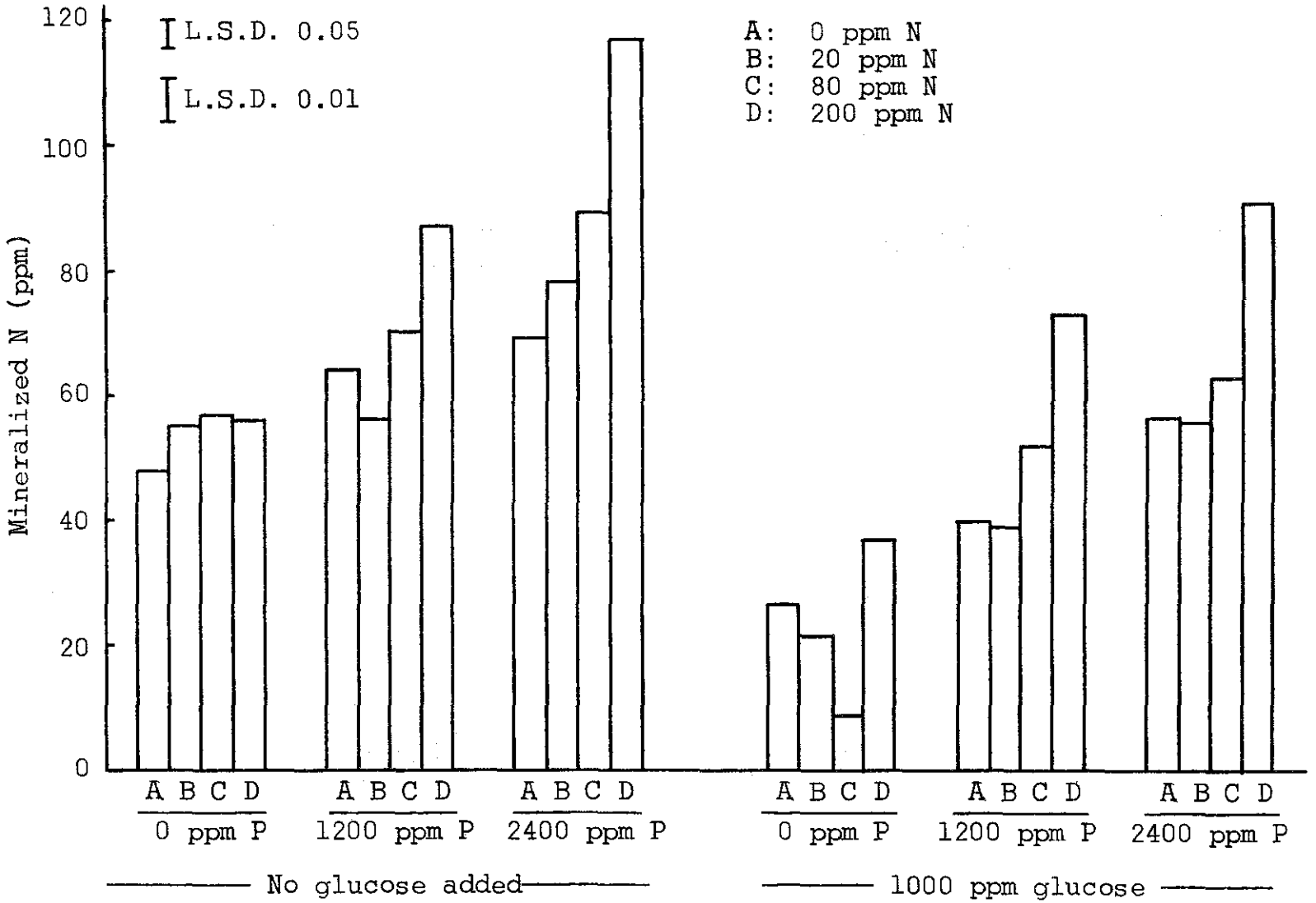

Figure 15. Nitrogen mineralized after incubating San Jorge soil for 30 days with the indicated treatments

at both the 1200 and 2400 ppm P levels with respect to the control. This effect was observed at all levels of N with the exception of the 20 ppm N level when 1200 ppm P had been added. In the absence of added N the differences in mineralized N at 1200 and 2400 ppm of P were not significant. The effect of $Ca(H_2PO_4)_2 \cdot H_2O$ increasing mineralized N was also observed in the treatments receiving glucose.

The addition of glucose resulted in either a net immobilization of N or a decrease in mineralized N with respect to the control or the corresponding treatments without glucose. This probably means that the increase in microbial activity due to the additions of glucose, as determined by CO_2 evolution, demands inorganic N to fulfill the requirements of microbial cell synthesis.

Nitrogen additions increased mineralized N at all levels except the 20 ppm N level with 1200 ppm P. The effect of $Ca(H_2PO_4)_2 \cdot H_2O$ on N mineralization was noticeably enhanced by adding inorganic N with the exception of the 20 ppm N level at the 1200 ppm P level.

Effect of Calcium Phosphate, Potassium Phosphate, and Calcium Chloride on Carbon and Nitrogen Mineralization and Soil Acidity

The increases in microbial respiration and N mineralization due to additions of $Ca(H_2PO_4)_2 \cdot H_2O$ found in previous experiments suggested the necessity to determine whether those effects were due to the increase

in the soil P level, to the added Ca or both. Therefore, and experiment was conducted in which four levels of P (0, 800, 1200, and 2400 ppm P) were added to San Jorge soil, using two sources of P: $Ca(H_2PO_4)_2 \cdot H_2O$ and KH_2PO_4. Treatments with $CaCl_2 \cdot 2H_2O$ were also included to observe the effect of Ca on C and N mineralization. The levels of $CaCl_2 \cdot 2H_2O$ were those required to add the same amounts of Ca as those contained in the 0, 800, 1200, and 2400 ppm P as $Ca(H_2PO_4)_2 \cdot H_2O$.

The soil sample used in this experiment was one which had been stored at about 17 C during 10 months in Bogota (Colombia) and then sent to Raleigh, North Carolina. Analyses of the inorganic forms of N at the arrival of the sample revealed a higher inorganic N content as compared to samples of the same soil stored at 5 C. This increase in inorganic N was probably due to the storage conditions. While the results of this experiment can not be directly compared with those of previous experiments, it is felt that the differences due to the treatments are valid.

The incubation conditions, CO_2 evolution measurements and the estimation of N mineralization were done using the same procedures previously described.

Table 9 presents the cumulative CO_2 evolution after 10 and 30 days of incubation. The data at 10 days show

Table 9. Effect of $Ca(H_2PO_4)_2$; KH_2PO_4 and $CaCl_2$ on CO_2 evolution (cumulative), N mineralization and pH of San Jorge soil

Treatment	Cumulative CO_2 Evolution (mg $CO_2/10^2$g Soil)		Mineralized N (ppm)	pH[a]
	10 Days Incubation	30 Days Incubation	30 Days Incubation	30 Days Incubation
Control	20.41	40.84	103.0	4.72
800 ppm P as $Ca(H_2PO_4)_2$	21.17	43.17	105.8	4.73
1200 ppm P as $Ca(H_2PO_4)_2$	21.57	44.28	99.7	4.75
2400 ppm P as $Ca(H_2PO_4)_2$	22.87	45.86	113.8	4.80
800 ppm P as KH_2PO_4	21.31	43.94	113.8	4.97
1200 ppm P as KH_2PO_4	25.01	47.41	97.7	5.05
2400 ppm P as KH_2PO_4	22.12	45.62	106.3	5.27
516 ppm Ca as $CaCl_2$	21.30	42.18	130.8	4.00
775 ppm Ca as $CaCl_2$	21.99	45.24	148.8	4.03
1549 ppm Ca as $CaCl_2$	22.21	41.82	172.1	3.78
L.S.D. 0.05	2.24	N.S.[b]	11.2	0.19
L.S.D. 0.01	3.03		15.2	0.26

[a]pH before incubation: 5.1.

[b]N.S.: not significant.

an increase in CO_2 evolution due to the treatments of 2400 ppm P as $Ca(H_2PO_4)_2 \cdot H_2O$ and 1200 ppm P as KH_2PO_4. The cumulative CO_2 evolution values at 30 days were not statistically different. However, it can be noticed that at this time the high levels of $CaCl_2 \cdot 2H_2O$ have the tendency to decrease the CO_2 evolution whereas the high levels of $Ca(H_2PO_4)_2 \cdot H_2O$ and KH_2PO_4 have the opposite effect. Rates of CO_2 evolution (Figure 16 and Appendix Table 6) confirm this observation. The high $CaCl_2 \cdot 2H_2O$ treatment reduced the rate of CO_2 evolution during the first 24 hours; then it caused an increase in the rate, but finally the rate of CO_2 evolution for this treatment was even lower than that of the control. This might indicate that the effect of $CaCl_2 \cdot 2H_2O$ could have been one of net decrease in cumulative CO_2 evolution with respect to the control provided the incubation time would have been longer. Similar effect of $CaCl_2 \cdot 2H_2O$ on CO_2 evolution in a volcanic ash soil from Hawaii was found by Singh et al. (1969) and it was attributed to a decrease in microbial activity due to breakdown of cells as a consequence of the increased osmotic pressure. However, the changes in pH of the soil after incubation with the different treatments (Table 9) suggest that the increased acidity caused by $CaCl_2 \cdot 2H_2O$ could also account for the decrease in microbial activity as measured by CO_2 evolution. Calcium phosphate did not have significant effect on pH and additions of KH_2PO_4

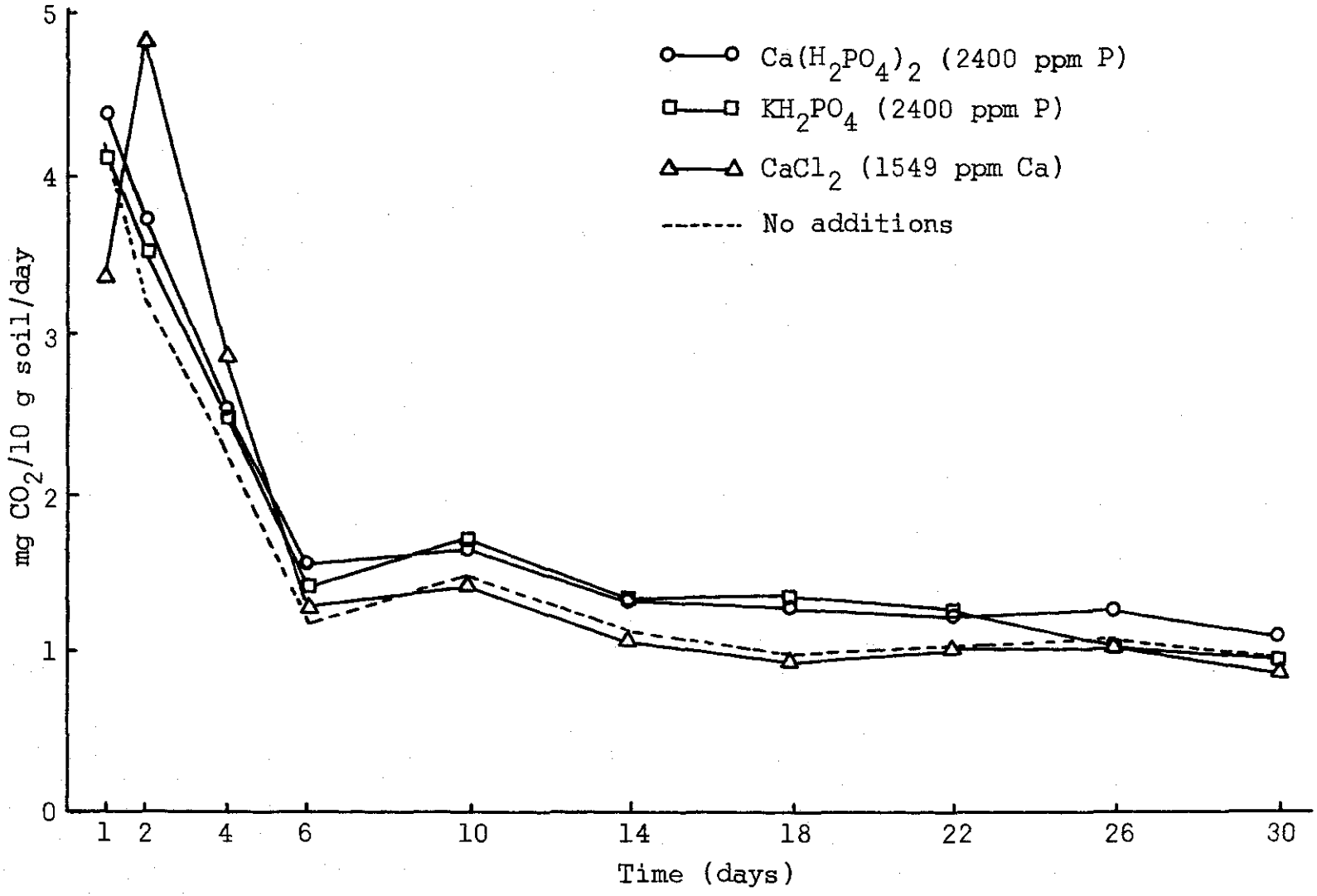

Figure 16. Effect of $Ca(H_2PO_4)_2$; KH_2PO_4 and $CaCl_2$ on the rate of CO_2 evolution from San Jorge soil

significantly increased the pH with respect to the control. This difference probably contributed to the greater evolved CO_2 found for the same levels of KH_2PO_4 as compared to $Ca(H_2PO_4)_2 \cdot H_2O$ at the same rate of P added.

The net change in inorganic N content after 30 days of incubation is also found in Table 9. The different levels of $CaCl_2 \cdot 2H_2O$ caused large increases in inorganic N content. The fact that these increases did not correspond to increases in microbial activity suggests that the changes in inorganic N due to additions of $CaCl_2 \cdot 2H_2O$ may be due to a non-biological process as indicated by Agarwal et al. (1971; 1972b) and Broadbent and Nakashima (1971). Furthermore, the nonbiological process responsible for the increase in inorganic N might be somehow related with the change in pH caused by the additions of $CaCl_2 \cdot 2H_2O$.

Calcium phosphate and KH_2PO_4 caused a slight increase in inorganic N which was not statistically significant. However, $Ca(H_2PO_4)_2 \cdot H_2O$ seemed to have a greater effect than KH_2PO_4 at the 2400 ppm P level despite the larger CO_2 evolution and increase in pH caused by the latter treatment. This effect might be due to the fact that Ca has been found to have a larger effect than K releasing inorganic N (Agarwal et al., 1971). No explanation is provided for the decrease in inorganic N release caused by $Ca(H_2PO_4)_2 \cdot H_2O$ and KH_2PO_4 at the 1200 ppm P level.

These results seem to indicate that the increase in N mineralization due to additions of $Ca(H_2PO_4)_2 \cdot H_2O$ previously observed may be partially attributed to the effect of Ca releasing inorganic N. It is possible that $CaCl_2 \cdot 2H_2O$ increased N release by a nonbiological effect which might be related with the change in pH caused by this salt.

San Jorge soil, which was used in this experiment, has a low Ca:Mg ratio (Table 3). It is thought that the effect of Ca on C and N mineralization may be different in soils having a more balanced proportion of these two cations.

Effect of Phosphorus on Carbon Mineralization as Related with the Level of Amorphous Clay Mineral in the Soils

Phosphorus was added at the rates of 0, 100, 200, 400, 1200, and 2400 ppm to Tibaitata and San Jorge soils in order to compare the effect of increasing the availability of this nutrient on the rates of C and N mineralization in two soils differing in the content of amorphous aluminosilicates and having different patterns of P fixation. P was added as KH_2PO_4 assuming that the effect of this substance on microbial processes in the soil would be due mainly to the P and not to the K since the availability of this cation is rather high in the soils being studied.

The effect of the addition of 2400 ppm P on the rates of CO_2 evolution is observed in Figure 17, and the data for the other levels of P are included in Appendix Table 7.

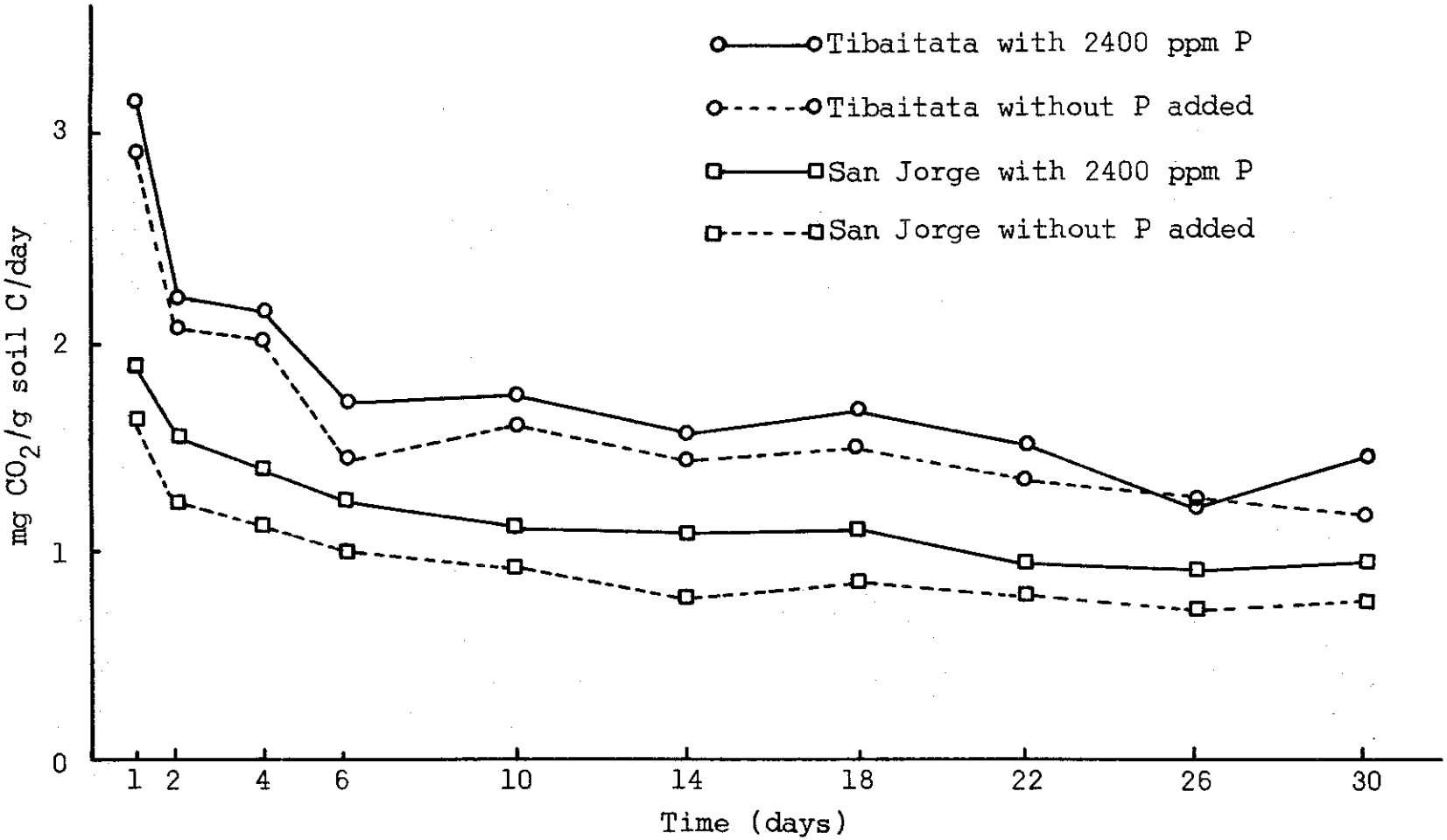

Figure 17. Effect of KH_2PO_4 on the rate of CO_2 evolution per g of soil C from two soils

The differences in rates of CO_2 evolution between the two soils without P is noticeable. Tibaitata soil which has a lower content of amorphous alumino-silicates showed greater rates of CO_2 evolution than San Jorge soil.

The additions of P at all levels caused significant increases in the rates of CO_2 evolution in both soils, with the exception of the 200 ppm P level in the Tibaitata soil. These results suggest that P might have been limiting for carbon mineralization in both soils under natural conditions.

The increases in CO_2 evolution seemed to be larger for San Jorge soil than for Tibaitata soil in both the low and high range of P levels. However, the relative effect of P on microbial activity as measured by CO_2 evolution does not seem to have a close relationship with the P fixation patterns of the two soils. Other factors such as the initial available P level, the level of other nutrient elements, or soil acidity, may be determining the patterns of response to P.

Although it was originally intended to study the effect of P on N mineralization as well as C mineralization, some unidentified problem in analysis prevented the evaluation of N mineralization on the samples used for this purpose.

SUMMARY AND CONCLUSIONS

This study was conducted to determine the influence of additions of readily available C, inorganic N and P on the mineralization of soil organic C and N in volcanic ash soils.

Surface horizons of four volcanic ash soils from Colombia were studied: La Ceja (Typic Distrandept), Tibaitata (Andic Aquic Eutropept), Facatativa (Typic Placandept) and San Jorge (probably a Dystrandept).

The chemical analyses of the soils showed that Tibaitata is the least acid and has a higher effective cation-exchange capacity and base saturation than the other three soils.

Mineralogical analyses revealed that the clay fraction of the study soils is dominated by amorphous aluminosilicates. Small amounts of kaolinite are present in the Tibaitata soil, as well as less amorphous materials than in the other three soils.

Tibaitata soil was found to have a relatively low P fixation capacity whereas the other soils have a very high capacity to fix phosphates.

Incubation studies were conducted under aerobic conditions to evaluate the effect of different C, N, and P treatments on microbial respiration and nitrogen

mineralization. The main results and conclusions of the microbiological studies are the following:

1. Carbon dioxide data showed that soil C mineralization is probably not increased by additions of readily available C to these soils.

2. Additions of readily available C to the soils caused either net immobilization of N or a decrease in N mineralization with respect to unamended soils. It was concluded that the lack of energy and C for microbial growth does not seem to be a limiting factor for organic matter mineralization in volcanic ash soils.

3. Phosphorus additions from 400 to 2400 ppm P as $Ca(H_2PO_4)_2 \cdot H_2O$ increased the rate of C mineralization and utilization of readily available C added to the soils.

4. The level of P addition that caused the greatest increase in N mineralization was 2400 ppm P. In soils of volcanic origin P availability for microbial growth probably limits the rate of mineralization of both C and N.

5. Inorganic N added to one of the soils at the rates of 20, 80, and 200 ppm increased the amount of soil N mineralized and seemed to enhance the effect of P on N mineralization.

6. Readily available C added to the soil decreased N mineralization even when high levels of inorganic N and P had been added.

7. A comparison of the effect of $Ca(H_2PO_4)_2 \cdot H_2O$, KH_2PO_4 and $CaCl_2 \cdot 2H_2O$ on soil C and N mineralization showed that the increase in N mineralization caused by additions of $Ca(H_2PO_4)_2 \cdot H_2O$ may be in part the result of the added Ca.

8. Calcium phosphate, KH_2PO_4 and $CaCl_2 \cdot 2H_2O$ clearly differed in the way they changed soil pH. Calcium chloride increased the inorganic N content of the soil without increasing microbial respiration; therefore, its effect was thought to be of a nonbiological nature. The effect was accompanied by a drastic decrease in soil pH.

9. Additions of 100, 200, 400, 1200, and 2400 ppm P as KH_2PO_4 increased microbial respiration in two soils differing in amorphous clay content and P fixation capacity. Microbial respiration was increased in a fashion that did not show relation with the P fixation patterns of the soils.

10. In two instances it was observed that the rate of mineralization of soil C was higher for soils having lower content of amorphous clay minerals than for soils richer in them.

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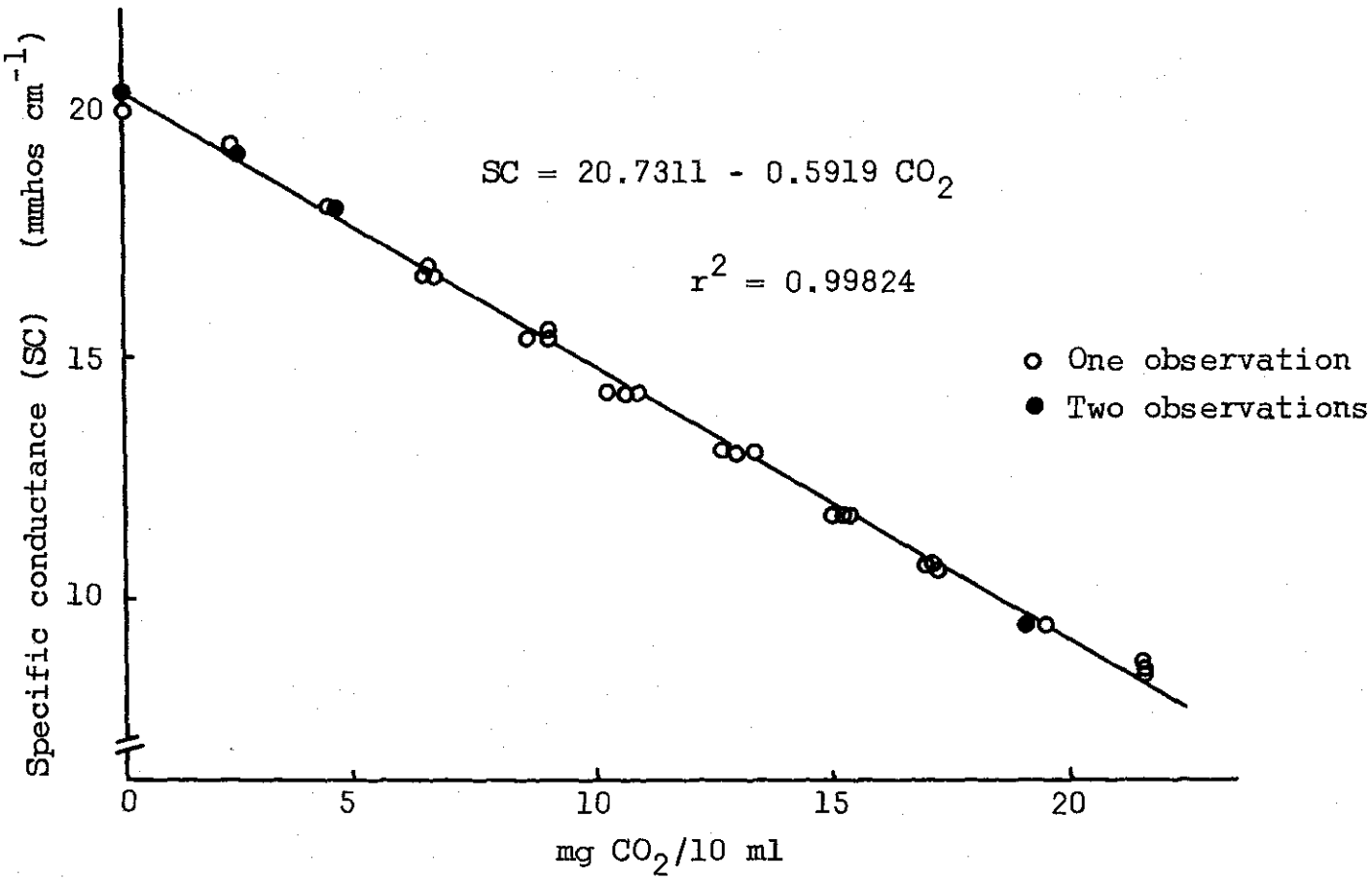
APPENDIX



Appendix Figure 1. Regression equation obtained for the conductimetric determination of CO_2

Appendix Table 1. Number of microorganisms in Cecil soil used as inoculum

	Number of Colonies per g of Dry Soil[a]
GNA (Bacteria + actinomycetes)[b]	11.9×10^6
PGA (Fungi)[c]	4.6×10^6

[a]Numbers are the average of two replications.

[b]Glucose nutrient agar (GNA) consisted of the following ingredients: Dextrose 5.0 g, peptone 5.0 g, beef extract 3.0 g, yeast extract 1.0 g, agar 15.0 g and distilled water 1 liter.

[c]Peptone-glucose acid agar (PGA) consisted of the following ingredients: KH_2PO_4 1.0 g, $MgSO_4 \cdot 7H_2O$ 0.5 g, glucose 10.0 g, agar 15.0 g and water 1 liter. After autoclaving, 10 ml of 0.5 N H_2SO_4 were added to each liter of medium.

Appendix Table 2. Phosphorus extracted with Bray II solution (0.1 N HCl + 0.03 N NH_4F) after 14 days of incubation with different amounts of P added

	P Added (ppm)							
Soil	0	100	200	400	600	800	1200	2400
La Ceja	0.6	1.6	1.8	3.0	3.3	6.1	7.7	14.3
Tibaitata	2.1	11.4	25.4	64.8	106.6	171.8	189.8	460.4
Facatativa	0.2	1.1	1.3	2.4	2.7	6.2	6.8	13.1
San Jorge	0.6	2.7	3.0	6.5	7.0	14.8	15.8	39.5

Appendix Table 3. Cumulative CO_2 evolution (mg CO_2/10 g soil) from three soils incubated with different rates of glucose

Soil	Glucose (ppm)	Time (hours)						
		24	48	83	120	240	478	718
La Ceja	0	5.54	8.32	11.32	14.27	19.53	32.61	46.15
	100	6.39	10.04	12.83	16.18	22.49	35.29	50.32
	1000	6.49	10.47	14.93	17.67	24.88	34.18	48.52
	10,000	26.35	62.99	78.59	87.52	100.49	120.25	139.51
Tibaitata	0	2.91	4.78	6.81	8.65	12.29	19.06	26.66
	100	2.63	5.16	6.73	8.58	11.47	20.20	31.44
	1000	7.15	9.90	12.39	15.12	19.78	27.55	35.60
	10,000	13.33	39.63	60.16	70.64	83.55	99.21	112.71
Facatativa	0	7.22	12.10	17.00	21.07	28.79	44.10	58.05
	100	7.91	12.92	17.67	21.90	29.64	45.18	59.42
	1000	11.30	18.26	23.77	28.12	36.74	54.56	71.58
	10,000	14.48	44.44	64.69	85.05	106.53	130.50	150.02
L.S.D. 0.05 (Soil)		2.56	2.59	2.59	3.99	5.59	6.08	6.13

Appendix Table 4. Mineralized N (NH_4 + NO_3 + NO_2) in three soils incubated with different rates of glucose

Soil	Glucose (ppm)	N (ppm)	
		20 days	30 days
La Ceja	0	60.67	55.77
	100	75.47	60.73
	1000	44.33	36.13
	10,000	-116.43[a]	-100.03
Tibaitata	0	47.70	46.50
	100	-1.10	52.53
	1000	-15.50	10.70
	10,000	-51.13	-29.73
Facatativa	0	112.03	129.47
	100	141.83	110.77
	1000	63.63	73.57
	10,000	-67.07	-44.67
L.S.D. 0.05		21.32	22.30
L.S.D. 0.01		28.90	30.22

[a]Negative values indicate net N immobilization.

Appendix Table 5. Rates of CO_2 evolution (mg CO_2/10 g soil) per day for San Jorge soil incubated with different treatments of N, P and glucose, during 30 days

N (ppm)	P (ppm)	Time (Days) 1	2	3	5	8	11	14	17	21	27	30	Mean
						No Glucose Added							
0	0	2.93	2.02	1.67	1.67	1.59	1.46	1.43	1.27	1.16	1.15	1.06	1.58
0	1200	2.93	2.19	1.67	1.68	1.54	1.46	1.27	1.27	1.23	1.19	0.95	1.58
0	2400	3.26	2.19	1.67	1.83	1.73	1.66	1.43	1.48	1.40	1.37	1.11	1.74
80	0	2.59	2.02	1.49	1.59	1.45	1.25	1.22	1.17	1.09	1.02	0.95	1.44
80	1200	2.92	2.19	1.67	1.68	1.59	1.46	1.33	1.27	1.23	1.19	1.06	1.60
80	2400	2.92	2.19	1.84	1.67	1.59	1.51	1.43	1.38	1.33	1.21	1.12	1.66
200	0	2.92	2.19	1.49	1.68	1.54	1.46	1.22	1.17	1.23	1.15	0.95	1.55
200	1200	2.92	2.02	1.49	1.51	1.35	1.30	1.17	1.17	1.09	1.06	0.95	1.46
200	2400	3.09	2.19	1.49	1.59	1.59	1.50	1.38	1.38	1.44	1.29	1.12	1.64
						1000 ppm Glucose Added							
0	0	7.80	3.03	2.02	1.83	1.59	1.51	1.27	1.22	1.12	1.09	1.01	2.14
0	1200	7.80	3.03	2.19	1.83	1.73	1.61	1.38	1.38	1.37	1.31	1.06	2.25
0	2400	8.16	3.19	2.36	1.99	1.87	1.71	1.48	1.43	1.37	1.29	1.12	2.36
80	0	7.55	3.19	2.19	1.76	1.59	1.46	1.38	1.22	1.19	1.17	0.95	2.15
80	1200	7.80	3.03	2.02	1.99	1.59	1.61	1.33	1.33	1.26	1.28	1.06	2.21
80	2400	8.04	3.35	2.19	2.07	1.59	1.66	1.43	1.27	1.26	1.31	1.17	2.30
200	0	7.05	3.19	2.19	2.06	1.78	1.66	1.38	1.33	1.33	1.26	1.12	2.21
200	1200	7.68	3.19	2.19	1.91	1.64	1.51	1.33	1.33	1.33	1.23	1.12	2.22
200	2400	5.78	2.69	2.05	1.90	1.77	1.49	1.43	1.37	1.34	1.12	1.34	2.03
L.S.D.	0.05	0.67	0.19	0.14	0.13	0.11	0.11	0.09	0.06	0.07	0.08	0.09	
L.S.D.	0.01	0.92	0.26	0.19	0.18	0.15	0.15	0.12	0.09	0.10	0.11	0.12	

Appendix Table 6. Rates of CO_2 evolution (mg CO_2/10 g soil) per day for San Jorge soil incubated with different rates of $Ca(H_2PO_4)_2 \cdot H_2O$; KH_2PO_4 and $CaCl_2 \cdot 2H_2O$

Treatment	Time (Days)									
	1	2	4	6	10	14	18	22	26	30
Control	4.18	3.20	2.23	1.19	1.48	1.14	0.99	1.03	1.09	0.93
800 ppm P as $Ca(H_2PO_4)_2$	4.37	3.40	2.36	1.29	1.52	1.14	1.12	1.16	1.14	0.95
1200 ppm P as $Ca(H_2PO_4)_2$	4.45	3.50	2.41	1.24	1.58	1.20	1.16	1.16	1.14	1.02
2400 ppm P as $Ca(H_2PO_4)_2$	4.38	3.70	2.54	1.55	1.65	1.31	1.28	1.24	1.25	1.09
800 ppm P as KH_2PO_4	4.28	3.30	2.45	1.29	1.56	1.20	1.12	1.16	1.16	1.02
1200 ppm P as KH_2PO_4	4.37	3.50	2.45	1.45	1.69	1.39	1.24	1.26	1.27	1.09
2400 ppm P as KH_2PO_4	4.09	3.50	2.50	1.40	1.68	1.31	1.37	1.26	1.01	0.92
516 ppm Ca as $CaCl_2$	4.18	3.70	2.41	1.29	1.50	1.11	0.99	1.05	1.09	0.98
775 ppm Ca as $CaCl_2$	4.09	4.27	2.54	1.19	1.54	1.16	1.51	1.05	1.11	0.98
1549 ppm Ca as $CaCl_2$	3.33	4.82	2.85	1.29	1.44	1.07	0.93	1.03	1.00	0.88
L.S.D. 0.05	0.49	0.31	0.17	0.14	N.S.[a]	0.19	N.S.	0.14	N.S.	N.S.
L.S.D. 0.01	0.66	0.42	0.23	0.20		0.25		0.18		

[a]N.S. = not significant.

Appendix Table 7. Rates of CO_2 evolution (mg CO_2) per g of soil C per day of Tibaitata and San Jorge soils with different rates of KH_2PO_4

P (ppm)	Time (Days) 1	2	4	6	10	14	18	22	26	30
					Tibaitata Soil					
0	2.90	2.07	2.01	1.43	1.60	1.42	1.48	1.33	1.24	1.18
100	2.77	2.07	1.94	1.36	1.68	1.45	1.48	1.39	1.27	1.18
200	2.77	2.07	1.87	1.79	1.60	1.31	1.42	1.24	1.24	1.21
400	3.04	2.07	2.08	1.72	1.66	1.42	1.45	1.33	1.24	1.30
1200	3.04	2.07	2.08	1.72	1.68	1.49	1.56	1.39	1.36	1.36
2400	3.17	2.21	2.15	1.72	1.77	1.56	1.67	1.51	1.21	1.45
					San Jorge Soil					
0	1.63	1.23	1.13	1.01	0.92	0.78	0.83	0.79	0.72	0.75
100	1.66	1.37	1.17	1.01	0.93	0.81	0.89	0.82	0.76	0.80
200	1.63	1.30	1.17	1.07	1.01	0.88	0.97	0.86	0.81	0.84
400	1.70	1.30	1.23	1.10	1.02	0.90	0.96	0.87	0.80	0.79
1200	1.70	1.30	1.33	1.17	1.09	0.94	0.98	0.90	0.83	0.84
2400	1.89	1.56	1.40	1.26	1.13	1.09	1.09	0.94	0.91	0.95
L.S.D. 0.05	0.16	0.12	0.08	0.14	0.05	0.05	0.05	0.06	0.10	0.05
L.S.D. 0.01	0.21	0.16	0.10	0.19	0.06	0.07	0.06	0.08	0.13	0.07