
Soil Acidity and Liming in Tropical Fruit Orchards

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1. Introduction

In Brazil, agribusiness generates some US\$ 330 billion in revenue per year and is the most important sector of country's economy, accounting for 30% of GDP, 36% of exports and 37% of the jobs. This activity is one of the main reasons for Brazil's trade surplus in recent years, with annual farm exports worth more than US\$ 60 billion [1].

Based on these figures, it is no exaggeration to say that more than one-third of the Brazilian annual wealth is supported by a single natural resource: the soil. This justifies the importance of studies on how to preserve and improve this valuable resource. According to [2], soils have natural limits to their ability to nourish plants and sustain crop productivity. The degradation of soil quality reduces this ability and at the same time deteriorates the quality of water for various uses. It is senseless to claim that agricultural technology can compensate for poor soil management.

Fruit growing is an important component of Brazilian agriculture, occupying 2.3 million hectares and producing 41 million metric tons of fruit annually, totalling some US\$ 10 billions. This ranks Brazil among the world's leading fruit producers [3]. Despite this standout position, fruit yield remains unsatisfactory compared to many other countries. Among factors contributing to this situation, perhaps the most important is the deficient use of techniques to manage soils, crops and the environment.

Because of advances in genetic improvement in recent decades, plants now produce more yields of higher-quality fruits, but the demand for and the export of nutrients, as can be expected, are also higher. On the other hand, Brazilian soils tend to be naturally acic and low in fertility and/or are subjected to overexploitation, leading to exhaustion. Soil acidity is one of the main factors that reduce crop yields as in other tropical regions of the globe. Liming is a widely used technique in annual cropping systems but for perennials such as fruit trees,

liming is more complicated due to the characteristics of these plants and the lack of scientific knowledge on this subject. Fruit trees, like all other perennials, keep producing for many years in practically the same volume of soil, which is the reason why soil acidity requires special attention. Despite the high importance of lime application for most fruit trees, there is a lack of information on the effects of this soil treatment technique during the planting, formation and production stages of orchards.

Therefore, it is important to study the effects on orchards of soil acidity correction, especially through liming, by monitoring soil chemistry and the response of the trees. Better knowledge in this respect can improve fruit crop productivity that translates into higher profits for farmers.

2. Soil acidity and liming

The soil, from where mankind has drawn its main sustenance since the beginning of the civilization, requires adequate management to maintain its fertility and nutrient availability sufficient to sustain the fundamental role of crops in supporting human life.

Among soil environmental factors, acidity (pH, base saturation, potential acidity and nutrient solubility) is the one that affects most crop yields, particularly in tropical regions [4]. According to [5], the low fertility found in acidic soils is strongly associated with deficient levels of exchangeable bases and excessive amounts of aluminum and manganese. The application of fertilizers that acidify the soil aggravates this problem, unless a well-planned liming program is implemented.

Some soils are naturally acidic due to relative shortage of basic cations in the original material or to processes that causes the loss of elements like potassium, calcium and magnesium [6]. Other soils, although not originally acid, become so due to the removal of exchangeable cations from the surface of colloids, caused by: *a*) rainwater; *b*) alteration of clay minerals; *c*) ion exchange of roots; *d*) decomposition of organic matter; and *e*) addition of nitrogen fertilizers.

Although liming is recognized as a beneficial practice to reduce soil acidity, it is often not employed, or is conducted inadequately. Limestone raises soil pH, neutralizes toxic aluminum and supplies calcium and magnesium to the crops. These factors promote the development of root systems and enhance the use of nutrients and water by the plant [7]. In soils of tropical regions, acid reaction and low levels of basic cations such as calcium are ever-lasting problems. Under these conditions, the application of limestone is an inexpensive, fast and efficient way to tackle both problems [8].

Among Brazilian minerals, limestone occupies first place: the country has estimated reserves of some 53 billion metric tons well distributed throughout the country and generally of good quality, making it a relatively inexpensive agricultural input. However, despite the abundance of limestone and the need for liming, this soil corrective measure is not used at a sufficient extent in the majority of Brazilian farming regions [5].

The application of limestone on annual crops, with homogeneous incorporation in the soil, is a common practice, although not recognized as it should be. In perennial crops, the incorporation of limestone is more complex due to the intrinsic characteristics of these plants and the lack of scientific and technological information [9]. This is the case, for example, for the majority of fruit crops in Brazil.

In acid soils with high aluminum saturation, liming promotes the neutralization of the toxic Al in the surface layers, hence enabling more intense proliferation of roots with positive effect on plant growth. However, it is important to consider the need to incorporate the limestone thoroughly into the soil at the time of planting perennial crops because surface application alone acts slowly on the deeper soil layers and a soil insufficiently corrected at the establishment of the orchard can impair crop productivity for a long time [10]. The homogeneous incorporation of limestone allows greater contact between the amendment and the sources of acidity, speeding up the corrective effects that support efficient use of water and nutrients by the plant in the amended layer.

The importance of the root system is obvious because there is a close dependency between root development and the aboveground portion of the plant. The greater or lesser success of applying limestone and fertilizers, in turn, depends on the nature of the root system and on the volume of the soil effectively exploited by the particular plant species. Correction of acidity is the most efficient way to eliminate chemical barriers to the full development of the roots, and consequently, of the plant.

Unlike other agricultural inputs such as fertilizers, herbicides and insecticides, limestone can be considered an investment, because its benefits last over more than one harvest. This is due to the low solubility of the common limestones and the variability of particle sizes in crushed limestone, giving them different capacities to neutralize acidity over time. Therefore, two factors should be considered: the rate at which the acidity is corrected and the duration of the effects of liming. Fine particles promote rapid acidity correction, but this effect declines more quickly due to their faster solubilization. Therefore, the most efficient liming involves application of material with varied grain sizes to promote fast initial acidity correction with sufficient residual effect as well. The Brazilian law (2006) states that the reactivity of liming materials after a period of three months following soil application is zero for large particles more than 2 mm in diameter, 20% for particles in the range of 0.84 and 2 mm in diameter, 60% for particles from 0.30 to 0.84 mm in diameter, and 100% for fine particle less than 0.30 mm.

Because of the residual effect of limestone, liming materials applied to the soil at the time of planting orchard seedlings can keep the soil within acceptable acidity range for a certain period of time. However, determining the duration and intensity of the residual effect of liming at the moment of planting fruit orchards has not been widely studied, both due to experimental constraints and the time necessary to obtain satisfactory results [11-13].

Based on the above aspects, the best approach for liming is to apply limestone with larger grain size at the time of planting fruit orchards, with homogeneous incorporation in the soil, to prolong the residual effect, followed by use of fine material on adult trees, limited to the

surface, because the incorporation of corrective materials into the soil may induce phytosanitary problems to the plants. Materials with finer particles can move more easily through the soil profile, correcting the acidity only in the surface layers.

Considering the perennial nature and cultivation conditions of fruit trees, the path of limestone particles in the soil can vary along with various factors, including physical ones, through the channels left by the decomposition of roots [14]. According to [15] and [16], another explanation for particle flow through the soil profile is the formation of ion pairs (Ca^{2+} and Mg^{2+}) and organic acids (RO^- and RCOO^-) of high solubility and low molecular weight that can be leached to deeper layers. Besides these mechanisms, according to [17] other compounds may form such as $\text{Ca}(\text{HCO}_3)_2$ and $\text{Mg}(\text{HCO}_3)_2$. Nitrogen fertilization, in turn, can promote the formation of soluble salts, such as calcium nitrate, which percolate down through the soil in forms dissolved in water [18]. According to [11], it is probable that the sum of the contributions of all these processes is more important than each one individually. Finally, the movement of these particles depends on the dose of the corrective measure employed, the time after application, soil type and the type of fertilization applied to the orchard.

3. Sampling of leaves and soil in fruit orchards

The soils in Brazil are mainly tropical, are low in fertility and normally show acid reaction. This is particularly due to their weathering during soil formation. This is one of the main reasons for applying lime and fertilizers in farmed areas. Another important factor is that because of Brazil's continental dimensions, it has a wide range of climate and soil characteristics, requiring different liming and fertilization regimes depending on orchard location.

Furthermore, different soils have different nutrient deficiencies, and plant species vary greatly in their nutritional demands. Therefore, the only reliable way to identify the best acidity corrective measure or fertilizer for use in a determined place for a particular crop is soil analysis.

Besides soil analysis, which is a well-established practice in agriculture, it is also important for the majority of fruit trees to analyze the leaves for determining the pattern of nutrient uptake over time [19]. Because adult fruit trees require a certain degree of nutritional stability, leaf diagnosis allows adjusting fertilization programs over the years so as not to impair fruit harvest in the same year. Hence, leaf sampling and soil analysis are useful methods to monitor the effects of liming and fertilization on plant nutrition. Growing fruit trees is a long-term activity where the plants continue exploiting practically the same volume of soil for many years. In this situation, chemical impediments (acidity) as well as physical ones (soil compaction) can reduce the efficiency of the roots in exploiting the soil. Therefore, the only way to determine to what extent plants are using the nutrients applied via fertilization and liming is to diagnose their nutritional status by leaf analysis.

Chemical analysis is the easiest and most practical way to assess soil fertility. Proper sampling is essential to obtain reliable results because if the samples are not representative, the

results do not accurately reflect the true soil fertility. Soil sampling is a common practice among farmers for annual crops, but it has not been widely studied for perennial crops such as fruit trees, raising doubts on its reliability. The present recommendations are to sample the area that receives soil treatment. However, some works have shown a higher correlation between leaf nutrient levels of fruit trees and soil nutrient levels in the paths between rows than in the rows [12, 20]. So, which soil samples should be analyzed, those from the treated area or between the rows? How should correlations be interpreted? And at what depth should the soil be sampled? These are difficult questions to answer, and according to [8], it also is not easy to design studies for this purpose.

At the time of planting fruit orchards, the soil sampling procedure is the same as for annual crops, namely across the entire representative area. In producing orchards, it is important to sample the region under the projection of the tree crowns, which is the area that usually receives fertilizers. Samples should be collected at the end of harvest from 20 points in each homogeneous plot (same cultivar, age, productivity, soil type, management and fertilization). At the same time, samples should be taken between the rows to measure lime requirements if necessary. Studies have shown that acidification occurs more intensely under the projection of tree crowns due to nitrogen fertilization, application of organic wastes and accumulation of plant material from pruning. As a rule, limestone is more often applied in strips under crown projection than onto areas between rows.

The most common method to calculate lime requirement in Brazil is base saturation [10]. The formula is as follows:

$$LN \text{ (ton ha}^{-1}\text{)} = \frac{(V_2 - V_1) \times CEC}{TRNP \times 10}$$

where:

LN is the need for limestone, in ton ha⁻¹;

V₂ is the target base saturation for the crop;

V₁ is base saturation of the soil;

CEC is soil's cation exchange capacity; and

TRNP is the total relative neutralization power, which considers the quantity of carbonates present in the limestone and lime's granulometry.

The soil layer typically sampled is the surface 0 to 20 cm. However, fruit trees exploit a much larger soil volume compared to annual plants, so it is important to analyze the properties of the deeper layers, especially regarding calcium and aluminum concentrations. This may lead to gypsum application, which neutralizes toxic Al and allows increasing Ca concentration in deeper layers, an important factor for the proliferation of the root system and its exploitation of a larger soil volume.

Gypsum is indicated, for crops in general, when analysis of the soil from the 20-40 cm layer reveals calcium concentrations lower than 4 mmol_c dm⁻³ and/or aluminum saturation above 40%. The need for gypsum is estimated by the following equation [10]:

$$GN \text{ (kg ha}^{-1}\text{)} = 6 \times \text{clay}$$

where:

GN is the need for gypsum, in kg ha⁻¹; and

Clay is the soil clay content, in g kg⁻¹.

For diagnosing the nutritional status of plants, leaf analysis is the most efficient technique, but also the one where errors occur most frequently. Each plant species has its own sampling procedure. Thus, the leaves to be collected and the time of the year are critical for successful diagnosis of the plant nutritional status. In the case of fruit trees, such as the guava tree, the third pair of leaves should be collected from each plant, with 25 pairs being collected from each homogeneous plot. This should be done at the time of full flowering [21]. These leaves should be immediately taken to the laboratory for washing, drying, grinding and analysis. The next step is to interpret the results, based on studies conducted under field conditions in high-yielding orchards.

In summary, when performed correctly, analysis of soil and leaf samples can allow making recommendations on liming and fertilization to improve fruit yield and quality, and hence increase the profits of fruit growers.

4. Considerations on fruit growing areas and fructiferous plants

By comparison with other regions of the world, Brazil is endowed with adequate characteristics of soil, climate, water availability and diversity of fruit species that give it great potential as a fruit producer and exporter.

These favorable conditions for the development of fruit growing regions expand agroindustrial activity and boost exports, not only because of the nutritive value of fruits, but also because of the perspective they represent to increase farm production. Besides this, cultivation of perennial species, as are most fructiferous plants, triggers the occupation of areas with soils classified unsuitable for the majority of annual crops.

Despite those advantages, there is still a lack of information on the correct management of soil fertility, the choice of inputs and the nutritional needs of fruit-bearing plants, preventing Brazil from realizing its full agribusiness potential.

Because fruit orchards are perennials and trees' roots remain practically restricted to the same soil space for many years, it is important to incorporate homogeneous amounts of limestone to deep levels before planting so the root system can develop adequately for efficient uptake of water and nutrients. This enhances the development and nutritional status of the plants with less need for fertilizers, thus improving the cost-benefit ratio of inputs and boosting crop productivity. In producing orchards, repeatedly applied high doses of nitrogen over restricted areas (projection of the tree crowns) aggravate the problem of soil acidity, hence requiring regular soil chemical analysis.

Fruit growing is an important activity in most Brazilian regions, especially those covered with latosols (oxisols) and argisols (ultisols), which are generally deep and permeable, hence providing ideal conditions for perennial crops that produce a broad and well developed root system. Nevertheless, these soils have a strong acid reaction and are low in nutrients, so they need liming and fertilization.

Roots do not develop satisfactorily in highly acid soils. Among the acidity factors, aluminum toxicity and calcium deficiency are indicated as the most relevant restrictions to root growth. Regarding acidity correction with application of limestone at soil surface without no incorporation, research reported low movement of the lime to deeper layers, depending on the dose applied, the time elapsed and the fertilization regime.

Knowledge to support adequate management of soil fertility and plant nutrition is particularly important for fruit growing systems, given the influence these production factors on the qualities of fruits, such as color, size, taste, aroma and appearance. Meeting plants' nutrient needs is one of the key factors for the success of this activity, because besides affecting yield and quality, adequate nutrition increases plant growth, tolerance to pests and diseases and postharvest longevity. On the one hand, the demand of this group of plants for mineral elements is relatively high, while on the other tropical soils in which they are normally cultivated are low in nutrients, making it imperative to apply nearly all the nutrients necessary for their full development. This leads to the use of high amounts of fertilizers [21, 11] and corrective measures [12, 13, 22] in orchards and requires technical competence for economically rational use of these inputs. For Brazilian conditions, the analyses can be interpreted with the help of the Fert-Goiba software [23].

Information on the effects of liming on the development and nutritional status of fructiferous plants is very limited in the literature despite the widespread scientific recognition of the importance of acidity correction. Much more attention has been paid to these aspects in annual cropping systems, but those findings cannot be transferred directly to perennial plants because the latter do not react the same way to liming and fertilization for a various reasons as follows [24]:

- a. The roots of perennial plants like fructiferous ones exploit a large volume of soil, which increases as plant ages, and little is known about the nutritional reserves in deeper soil layers.
- b. Roots, trunk, branches and leaves of perennial plants form large reservoirs of nutrients. Therefore, these plants have hidden early deficiency that makes it difficult for the farmer to implement corrective measures at the right time. Furthermore, it takes longer periods of time for these reservoirs to replenish, making these plants slower to react to nutrient applications.
- c. The regular pruning of fructiferous plants complicates the problem of liming and fertilization. By restricting vegetative development, pruning hides even more deficiency symptoms and hence the effects of corrective measures. However, in many cases pruning is essential, because, as the saying goes, "hunger for light is just as harmful as hunger for nutrients."

- d. Liming and fertilization of orchards are determinant not only in the current growing season, but also for harvests to come because the inputs applied at one time will also supply the pending production by promoting the formation of new fruit-bearing shoots and building up nutrient reserves in the roots and the aboveground biomass for the following seasons.

For a long time some fruit trees, especially those native to tropical regions like guava and carambola, were considered to be rustic plants, so their development was thought to be independent of edaphoclimatic conditions as is still felt today about pastures. However, it is not possible to imagine that a soil can be exploited by a crop indefinitely without replenishing the nutrient reserves or correcting the acidity. However, due to the characteristics of perennial fruit-bearing plants, the difficulties of conducting long-term experiments under present research funding support tend to discourage researchers.

5. Liming at planting and during formation of fruit orchards

Because soil acidity is one of the most important factors limiting farm production in tropical regions, an experiment was performed to assess the effects of liming on soil fertility as well as the mineral nutrition and yield of guava (*Psidium guajava*) [12]. The limestone (CaO=45,6% and MgO=10,2%) was incorporated into the soil in July and August 1999 and the orchard was planted four months later (December 1999) using the Paluma cultivar propagated by cuttings. The corrective measure was applied manually on the entire field area, half incorporated with a moldboard plow and the other half applied and incorporated later using a disk plow (both implements reaching a depth of 0–30 cm). The soil was a dystrophic red latosol with base saturation (V) of 26% in the 0–20 cm layer. The experimental design consisted of random blocks of five treatments and four repetitions. The limestone (reactivity = 94%) rates were 0, 1.85, 3.71, 5.56, and 7.41 ton ha⁻¹. Chemical analysis of the soil was carried out for 78 months after liming and nutrient status and tree productivity were evaluated during five consecutive harvests. Liming changed chemical attributes of the soil related to acidity down to a depth of 60 cm, raising the pH, Ca, Mg, sum of bases (SB) and base saturation (V) and diminishing potential acidity (H+Al).

During four years after orchard establishment, there was a significant correlation between leaf and soil Ca (Table 1). In general, the same pattern occurred for Mg, with higher correlation of leaf Mg levels with Mg concentration in the soil between the rows. This can indicate that with the exhaustion of these bases in the tree rows, the roots of guava trees could absorb nutrients effectively between the rows, indicating the importance of liming the entire area.

The yearly productivity during the experimental period (2002 to 2006) and the accumulated guava yields are presented in Figures 1a and 1b. Note the close fit of the production data to polynomial functions of the lime rates.

Soil nutrient	2001		2002		2003		2004		2005	
	Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
Ca (R)	0.91*		0.99**		0.95*		ns		ns	
Ca (B)	0.94*		0.96**		0.99*		0.97*		0.93*	
Mg (R)		ns		0.79*		ns		ns		ns
Mg (B)		ns		0.92*		0.97*		0.81*		0.84*

R: in tree rows; B: between tree rows. **, * and ns: significant at $p < 0.01$, $p < 0.05$ and not significant, respectively. The values are means of four repetitions each year.

Table 1. Correlation coefficients between Ca and Mg concentrations in the soil (0–20 cm) between and in the tree rows and leaf Ca and Mg concentrations in guava trees over the experimental period

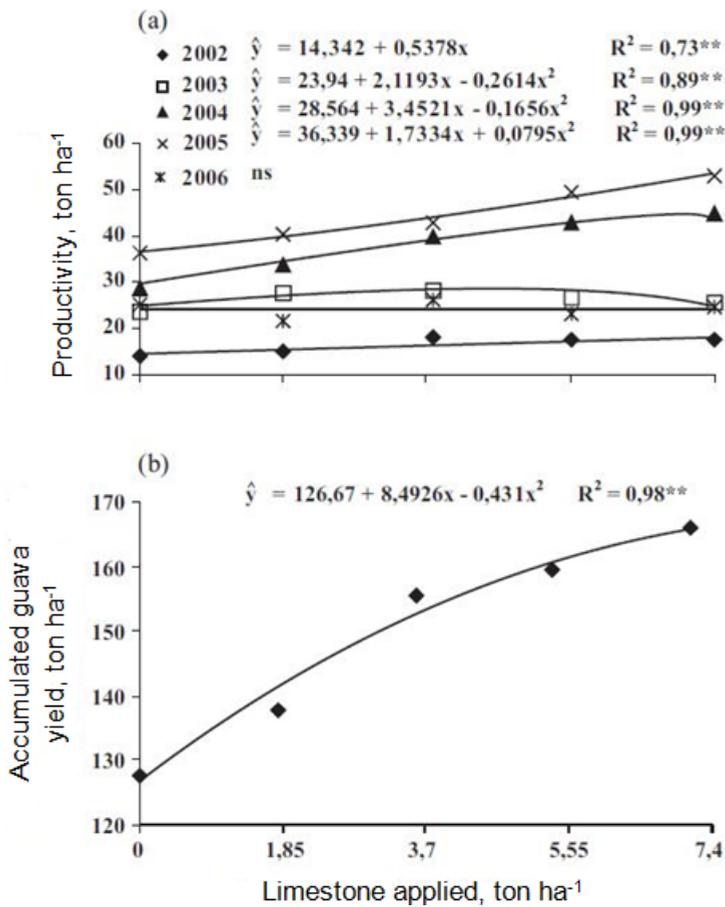
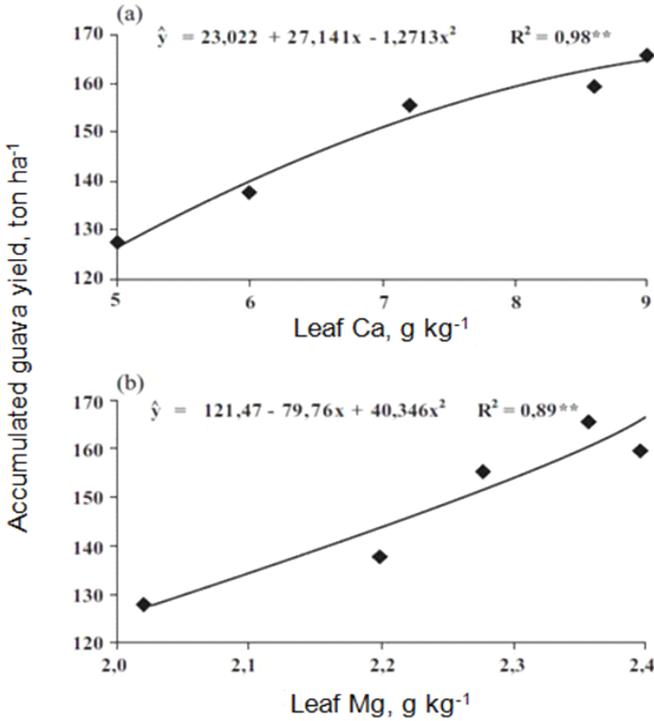


Figure 1. Effect of applying limestone on guava fruit yield for yearly harvests (a) and cumulated production (b).

Leaf Ca and Mg concentrations increased with lime rate and showed quadratic effects (Figure 2).



The points are means of four treatment replications per year for 5 years, totalling 20 replicates.

Figure 2. Relationships between the leaf concentrations of Ca (a) and Mg (b) and cumulated guava production.

The graph of the Ca/Mg ratio versus cumulated fruit yield shows, on the other hand, that the lower the ratio, the lower was fruit production (Figure 3).

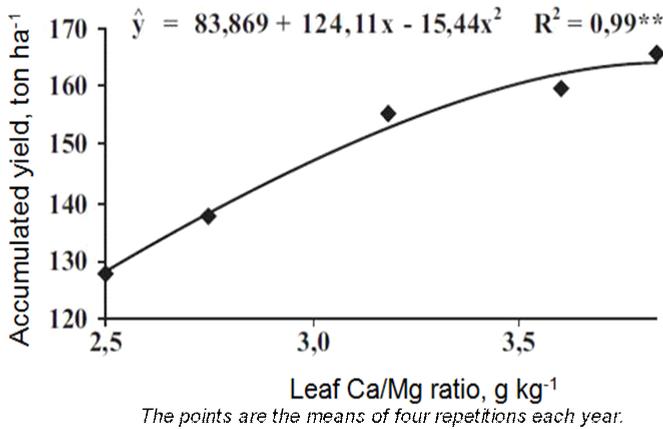


Figure 3. Relationship between leaf Ca/Mg and cumulated guava production for harvests cumulated between 2002 and 2006.

The cumulated fruit yield (2002-2006 harvests) increased quadratically with base saturation of the surface soil layer both in and between rows (Figure 4). Although model maximum goes beyond the values observed in the experiment, it can be inferred that satisfactory cumulated fruit production can be reached when V is closed to 50% in the rows and 65% between the rows.

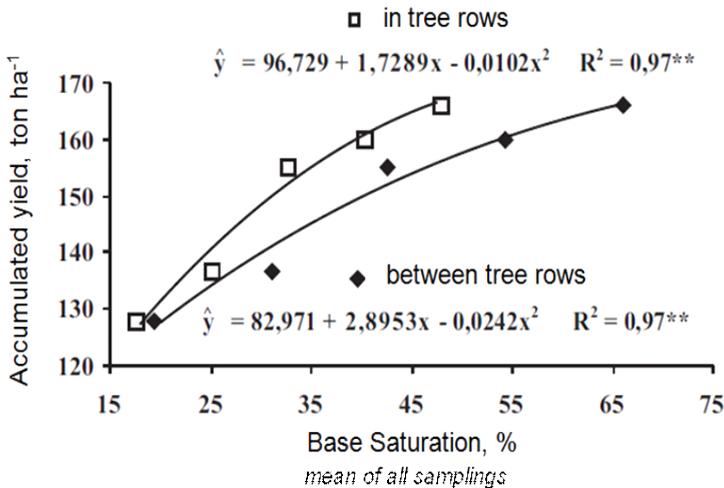


Figure 4. Relation between base saturation in the 0-20 cm soil layer, in and between the rows, and cumulated guava fruit production from 2002 to 2006.

The application of limestone to acidic soils promotes root development and, consequently, the uptake of water and nutrients. Determination of the exchangeable Ca and Mg concentration in the soil determined using an exchange resin gives an indication of the potential growth of the root system, especially at planting and tree formation stages and in situations where there are low levels of Ca. In [25], the authors evaluated the effects of liming on root system development and the mineral nutrition of guava trees grown in an acid dystrophic red latosol. They analyzed soil samples taken at four equidistant points 75 cm from the trunks in two layers (0–20 and 20–40 cm depth), in plots that received 0, 3.7 and 7.4 t ha⁻¹ of limestone (reactivity = 94%). The corrective measure was applied before planting, incorporated with a disk plow in the 0–30 cm layer and harrowed to level soil surface. Forty-two months after incorporation of the limestone and the third year of guava tree cultivation, the roots were sampled with a cylindrical auger to assess the dry matter and lime content. Liming corrected soil acidity, increased base saturation and the availability and absorption of Ca by the plants and promoted root development. Calcium concentrations of 30 mmol_c dm⁻³ in the soil and 7.5 g kg⁻¹ in the roots were associated with greater root growth.

Furthermore, liming, by raising the amounts of Ca and Mg in the soil and the plant, can improve fruit quality. On this crucial point, [26] studied the effects of liming on the quality of guava fruits and observed that this practice did not affect their physical characteristics, such as weight, transverse diameter, length, flesh weight and flesh percentage. However, the application of limestone caused a linear increase in Ca concentrations in leaves and fruits, lowering weight loss of fresh matter and producing firmer fruits when Ca concentrations in the fruits reached at least 0.99 g kg⁻¹. Therefore, the provision for adequate Ca improved fruit quality regarding postharvest longevity.

These beneficial effects of Ca on fruit quality can be explained by the role this element in plant nutrition. In this respect, [27] observed that in guava fruits that received calcium in the form of limestone, cell walls and middle lamellae were well defined and structured, keeping the cells cemented. In contrast, in fruits from the plants not receiving limestone, the cell walls and middle lamellae were destructured and disorganized, respectively. The authors concluded that liming is an effective measure to improve the sub-cellular organization of guava fruits, contributing to tissue integrity.

Studies of the effects of liming on the biometric variables of plants are limited. In [28] the effect of limestone (CaO=45,6%; MgO=10,2% and reactivity=94%) application on trunk diameter, height and crown volume of Paluma trees was assessed under field conditions. The experimental design consisted of random blocks of five treatments and four repetitions. The treatments consisted of rising doses of liming in the 0-30 cm layer as follows: D₀ = no limestone; D₁ = half the dose to raise V to 70%; D₂ = full dose to raise V to 70%; D₃ = 1.5 times the dose to raise V to 70%; and D₄ = 2 times the dose to raise V to 70%. Field evaluations were carried out during seven years, starting at orchard's planting in 1999-2000 until the 2005-2006 growing season. The limestone increased trunk diameter and crown volume over the years. These results confirmed the importance of correcting soil acidity and the benefits of applying limestone on the biometric variables of guava trees.

Another popular fruit in Brazil is carambola (*Averrhoa carambola*) or star fruit that also responds well to soil acidity correction and fertilization. Investigating three-year old plants in field conditions, [25] found that the accumulation of root dry matter of this *Oxalidaceae* is boosted by limestone application, improving the uptake of nutrients and tree development.

Due to the low solubility of limestone, the best practice is to homogeneously incorporate this corrective material down to an adequate depth across the orchard area before planting the seedlings. Indeed, it is not recommended to till the soil after the trees have been planted nor is it advisable to apply limestone in the planting hole, especially along with phosphorus.

Despite the recognized importance of correcting acidity, there is virtually no study on the residual effect of this practice on carambola orchards. The only Brazilian work that assessed the effect of liming on carambola trees [20] was carried out in the country's main producing region between 1999 and 2006. The authors observed that the application of limestone produced significant changes in soil pH, potential acidity (H+Al), sum of exchangeable bases, base saturation and Ca and Mg concentrations at depths of 0-20, 20-30, 30-40 and 40-60 cm. Besides this, there were linear increases in pH, Ca, Mg, SB and V% and linear decrease of (H+Al) with limestone rates, both between and in the tree rows at all depths. The greatest changes occurred in the layer where the lime had been incorporated (0-30 cm) due to its low mobility.

Cumulated carambola fruit production from 2002 to 2006 as function of limestone application is shown in Figure 5. The base saturation between the rows remained higher than under the crown projection throughout the experiment. This behavior was expected because the management the trees required the application of high nitrogen doses which acidify the soil as a result of nitrification [5]. In addition, roots absorbed Ca and Mg and exuded H⁺ [29]. Also, local irrigation was applied, which contributed to changes in the rates of ammonification, nitrification and denitrification. These rates, according to [30], are linked to the availability, location and forms of N in the soil profile. This is of fundamental importance in the mobility of nitrogen because of its low binding energy of nitrate to clay minerals and organic matter [31, 32], leading to nitrate leaching.

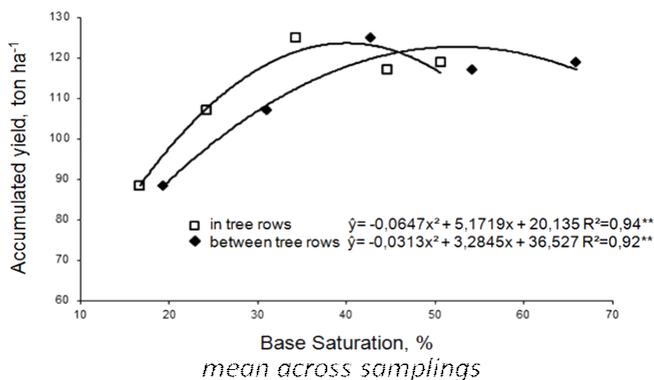


Figure 5. Relationships between cumulated fruit production from 2002 to 2006 and base saturation in the 0-20 cm soil layer between and within tree rows in a carambola orchard.

Figure 5 shows accrued fruit production (2002 to 2006 harvests) with rising base saturation in the 0-20 cm soil layer both between and within the rows. Therefore, 78 months after planting and acidity correction, maximum fruit production of 121 t ha⁻¹ was obtained in the pH range between 4.6 and 5.0 where the base saturation reached 40% to 53% in and between the rows, respectively, and leaf Ca and Mg levels were 7.6 and 4.0 g.kg⁻¹, respectively [20].

Figure 6 shows differences in cumulated fruit production from 2002 to 2006. As expected, the fruit output rose with years, irrespective of limestone dosage. The reason is that the trees became more productive with the growth in height and leaf area as the study was conducted in a new orchard.

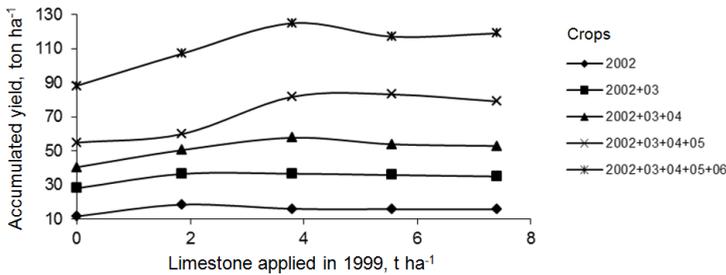


Figure 6. Cumulated production of carambola fruits related to limestone application rates at planting in 1999.

Figure 7 also shows that the cumulated fruit production increased yearly regardless of limestone rate. It is important to note that even after seven years, the control plots (zero limestone) still produced appreciable quantities of fruit, demonstrating the exceptional ability of the carambola tree to develop under adverse conditions.

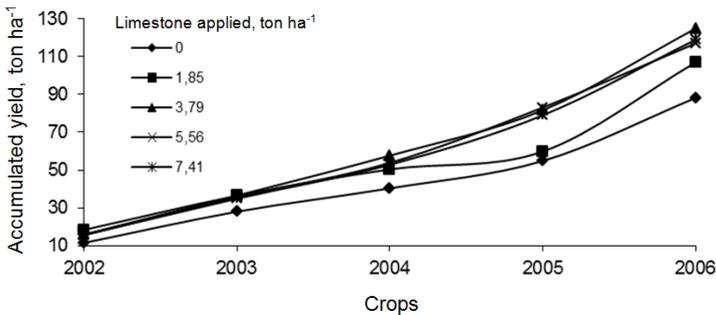


Figure 7. Cumulated carambola fruit production from 2002 to 2006 as function of limestone rates applied in 1999.

In a study of the economic aspects of liming, [22] observed that the cumulated production of carambola fruits as related with the application of different economically feasible rates of limestone coincided with the possible maximum output levels (Table 2). This occurred

due to the high productive capacity of this species and the high average price of the fruit on the market.

In this study, we considered the price per ton of lime applied, divided by sales price per ton of carambola. The most economical dose was calculated based on the derived regression equation between the production of fruit and lime rates applied, making it equal to the exchange ratio, which was 0.05784.

Accumulated production	Economic dose	Increase in fruit yield	Cost of limestone	Profit	Production ¹
	t ha ⁻¹	----- t of fruit per ha -----			%
2002 to 2003	4.5	8.4	0.3	8.1	100
2002 to 2004	4.8	16.0	0.3	15.7	100
2002 to 2005	5.3	28.8	0.3	28.5	100
2002 to 2006	5.3	34.2	0.3	33.9	100

¹ Percentage of fruit production with the most economic dose in relation to maximum production.

Table 2. Economic dose of limestone as function of cumulated production of carambola fruits and limestone cost for the 2002-2006 period

The percentage of fruit production obtained with the most economic lime dosage in relation to the maximum production would be 100%. Therefore, the application of the economic dose allowed savings on limestone without significant loss of production. It is thus realistic to conclude that carambola trees respond positively from an economic standpoint to the application of limestone, which boosts fruit yield up to the dose considered adequate and recommended by [20].

The main carambola growing areas in Brazil are located in regions where soils are acid and show low base saturation which limits the normal development of plants hence orchard productivity. The effect of liming on trunk diameter, crown volume and height of carambola trees was evaluated in an experiment was conducted in the state of São Paulo in a red latosol (oxisol), in the period from August 1999 to July 2006 [33]. The limestone doses rates were 0, 1.85, 3.71, 5.56 and 7.41 t ha⁻¹. The soil was chemically analyzed and the three biometric variables were assessed during five consecutive harvests. The neutralization of the soil acidity provided an increase in the biometric variables during the entire experimental period. Liming increased trunk diameter, tree height and crown volume. The nutrients in limestone – Ca and Mg – positively influenced the development of the trees.

6. Liming of established orchards

The low solubility of most limestones limits the mobility of these materials in the soil profile, requiring initial incorporation to obtain a beneficial effect in the zone exploited by the roots.

In fruit orchards already in production, the procedure recommended by the official bulletins in Brazil is light incorporation of limestone in the tree rows [10]. However, it is probable that this recommendation would change if there were more research findings, considering the various phytosanitary problems that can occur due to lime incorporation, such as injuries and reduction of volume of the roots, with consequent risk of infections, dissemination of diseases in the orchard, increased attack by pests, especially mites, cochineals [34] and nematodes [35], as well as soil destructuring and compaction.

In orchards with adult trees, the application of limestone at the surface, without incorporation, will gradually neutralize the acidity below the surface due to the movement of the particles through the profile, at a rate of 1 to 2 cm a year, if moisture and drainage conditions are suitable [36]. Therefore, surface liming, even though possible, requires time to produce beneficial effects. However, the information mentioned above was obtained under edaphoclimatic conditions different than the tropics. Other studies have shown that it is possible to apply limestone at soil surface without incorporation and obtained satisfactory results over time.

To assess the effect of surface liming on soil fertility, plant nutrition and the productivity of guava trees, an experiment was conducted in a commercial orchard grown on a red-yellow Argisol (Ultisol) in the main guava producing region of the state of São Paulo [37]. The randomized block design was a 2 x 5 factorial scheme with three repetitions, where the factors were two types of limestone (common, with PRNT=80%; and calcined, with PRNT=131%), applied at five rates (0, 0.5, 1, 1.5 and 2 times the recommended rate to raise base saturation to 70%) without incorporation. The results showed that surface liming with either common or calcined limestone reduced soil acidity in proportion to lime rate down to depths of 0-10 and 10-20 in the established guava orchard. In the 10-20 cm layer acidity declined 6 to 12 months after applying calcined limestone and 24 months after the application of common limestone. The chemical composition of the leaves and fruits and fruit yield were not influenced by the lime treatments. The authors attributed this to the fact that because the trees are perennial, they need time to respond to change in management. They concluded that it is possible to surface lime established guava orchards to correct soil acidity both in surface and lower layers. However, there is a need for further research to determine the specific criteria for this crop and for adjusting the rates to the optimum base saturation for this type of liming.

Orange (*Citrus sinensis*) growing is another important activity in Brazil, occupying some 850 000 hectares. Brazil is the top producer of oranges accounting for 25% of world's total production and is the world's leading exporter of orange juice. This means that of each five cup of orange juice consumed in the world, three come from Brazilian orchards [38]. A field experiment was conducted in a grove of adult orange trees (Pêra variety) established on a red latosol (oxisol) with five rates of calcined limestone (PRNT=131%) applied onto soil surface without incorporation [39]. Treatment effects were monitored for three consecutive years on the movement of the lime through the profile 6, 12, 18, 24, 30 and 36 months after application, on the chemical properties of the soil, on plant nutritional status and on fruit yield. Surface application of calcined limestone altered the base saturation as well as the soil chemistry in the three successive soil layers (0-10, 10-20 and 20-40 cm). The maximum soil

reaction upon liming occurred 12 to 18 months after lime application. Plants' nutritional status and fruit yield were significantly improved?. Cumulated production indicated that the ideal base saturation for orange trees was close to 50%. In the same experiment, [40] assessed the effect of limestone on the leaf Mn content. They found significant decreases in Mn levels with limestone additions. There was a high correlation between base saturation in the 10-20 cm soil layer and leaf Mn levels. Maximum fruit yields were associated with leaf concentrations between 33 and 70 mg Mn kg⁻¹. Another liming experiment allowed determining, by the Compositional Nutrient Diagnosis (CND), the Diagnosis and Recommendation Integrated System (DRIS) and the mathematical chance methods, the adequate nutrient ranges to obtain high yield in Pêra orange groves [41].

Despite still insufficient scientific basis, practical experience showed that the pH, and consequently base saturation, should not be allowed to decline drastically in established orchards. The reason is that it is very hard to correct high acidity in the soil layers down to depths exploited by adult trees within a reasonable time interval. The best strategy in these situations is to apply small amounts of finely ground limestone annually (example.g, 1 ton ha⁻¹), hence correcting acidity gradually, to avoid any sharp rise in acidity. It is clear, however, that soil analysis continues to be essential to assess the best timing and rates to apply lime at the surface without incorporation.

7. Conclusions

Soil acidity is a determinant factor limiting crop production in tropical areas. Fruit crops are perennials that exploit the same volume of soils during of time. As a result, soil acidity correction must be sustained in the roo zone to avoid aluminium toxicity and supply adequate amounts of calcium and magnesium to the crop. Research results show the economic advantages of liming to correct soil acidity and thus improve fruit yield and quality in Brazilian orchards.

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