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Lime incorporation up to 40 cm deep increases root growth and crop yield in highly weathered tropical soils

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ABSTRACT

Soil acidity is still a factor limiting crop yield in tropical soils. Our objective was to evaluate lime incorporation into the 0–40 cm depth as a strategy to improve soil chemical conditions and root growth within the soil profile and crop yield in highly weathered tropical soils. Lime rates ranging from 0 to 15 Mg ha^{-1} were incorporated into the 0–40 cm depth in three Brazilian oxisols. Soil response to lime rates was evaluated in both 0–20 and 20–40 cm depths at the end of each spring/summer cropping season as were crop yields over three consecutive years after lime incorporation. Maize + *Brachiaria ruziziensis* roots were evaluated within the 0–60 cm depth three years after liming. Overall, incorporating lime significantly increased Ca^{2+} and Mg^{2+} contents, pH, and base saturation (BS) in the 0–40 cm depth, with lime rates ≥ 9 Mg ha^{-1} having the greatest positive impact. By improving soil chemical conditions, the incorporation of high lime doses ($\geq$9 Mg ha^{-1}) increased crop root growth in the soil profile (up to 60 cm deep) and led to higher rainfed crop yields. The highest annual crop yields were observed under lime rates between 9 and 15 Mg ha^{-1}. Finally, incorporating high doses of lime into the soil profile decreased crop yield losses due to droughts. Combined, these results indicate that deep liming (40 cm) at the correct dose can increase the resilience of agricultural systems to water deficit and the yield potential of annual crops in highly weathered tropical soils.

1. Introduction

Brazil has potential to increase food production by recovering degraded pastures. It is estimated that 50–70 % of the total 170 million hectares of pasture in Brazil are degraded (Dias Filho, 2011). For instance, the degraded soils are acidic, with high toxic aluminum (Al) concentrations and low natural fertility (Fageria and Baligar, 2008, 2019). Adequate soil management can decrease Al toxicity and increase nutrient availability being crucial to increase crop yields and avoid expanding agricultural areas into native vegetation.

Worldwide, liming is one of the most common practices to improve soil chemical properties (*i.e.*, reduce Al and Mn toxicity, maximize nutrient availability for plants, and decrease P immobilization), which can also increase physical and biological soil quality and enhance crop production (Fageria and Baligar, 2008; Li et al., 2019). Proper liming increases soil pH values to optimal levels, provides Ca^{2+} and Mg^{2+}, neutralizes acidity and reduces toxic Al^{3+} levels (Fageria and Baligar, 2008; Kunhikrishnan et al., 2016; Li et al., 2019; Sousa and Lobato, 2004; van Raij, 2011; Sanchez, 2019). Increased Ca^{2+} and Mg^{2+} levels and soil acidity correction improve the soil condition for root growth (Fageria and Baligar, 2008), which is essential to increase crop yield and the resiliency of the production system, especially under rainfed systems.

In agricultural fields, lime is usually incorporated into the 0–20 cm depth by plowing and harrowing, under conventional tillage, or surface-applied without incorporation under no-till (NT) and pasture. However, depending on soil and climate conditions, lime migration into highly weathered soil profiles can be minimal (Nunes et al., 2019). Lime is

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relatively insoluble and does not move fast downward into the soil profile and its surface application or shallow incorporation is not effective to neutralizing Al toxicity below the application or incorporation zone (Santos et al., 2018a, 2018b). Consequently, subsurface soil acidity may result in limitations to deep root development in highly weathered soils and lead to crop yield decreases, especially under water deficits.

New liming strategies need to be developed to achieve faster lime response within deeper soil layers (Guarçoni and Sobreira, 2017; Teixeira et al., 2020a, 2020b). Lime incorporation into the 0–40 cm soil depths before initiating NT or pasture systems may result in fast and uniform amelioration of soil acidity within deep soil layers (Santos et al., 2018a, 2018b). In turn, it may improve root growth within the soil profile, increase root access to water and nutrients, increase crop yields and decrease crop losses due to short periods of drought (Ho et al., 2005; Lilley and Kirkegaard, 2011; Lynch, 2007; Wasson et al., 2012).

Past studies showed that lime incorporation up to 30 cm can reduce soil acidity and increase soil Ca and Mg content, root growth, and crop yield in Brazilian Oxisols compared to limestone incorporation up to 15 cm (Doss et al., 1979; Gonzalez-Erico et al., 1979). Recently, Moreira (2019) suggested that incorporating lime up to 40 cm deep to raise the pH, Ca^{2+} and Mg^{2+} to adequate levels and neutralize Al^{3+} may increase crop yields and increase crop resilience to climate change. Improving soil fertility within the soil profile increases crop root development, which can improve water and nutrients uptake by crops especially in areas with water limitation (Gómez et al., 2019). However, field studies are still needed to confirm the preliminary results and to define the correct lime doses associated with deep (40 cm) incorporation. Our hypotheses are that, depending on the dose, incorporating lime into the 0–40 cm soil depth: (i) improves soil chemical properties and root growth within that layer, (ii) increases crop yields, and (iii) and improves crop yield resilience under water deficits in highly weathered tropical soils. Our objective was to evaluate the effects of lime rate incorporated into the 0–40 cm depth on soil chemical properties, crop root growth and yield, and crop yield resilience in three highly weathered tropical soils.

2. Materials and methods

2.1. Experiment sites

The study was conducted under field conditions at three sites located in Lavras (Local1), Nazareno (Local2) and Ingaí (Local3), Campo das Vertentes mesoregion, Minas Gerais, Brazil (Fig. 1). The soils are classified as Latossolo Vermelho-Amarelo according to the Brazilian Soil Classification System (Santos et al., 2018a, 2018b) and Typic Hapludox according to Soil Taxonomy (Soil Survey Staff, 2014). The climate of the mesoregion is Cwa with dry and cold winters and hot and humid summers. The average temperature range between 30 °C and 11 °C. Rainfall during the study period can be observed in Fig. 2.

The experiments were conducted independently at the three sites. Before setting up the experiments, soils were cultivated with maize and extensive pastures. However, there was very little use of fertilizers and amendments under that system. In addition, no agricultural activity had been conducted on those soils for at least two years. The characteristics of the lime used in each location were as follow: Local1: Total relative neutralizing power (TRNP) = 83 %, CaO = 44 % and MgO = 14 %; Local2: TRNP = 83 %, CaO = 35 % and MgO = 20 %; and Local3: TRNP

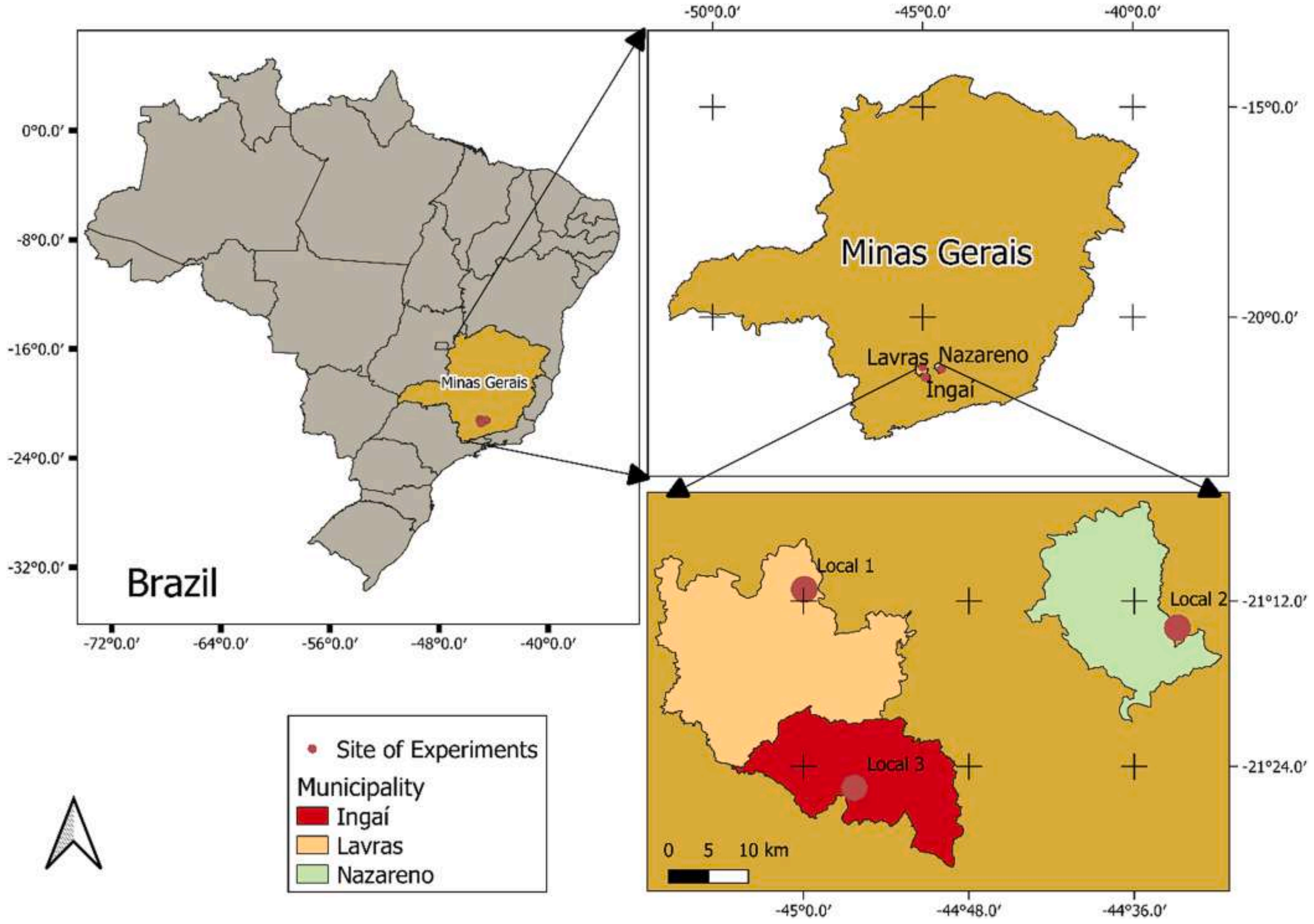

Fig. 1. Details of the three sites where the experiments were conducted over three years.

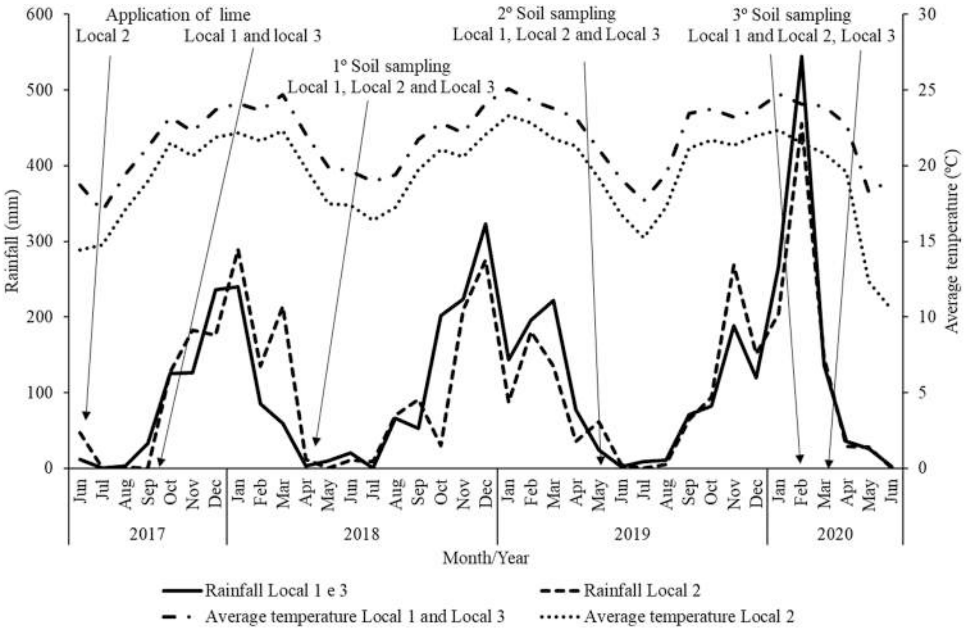

Fig. 2. Rainfall distribution and average temperature during the three years of the study.

= 77 %, CaO = 47 % and MgO = 14 %.

Soil physical and chemical characterization was performed prior to the initiation of the experiment using methods described by Silva (2009). Soil samples were air dried at room temperature, crushed and sieved (<2 mm) for obtaining the air-dried fine earth, which was stored for further characterization. The soil chemical characteristics before the beginning of the experiments are shown in Table 1 and the soil physical characteristics in Table 2.

2.2. *Experimental design and field trials*

At each site, trials were conducted using a randomized block design with six treatments and four replicates. The treatments consisted of six lime rates (0, 3, 6, 9, 12, and 15 Mg ha^{-1}) applied using the Bruttus 6000 (Stara©) gravity spreader, with an application range of 4.4 m. Rather than surface application or shallow (0–20 cm), as often recommended in Brazil (Alvarez and Ribeiro, 1999; Cantarella et al., 2022), limestone rates were incorporated up to 40 cm. After surface-applied, limestone was incorporated into the 0–40 cm soil layer with two heavy harrow passes (Piccin© heavy harrow 14 ×32" - 14 discs with 32-inch), followed by subsoiling (Baldan© 5-shank subsoil plow) and two slight disc harrow passes (Baldan© leveling harrow with 20 discs of 26 in. – 270 mm). The size of each plot was 8.74 × 30 m (262 m^2).

During the study, limestone was applied only once (i.e., in 2017) at the beginning of the study. The different lime rate application trials began on 06/27/2017, 09/14/2017, and 09/20/2017 at the Local2, Local1, and Local3, respectively. After lime incorporation, crops were planted during the 2017/2018 in the first season (October to February) and all operations were performed according to the farmer's management practices, including choice of cultivars, and fertilization (Table 3), pest control, weed, and disease management. Soybean (*Glycine max* (L) Merrill), maize (*Zea mays*), common bean (*Phaseolus vulgaris*) and wheat

Table 2
Sand, silt, and clay contents and texture of the soil by site and depth.

Depth	Sand	Silt	Clay	Textural classification
cm		g kg^{-1}		
Local 1				
0–20	235	303	462	Clay
20–40	239	277	485	Clay
Local 2				
0–20	251	208	541	Clay
20–40	232	197	571	Clay
Local 3				
0–20	444	161	395	Clay Loam
20–40	425	153	422	Clay

Clay and silt (pipette method); sand (sieving) (Silva, 2009).

Table 1
Soil chemical properties by site and depth before the beginning of the study.

Depth	pH	P	K	Ca	Mg	Al	H + Al	CEC	BS	OM	B	Cu	Fe	Mn	Zn
cm	(Water)	mg dm^{-3}			cmol$_c$ dm^{-3}				%	g kg^{-1}		mg dm^{-3}			
							Local1								
0–20	5.7	3.4	0.3	3.7	0.9	0.0	4.2	9.1	54	33	0.1	1.1	56	56	1.3
20–40	5.9	2.1	0.2	3.4	0.8	0.0	3.2	7.6	58	-	-	-	-	-	-
							Local2								
0–20	5.7	1.7	0.1	1.4	0.5	0.0	2.7	4.7	42	26	0.6	3.5	41	25	0.4
20–40	5.7	0.8	0.1	1.1	0.7	0.0	2.4	4.3	44	-	-	-	-	-	-
							Local3								
0–20	5.2	2.8	0.1	1.4	0.8	0.0	7.2	9.5	24	33	0.2	1.0	25	6.3	0.8
20–40	5.2	2.3	0.1	0.9	0.4	0.0	4.0	5.4	25	-	-	-	-	-	-

pH - pH in water (1:2.5 soil/solution); OM - soil organic matter ($Na_2Cr_2O_7$ 4 mol L^{-1} + H_2SO_4 5 mol L^{-1}) (Silva 2009); P and K mixed resin (van Raij et al., 1986); Fe, Zn, Mn and Cu (Silva, 2009); Ca, Mg e Al (KCl 1 mol L^{-1}); S - Sulfur extracted as sulfate and the result was converted to S, (H+Al) - potential acidity (SMP). CEC - cation exchange capacity at pH 7.0 obtained by adding Ca, Mg, K and H+Al; and base saturation [BS = ((Ca+Mg+K+H+Al)/CEC)) × 100].

Table 3
Crops and fertilization history within the three experimental sites.

Site	Year	Crop	Cultivar	Population (Seeds/ha)	Sowing	Harvest	Sowing fertilizer NPK	Dose (kg/ha)	Topdressing: KCl (kg/ha)	Topdressing: NH_4NO_3 (kg/ha)
Local1	2017/18	Soybean	M 6410 IPRO	290,000	11/25/2017	04/12/2018	02:30:30	300	0	0
	2018/19	Soybean	M 6410 IPRO	290,000	10/30/2018	03/19/2019	8–40–00–12.5 S	200	100	0
	2019/20	Soybean	M5917IPRO	300,000	10/27/2019	02/19/2020	13–33–00	150	200	0
Local2	2017/18	Soybean	NS 7670 RR	280,000	11/15/2017	04/17/2018	08:40:00	200	250	0
	2018/19	Soybean	NS 7670 RR	280,000	11/10/2018	03/31/2019	09:43:00	250	400	0
	2019/19	Wheat	BRS 264	4,000,000	04/18/2019	07/27/2019	11:54:00	200	0	150
	2019/20	Common Bean	IPR Tuiuiú	240,000	11/05/2019	02/01/2020	13–33–00 S15	250	200	205
	2020/20	Maize/Brachiaria[a]	P3646	62,000	02/18/2020	07/12/2020	13–33–00	250	0	340
Local3	2017/18	Common Bean	Perola	206,000	01/28/2018	04/28/2018	09:43:00	200	200	272
	2018/19	Soybean	SYN 13671 IPRO	280,000	11/13/2018	03/31/2019	11:54:00	200	200	0
	2019/19	Wheat	BRS 264	4,000,000	04/15/2019	07/27/2019	11:54:00	100	0	120
	2019/20	Soybean	Foco IPRO	290,000	11/03/2019	03/18/2020	11:54:00	200	170	0
	2020/20	Wheat	BRS 264	4,000,000	04/20/2020	07/30/2020	11:54:00	100	0	120

[a] Brachiaria (*Brachiaria ruziziensis*) intercropped with maize and planted at the same time as maize.

(*Triticum* spp.) were cultivated during the experiment. The production system of each research site was determined by farmers. Second season crops (wheat in April and maize in February) were grown only in Local2 and Local3, in the second (2018/19) and third (2019/20) year (Table 3).

The application of lime was done only in the first year, turning the soil over. After the first year, there was no soil disturbance, and all cultivation was under no-till (NT). The crops described in Table 3 were sown at depths of 3–5 cm, with deposition of planting fertilizers at about 10–12 cm depth, except for wheat, in which the depth of the seeds was about 3 cm and of the fertilizer 6 cm, due to the limitations of the seeder. For this operation, fertilizer NT seeders were used. At Local1, the seeder Jumil®– model JM 2570 with 4 rows was used; at Local2 and Local3, the machine available was the seeder Kuhn® – model PG 1000, with 10 sowing rows. For winter cultivation, the Prima® model 4590 seeder was used, with 27 rows in Local2 and Local3. Sowing operations in first season crops were always carried out about 10–15 days after weed desiccation. The crops of second season (wheat and maize) were sown immediately after the first season crops were harvested.

At Local1, total rainfall accumulation was 655, 1087 and 1045 mm, respectively during the first seasons (October to February) of 2017/18, 2018/19, and 2019/2020 (Fig. 2). In the first growing season, a water restriction lasting 16 days was recorded, which coincided with the phenological stage of soybean grain filling.

At Local2 no dry spells were observed during crop development in the first season. Total rainfall accumulation, during first seasons 2017/18, 2018/19 and 2019/20 were 954, 855 and 468 mm, respectively (Fig. 2). In the second season of the 2018/19 growing season at Local2, 74 mm was recorded during the wheat cycle. However, 69 mm were recorded in the first 29 days. Thus, the greatest water restriction occurred during the reproductive stage of the crop. In the second season of the 2019/20, the accumulated precipitation during maize growing was 300 mm. However, most of the precipitation occurred until about 45 days after sowing. During the 15 days that preceded the flowering of the crop, rainfall accumulation was 16.5 mm. After flowering, no precipitation was recorded for 16 days. After this period, until the phenological stage R4, rainfall accumulation was only 28.3 mm, and it stayed dry until R6 (physiological maturation).

At Local3, rainfall accumulation during the growing season of each crop was 191, 1060 and 1047 mm, respectively, during the first season of 2017/18, 2018/19 and 2019/2020 (Fig. 2). In the first crop, 18 days after flowering, an accumulation of 49.3 mm was observed. After this period, the crop underwent water restriction until harvest. In the other first season crops, no dry spells were observed. At Local3, recorded rainfall during the wheat growing of second season of 2018/19 was 49 mm, with 39 mm, which was accumulated between the first days after sowing and part during the flowering of the crop. Thus, during grain filling, there were at least 30 days of no rain. In the second season in 2020, the recorded rainfall was 26 mm, with 23 mm recorded in a single day during the flowering stage, thus marking a long dry spells period, during the grain filling phase of the crop.

2.3. Soil sampling

Soil sampling was carried out on the same day as the harvest of each crop grown in first season in the 2017/18, 2018/19 and 2019/2020. In Local1, from the first to the third year, the precipitation accumulated until the day of soil sample collection was 908, 2346 and 3649 mm, respectively. At Local2, the accumulated rainfall over the three years was 1131, 2237 and 3126 mm, respectively. At Local3, the accumulated rainfall until the day of soil sampling from the first to the third year was 908, 2366 and 3804 mm, respectively (Fig. 2).

Soil samples were taken from 0 to 20 and 20–40 cm depths. For each depth, five samples per plot were taken and mixed to make a composite sample. All samples were air-dried, ground, and passed through a 2-mm sieve and analyzed for selected soil physical and chemical characteristics.

Soil chemical properties (i.e., soil pH, Ca^{2+}, Mg^{2+}, and exchangeable K^+ and H+Al) were determined following methods described by Silva (1999). Soon after, soil pH was determined in water (1:2.5 soil/water ratio). K^+ was extracted by Mehlich-1 solution (H_2SO_4 0.0125 mol L^{-1} and HCl 0.05 mol L^{-1}) at a ratio of 1:10 (v/v) soil/solution and determined by flame emission spectroscopy. Exchangeable Ca^{2+} and Mg^{2+}

were extracted using a KCl 1 mol L^{-1} (1:10 v/v soil/solution) and determined by atomic absorption spectrophotometry with air–acetylene flame and 5 % lanthanum solution to prevent interference. Potential acidity (H+Al) was extracted with Ca $(OAc)_2$ 0.5 mol L^{-1} buffered at pH 7.0. The sum of exchangeable basic cations ($SB = Ca^{2+} + Mg^{2+} + K^{+}$), cation exchange capacity at pH 7.0 (CEC = SB + H+Al), and base saturation [BS = ((Ca+Mg+K+H+Al)/CEC) × 100] were then estimated.

2.4. Root distribution

In the second season of 2020, on 04/30/2020, roots were evaluated in the maize intercropped with Brachiaria grass (*Brachiaria ruziziensis*) at Local2. The trench was dug when the maize crop reached phenological stage R1 (female flowering - maize cobs with stigma-style presence). Six trenches were dug transverse to the planting row, one for each lime rate treatment. In each trench, the roots of three plants were exposed, and a 42 × 60cm area was evaluated per plant. A backpack sprayer was used to clean the soil profile for root exposure. After cleaning and exposing the roots, photographs were taken and analyzed in software for fiber and root image analysis, Safira 1.1 (Jorge and Silva, 2010). From the image analysis, root length (mm cm^{-2}), surface area (mm^2 cm^{-2}), and volume (mm^3 cm^{-2}) were determined.

2.5. Crop yield

Grain yield was determined by harvesting three 5-meter-long rows per experimental plot. Grain moisture was standardized to 13 %, and the yield of the area per plot was defined. The yield per hectare (10,000 m^2) was estimated from the yield per plot.

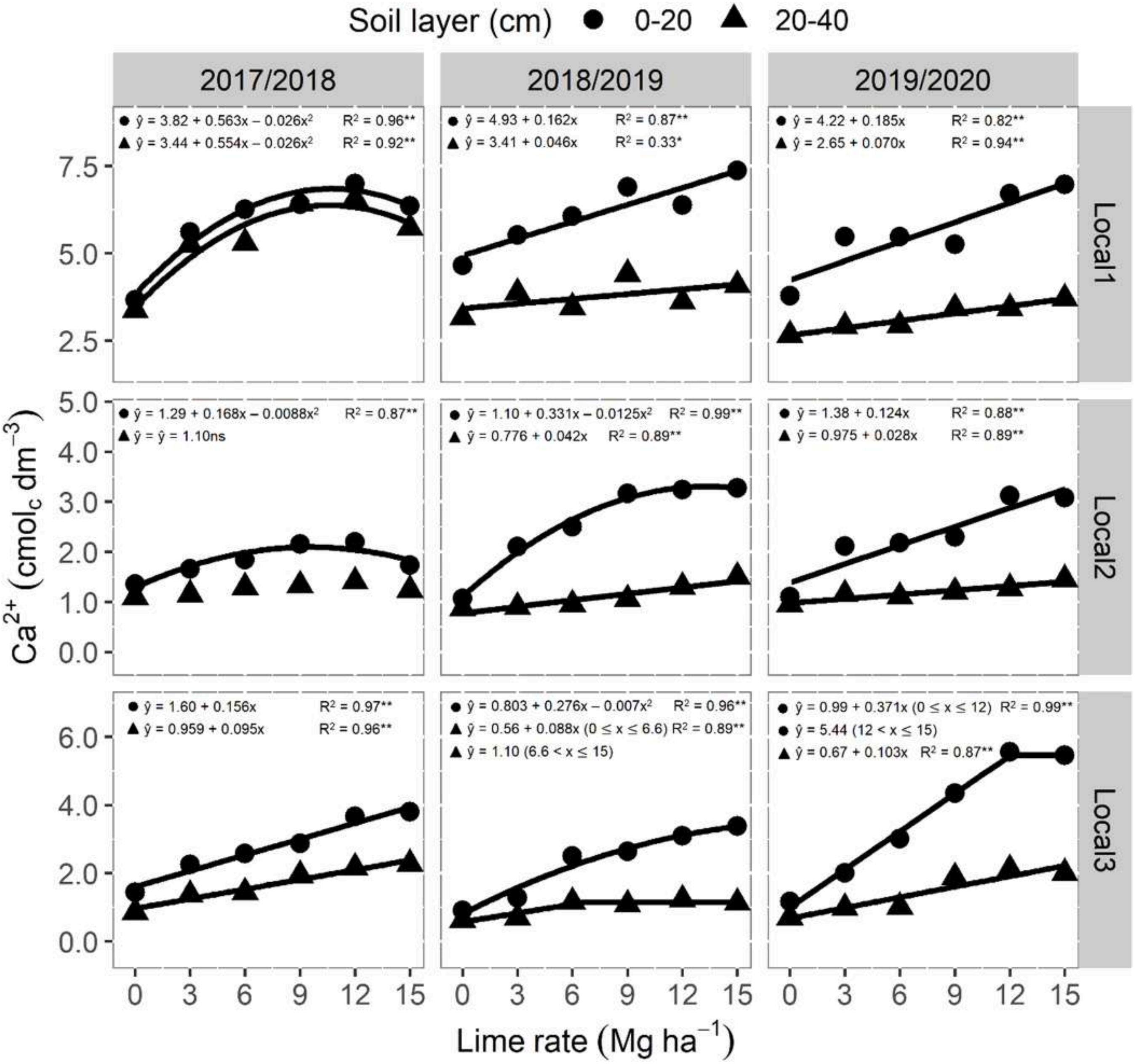

Fig. 3. Exchangeable Ca^{2+} by soil layer, site (Local1, Local2, and Local3) and cropping season (2017/2018, 2018/2019, and 2019/2020) as a function of lime rates incorporated in the 0–40 cm layer.

2.6. Statistical analysis

Data was analyzed with analysis of variance, and when there was a difference among limestone rates (treatments), a regression analysis was performed. The pH, Ca^{2+}, Mg^{2+}, and BS in the 0–20 and 20–40-cm layers, root length, surface area, and volume in the 0–20, 20–40 and 40–60-cm layers, and crop yield data were evaluated as a function of the limestone rates (0, 3, 6, 9, 12, and 15 Mg ha^{-1}). The tested models were linear, quadratic, and linear-plateau. The model choice was based on the significance of the goodness-of-fit parameters, lowest Akaike Information Criterion (AIC) and highest coefficient of determination (R^2). A regression analysis between maize yield and root parameters (length, area, and volume) was performed. All analyses and graph drawing were done with R version 3.6.3 software (R Development Core Team, 2019).

3. Results and discussion

3.1. Soil chemical properties

Lime incorporation into the 0–40 cm depth increased Ca^{2+}, Mg^{2+}, soil pH in water, and base saturation (BS) values in both 0–20 and 20–40 cm layers (Figs. 3–6). Most of the relationships between these soil chemical properties and limestone rates were linear or quadratic, which is in line with other studies (Crusciol et al., 2016; Esper Neto et al., 2019; Fageria, 2001b; Fageria and Baligar, 2008), however, the plateau behavior was also observed. The best-fit model may depend on the initial fertility and soil type, limestone characteristics, and rate applied (Li et al., 2019). In addition, the plateau model has been minimally tested, which explains its absence from studies that have evaluated lime rates.

In the first year, the positive response of soil chemical properties to

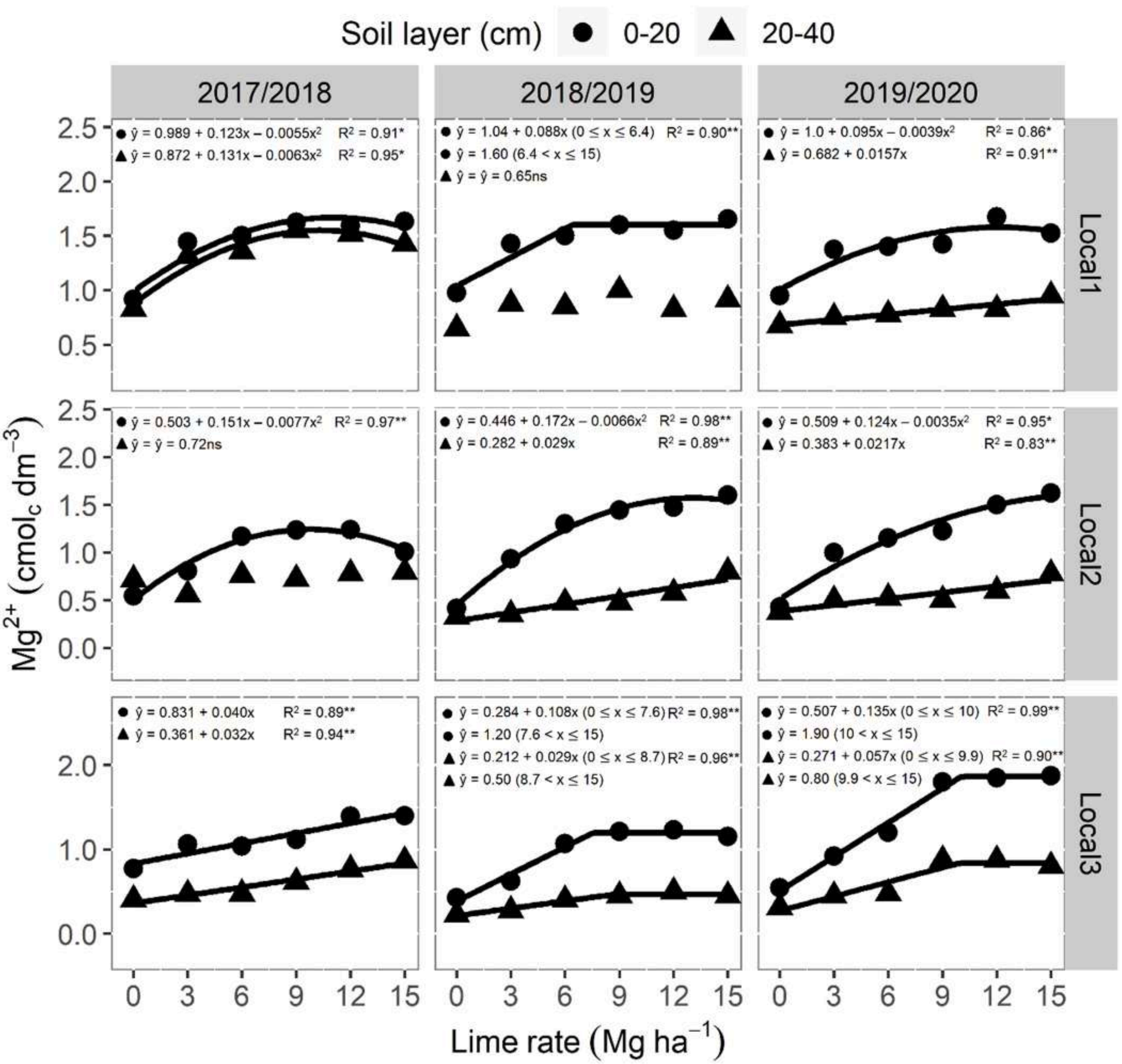

Fig. 4. Exchangeable Mg^{2+} by soil layer, site (Local1, Local2, and Local3) and cropping season (2017/2018, 2018/2019, and 2019/2020) as a function of lime rates incorporated in the 0–40 cm layer.

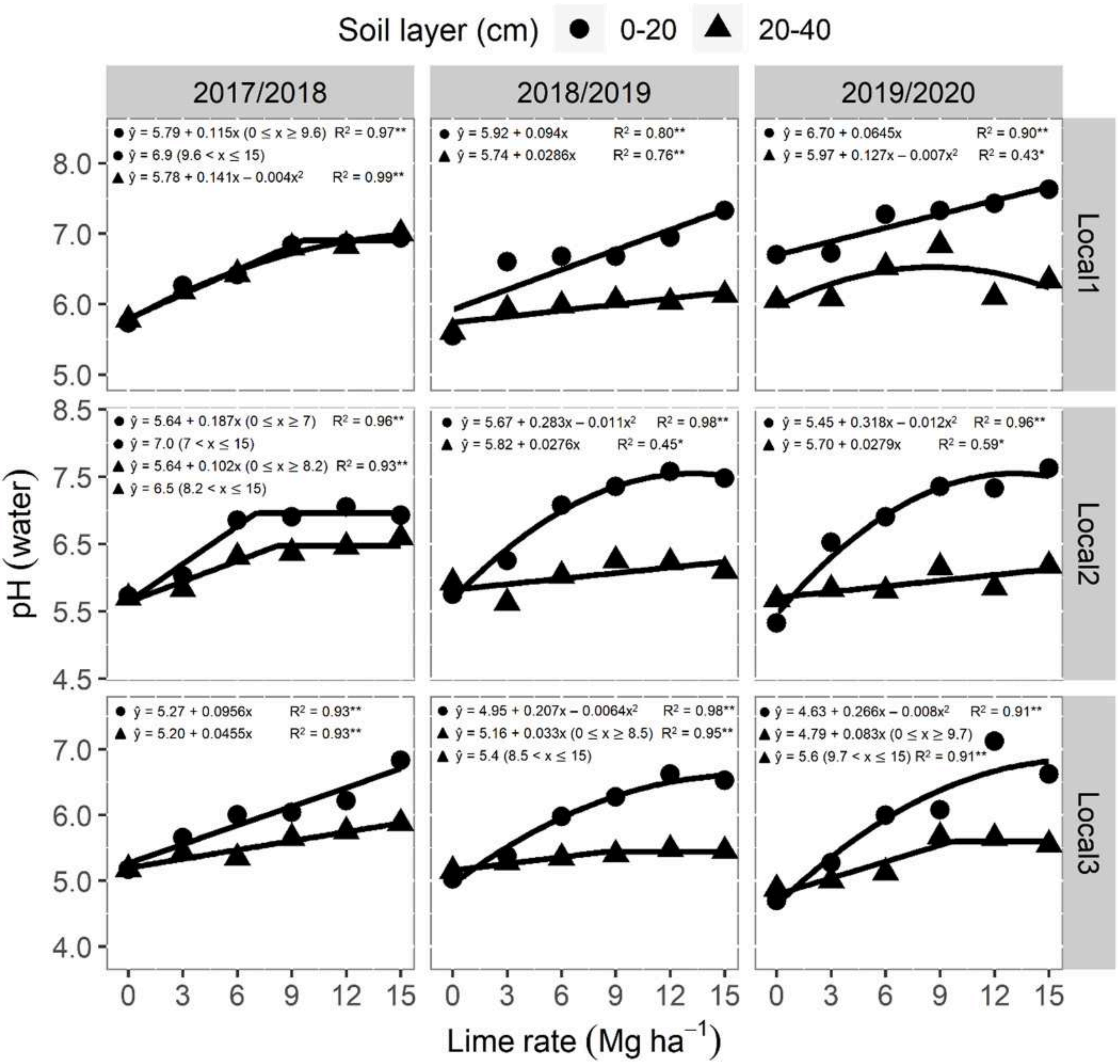

Fig. 5. Soil pH by soil layer, site (Local1, Local2, and Local3) and cropping season (2017/2018, 2018/2019, and 2019/2020) as a function of lime rates incorporated in the 0–40 cm layer.

lime rates in both 0–20 and 20–40 cm layers was similar, which suggests that lime incorporation was adequate (Fageria and Baligar, 2008). From the second year onwards, the impact of lime rates on chemical properties was higher in the 0–20 cm than in the 20–40 cm layer. This difference between layers (0–20 and 20–40 cm) from the second year onwards can be linked to two main factors: (i) faster lime reaction in the topsoil, since the environmental factors (*i.e.*, temperature and moisture) that drive lime reaction in the soil (Fageria and Baligar, 2008) are more active in the topsoil compared to subsoil layers; and (ii) leaching of Ca^{2+} and Mg^{2+} (Fageria et al., 1991; Fageria, 2001a), which reduced pH and BS in the 20–40 cm layer. Difference between layers was minimal at Local 1, where the soil had higher initial Ca^{2+}, Mg^{2+}, pH and BS values. Leaching in the 0–20 cm layer was not observed due to the high concentrations of Ca^{2+} and Mg^{2+} in the underlying layer (20–40 cm). These results indicate that the application of the correct limestone rate enables the soil acidity correction and the Ca^{2+} and Mg^{2+} increase below the layer where soil acidity corrector is incorporated (Fageria et al., 1991; Fageria, 2001a).

Based on the fitted models, the best limestone rates to increase Ca^{2+}, Mg^{2+}, pH, and BS values were those between 9.0 and 15.0 Mg ha^{-1} recommended for the 0–40 cm layer. These optimal doses are higher than lime rates that would be calculated by the base saturation (Cantarella et al., 2022) and neutralization of exchangeable Al^{3+} with increased Ca^{2+} and Mg^{2+} (Alvarez and Ribeiro, 1999) methods. Considering the results of the soil analysis of the 0–40 cm layer before the beginning of the experiments, the doses calculated with the liming recommendation method most used in Brazil to increase base saturation to 70 % of the 0–40 cm layer (Cantarella et al., 2022) would be 0 Mg ha^{-1} (Local1), 4.64 Mg ha^{-1} (Local 2) and 7.43 Mg ha^{-1} (Local 3).

The effect of lime rates on soil chemical attributes depends on several factors including lime type and its particle size (Álvarez et al., 2009; Li et al., 2019), soil buffering capacity and organic matter content (Bolan

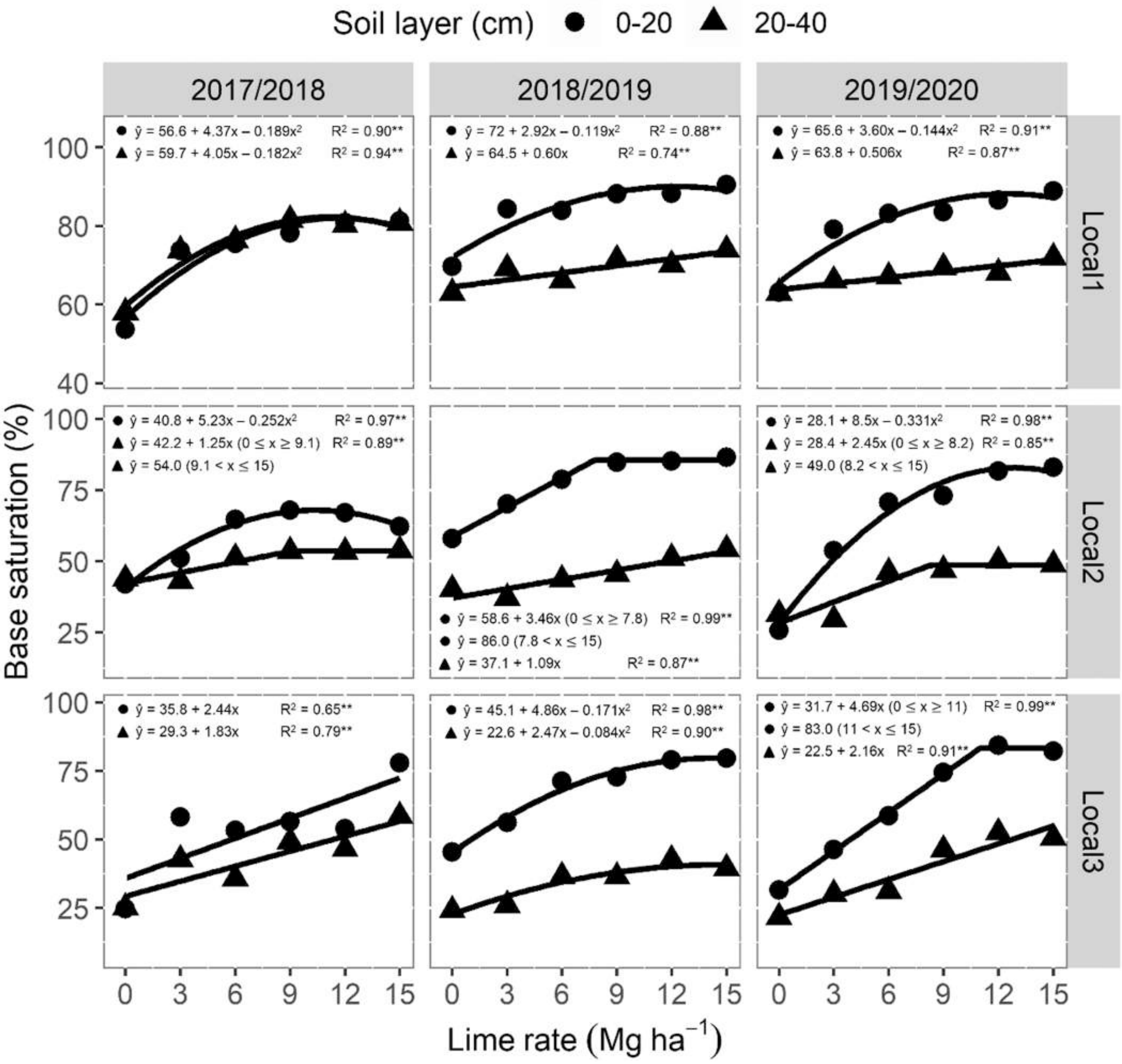

Fig. 6. Soil base saturation by layer, site (Local1, Local2, and Local3) and crop season (2017/2018, 2018/2019, and 2019/2020) as a function of lime rate incorporated in the 0–40 cm layer.

et al., 2003; Li et al., 2019), soil acidity, Ca and Mg contents, participation of cations in CEC and base saturation. In Brazil, lime rates have been recommended to achieve soil pH values between 6,0 and 6.5, base saturation between 50 % and 70 %, and Ca and Mg contents > 2.4 cmol$_c$ dm^{-3} and > 0.9 cmol$_c$dm^{-3}, respectively, considered ideal to crop development, besides neutralizing toxic Al up to the 0–20 cm layer (Alvarez and Ribeiro, 1999; Cantarella et al., 2022).

The positive impact of lime rates on soil chemical properties was similar in the first, second and third year after lime incorporation in all three sites . These results suggest that the reaction of lime was uniform over time. In a recent meta-analysis, Li et al. (2019) showed that the limestone reaction time occurred in the first three years after its application, corroborating our results. During the three years of study, lime rates ≥ 9 Mg ha^{-1} were able to maintain soil pH, BS, and Ca and Mg contents above the values considered optimum for crop development in soils under the Cerrado conditions (Alvarez and Ribeiro, 1999). Therefore, new applications of lime are not recommended in this period (0–3 years).

3.2. *Root growth*

A visual analysis of root distribution within the soil profile shows that lime incorporation into the 0–40 cm soil depth clearly increased crop root growth within deeper soil layers (0–60 cm), with rates ≥ 9 Mg ha^{-1} having the greatest positive impact (Fig. 7). There was a significant positive linear effect of lime rates on the root length, surface area and volume of the maize + brachiaria crops (Fig. 8). The positive effect of lime rates on root growth was greater in the 0–20 cm layer, followed by 20–40 and 40–60 cm depths, according to the slope values of the fitted linear models. Improved root growth in the soil profile reflects the improved soil chemical condition due to the lime incorporation up to 40 cm deep (Fageria and Baligar, 2008), especially for lime rates ≥ 9 Mg

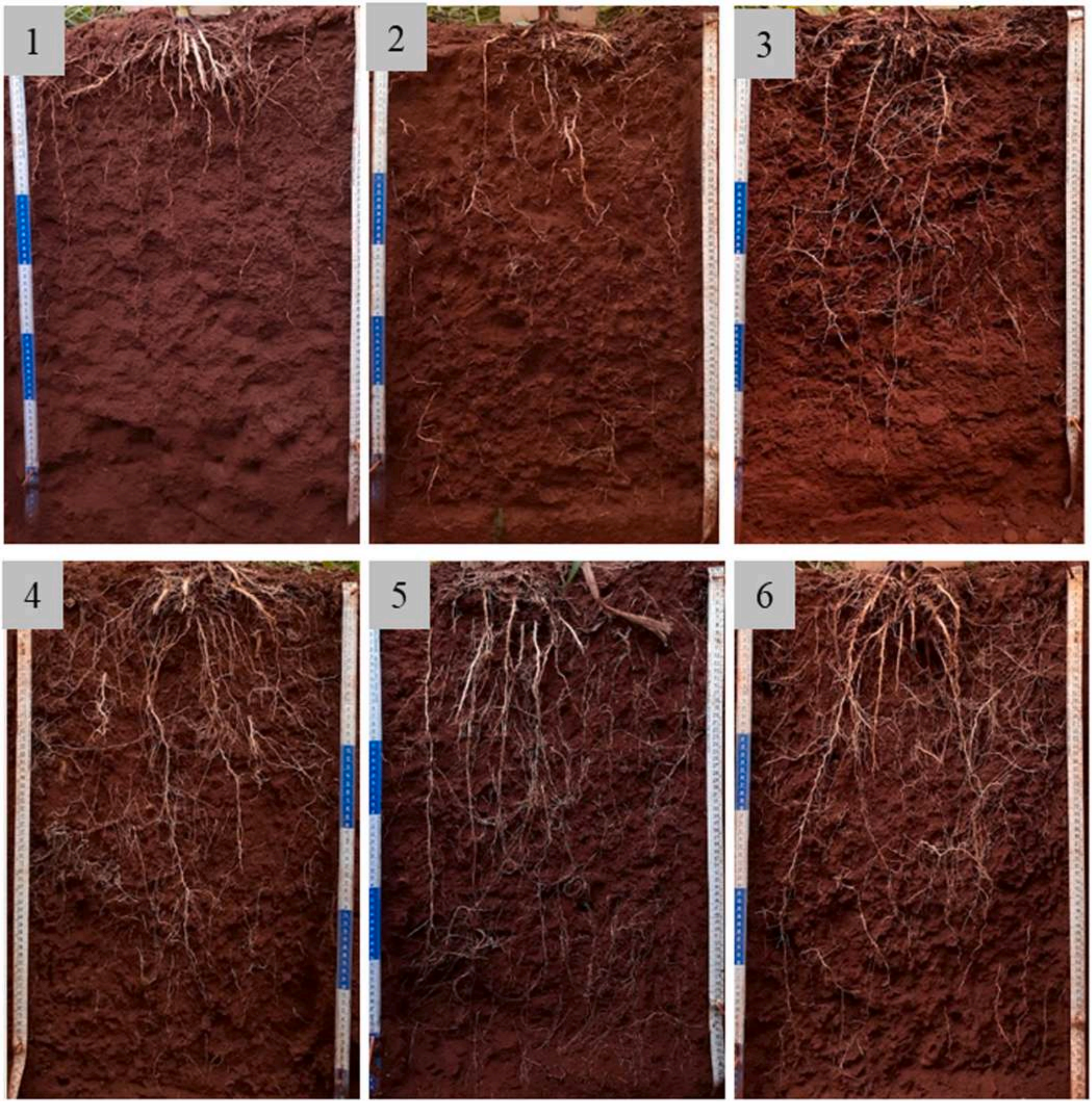

Fig. 7. Maize + brachiaria root distribution in the soil profile as a function of lime rates (1 = 0 Mg ha^{-1}; 2 = 3 Mg ha^{-1}; 3 = 6 Mg ha^{-1}; 4 = 9 Mg ha^{-1}; 5 = 12 Mg ha^{-1}; 6 = 15 Mg ha^{-1}) incorporated into the 0–40 cm depth.

ha^{-1} (Gonzalez-Erico et al., 1979; Miranda and Rowell, 1987; Gaiser et al., 2004; Haling et al., 2010; Bortoluzzi et al., 2014; Santos et al., 2018a, 2018b). These results are in line with past studies that have shown that liming increased soybean (Bortoluzzi et al., 2014), common bean (Silva et al., 2004), wheat (Caires et al., 2008, 2006), and maize (Friesen et al., 1980; Harun et al., 2015) root growth in the soil profile.

Aluminum toxicity and nutrient deficiency (e.g., Ca^{2+}, Mg^{2+}, P, and K^{+}) are the main chemical limiting factors of plant root growth in acid tropical soils (Fageria and Baligar, 2008; Haling et al., 2010; Keltjens and Dijkstra, 1991; Keltjens and Tan, 1993; Kunhikrishnan et al., 2016; Lopes and Guilherme, 2016; Miranda and Rowell, 1987, 2019). As the soils of the three locals did not present exchangeable Al (Table 1), the greater root development (Figs. 7 and 8) can be linked to the increased Ca and Mg contents in the soil profile promoted by liming (Fig. 3). Low Ca contents, as those initially observed in the soil of Local 2 and 3 (Table 1), can restrict root growth in the soil profile (Bortoluzzi et al., 2014; Santos et al., 2018a, 2018b) and increase yield losses due to water stress (Gonzalez-Erico et al., 1979; Miranda and Rowell, 1987; Gaiser et al., 2004; Haling et al., 2010). The impact of Ca^{2+} on root development occurs because Ca is part of the cell wall and is a component of hormonal peptides, which are linked to the cell elongation process (Ritchey et al., 1995).

There was a significant linear positive correlation between root growth (length, surface, and volume) and crop yield in Local 2 (Fig. 9). The variable that best explained the relationship between maize yield and root growth was root length (R^2 ranging from 0.51 to 0.64

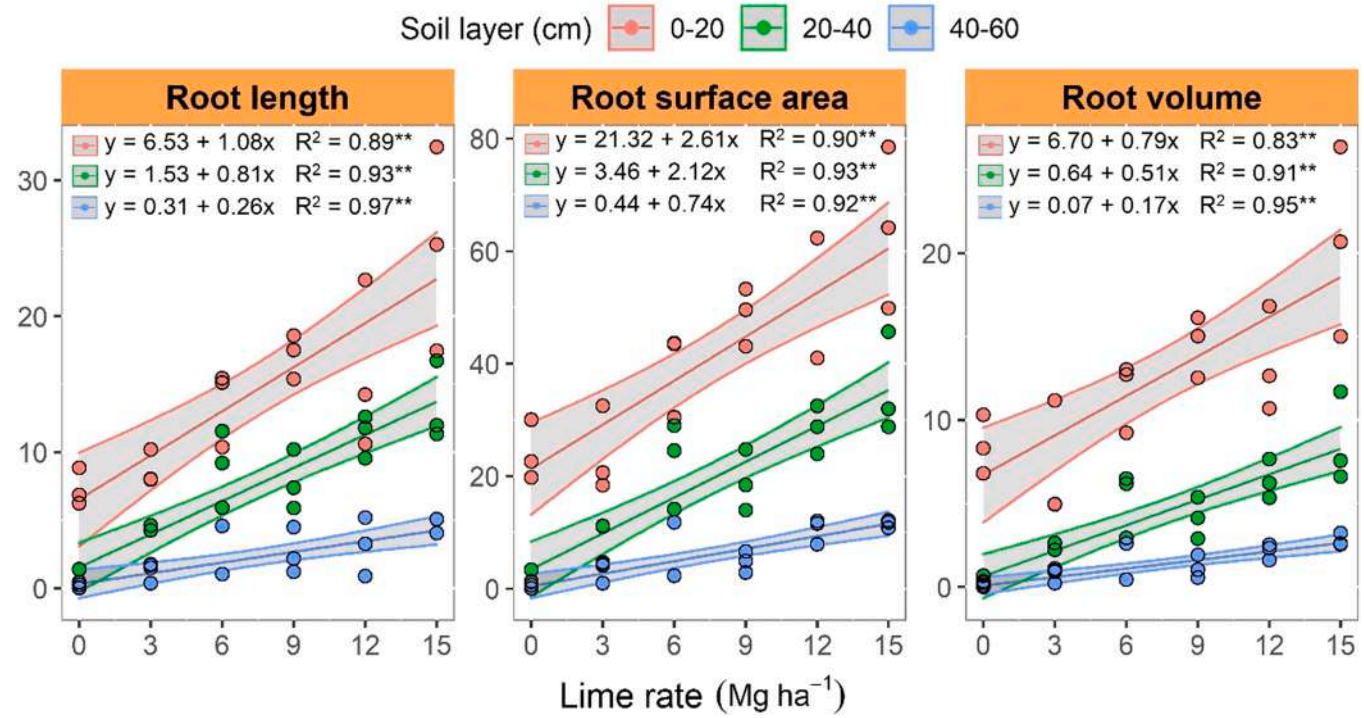

Fig. 8. Length (mm cm^{-2}), surface area (mm^2 cm^{-2}), and volume (mm^3 cm^{-2}) of roots of maize + brachiaria by soil layer as a function of the lime rates incorporated in the 0–40 cm layer.

depending on the soil layer evaluated). The greatest maize yield increase occurred with the increase in root growth in deeper soil layers, as can be observed by the higher slope in the 40–60 cm layer, followed by 20–40 and 0–20 cm, for all three root variables. The linear regressions (Fig. 9) suggest that for each 1 cm increase in root length in the 0–20, 20–40, and 40–60 cm layers, maize yield increased 1.01, 1.60, and 3.70 Mg ha^{-1}, respectively. For each 1 cm^2 increase in root surface area in the 0–20, 20–40, and 40–60 cm layers, maize yield increased by 0.40, 0.59, and 1.47 Mg ha^{-1}, respectively. For each 1 cm^3 increase in root volume in the 0–20, 20–40, and 40–60 cm layers, the maize yield increased by 1.15, 2.27, and 6.14 Mg ha^{-1}, respectively.

3.3. *Crop yield*

Crop yield increased with lime incorporation. However, crop yield response to lime incorporation varied with crop type, site, lime rate, and time after liming (Fig. 10). Yield increases were expected since limestone rates improved soil chemical conditions (Figs. 3–6) and led to higher root growth within the soil profile (Figs. 7–8), which can have a positive effect on crop yield (Fageria and Baligar, 2008; Kunhikrishnan et al., 2016; Li et al., 2019). In general, as also observed for the soil chemical properties, the greatest crop yield increases were found for lime rates between 9 and 15 Mg ha^{-1} (Fig. 10). It is worth noting that, based on the initial soil chemical conditions, the most traditional lime recommendation methods used in the studied region (Brazilian Cerrado) would not recommend liming for Local 1 and would recommend lower than ideal limestone doses for Local 2 and 3. However, crop yield still responded to high lime doses incorporated into the 0–40 cm soil depth.

The lime rates for greatest yield (≥9 Mg ha^{-1}) increased the pH in water values to 6.8–7.7, the BS to 83–88 %, and the percentage of Ca^{2+} in the CEC to 50–70 % and Mg^{2+} in the CEC to 20–30 % in the 0–20 cm layer. In the 20–40 cm layer, the pH (water) values were in the range of 5.6–6.5, BS 50–70 %, percentage of Ca^{2+} in the CEC to 30–50 %, and Mg^{2+} in the CEC to 10–20 %. These pH and BS values in the 0–20 cm layer are above the general target values between 6 and 6.5 and 50–70 %, respectively, recommended in the liming recommendation used in the Cerrado region (Alvarez and Ribeiro, 1999; Sousa and Lobato, 2004; Cantarella et al., 2022). Those recommendations were developed with studies carried out in the 80's and 90′s and were essential to transform Brazilian agriculture. However, in the current scenario of production with more productive and acidity-sensitive cultivars and with increasingly constant dry spells (Lopes and Guilherme, 2016), it is increasingly necessary to increase the resilience of plants, for example, providing conditions to develop your root system. The 0–20 cm soil layer dries faster thus, a more robust and deeper root system promotes root growth to deeper layers increasing plant resilience (Sanchez, 2019).

During the second season at Local2, maize crop experienced a dry period during the beginning of the reproductive phase (the greatest water requirement by maize). However, in the soil where 15 Mg ha^{-1} of limestone was incorporated, maize yield was 55.5 % (7.62 Mg ha^{-1}) higher than in the control plot (4.9 Mg ha^{-1}). It is worth mentioning that the entire maize crop cycle, from planting to harvest, took place with only 300 mm of water. During one of the most demanding periods of maize cultivation, 15 days that preceded the flowering of the crop and 16 days after flowering, rainfall accumulation was only 16.5 mm. Between the end of this period and the phenological stage R4, rainfall accumulation was only 28.3 mm. From there until R6 (physiological maturation) stage there was water restriction. More than four decades ago, when the opening of fields in the Brazilian Cerrado region was starting, some researchers demonstrated that deep liming increased crop yields compared to shallow incorporation (Doss et al., 1979; Gonzalez-Erico et al., 1979), but without explaining the reasons for this fact. In the current research, we showed that for the present production systems in Brazil, with first and second seasons, with cultivars more sensitive to acidity, lime rates incorporated up to 40 cm contributes to crop development (Fig. 10) by increasing soil fertility (Figs. 3–6) and root development within the soil profile (Fig. 8).

Incorporation of high lime doses (≥9 Mg ha^{-1}) into the soil profile (0–40 cm) also improved crop resilience. Overall, improved soil fertility due to lime incorporation (Figs. 3–6) led greater root length, area, and volume within the soil profile (Fig. 8), which increased water and nutrient absorption by crops and increased crop yield even with water

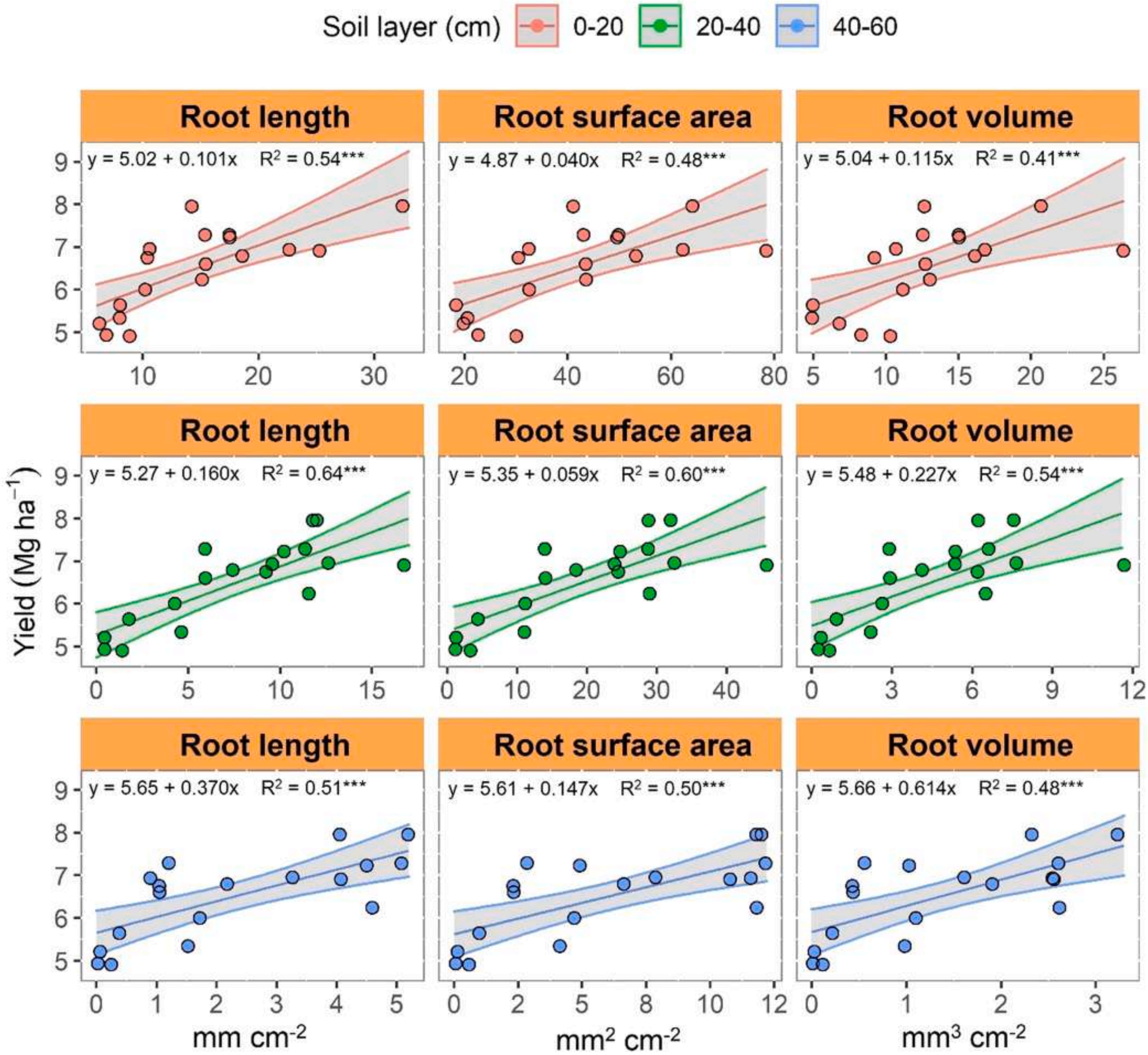

Fig. 9. Relationships between maize yield during the 2020 s season and root length, surface area, and volume of maize + brachiaria at depths of 0–20, 20–40, and 40–60 cm.

deficits (Ho et al., 2005; Lynch, 2007; Wasson et al., 2012). Caires et al. (2008) also found that crop (i.e., soybean, maize, and wheat) development respond to high doses of lime under water deficit in Brazil. Their study found more than 100 % increase in root length and 210 % increase in wheat yield resulting from limestone application. In addition to root growth, liming also improved water, P, and N use efficiency by maize (Gaiser et al., 2004; Victoria et al., 2019; Qaswar et al., 2020).

The maize plants that received the highest doses of incorporated lime presented visually greater development than those that did not receive lime (Fig. 11). This can be compared through the height of the plants of the treatments with a ruler of 2 m that was positioned between the plants. For this reason, there was a good relationship between maize yield during the 2020 s season in Local2 and root length, surface area, and volume of maize + brachiaria at depths of 0–20, 20–40, and 40–60 cm (Fig. 9).

Finally, these results of experiments at three sites and three years show the need for improvement in liming recommendation methods for highly weathered soils. The limestone rate should increase Ca and Mg percentage in the CEC of 0–20 cm layer to values around 60 % and 20 %, respectively. In addition, the conventional recommended liming values of BS of 50–70 % (Alvarez and Ribeiro, 1999; Cantarella et al., 2022) can be increased to approximately 85 %, since the values obtained in the field are different from those obtained through the calculations proposed by Cantarella et al. (2022).

4. Conclusion

This field study focused on the effects of lime rates incorporated into the 0–40 cm depth on chemical properties, crop root growth within the soil profile, and crop yields in three highly weathered tropical soils. Overall, we concluded that: (i) incorporating high lime doses (≥9 Mg ha^{-1}) up to 40 cm deep improves soil chemical condition (*i.e.*, Ca and Mg contents, soil pH, and base saturation) within the 0–40 cm soil depth, which in turn significantly increases crop root growth (*i.e.*, root length, surface area, and volume) within the 0–60 cm layer; (ii) lime incorporation increased crop yields, with lime rates ≥ 9 Mg ha^{-1} having

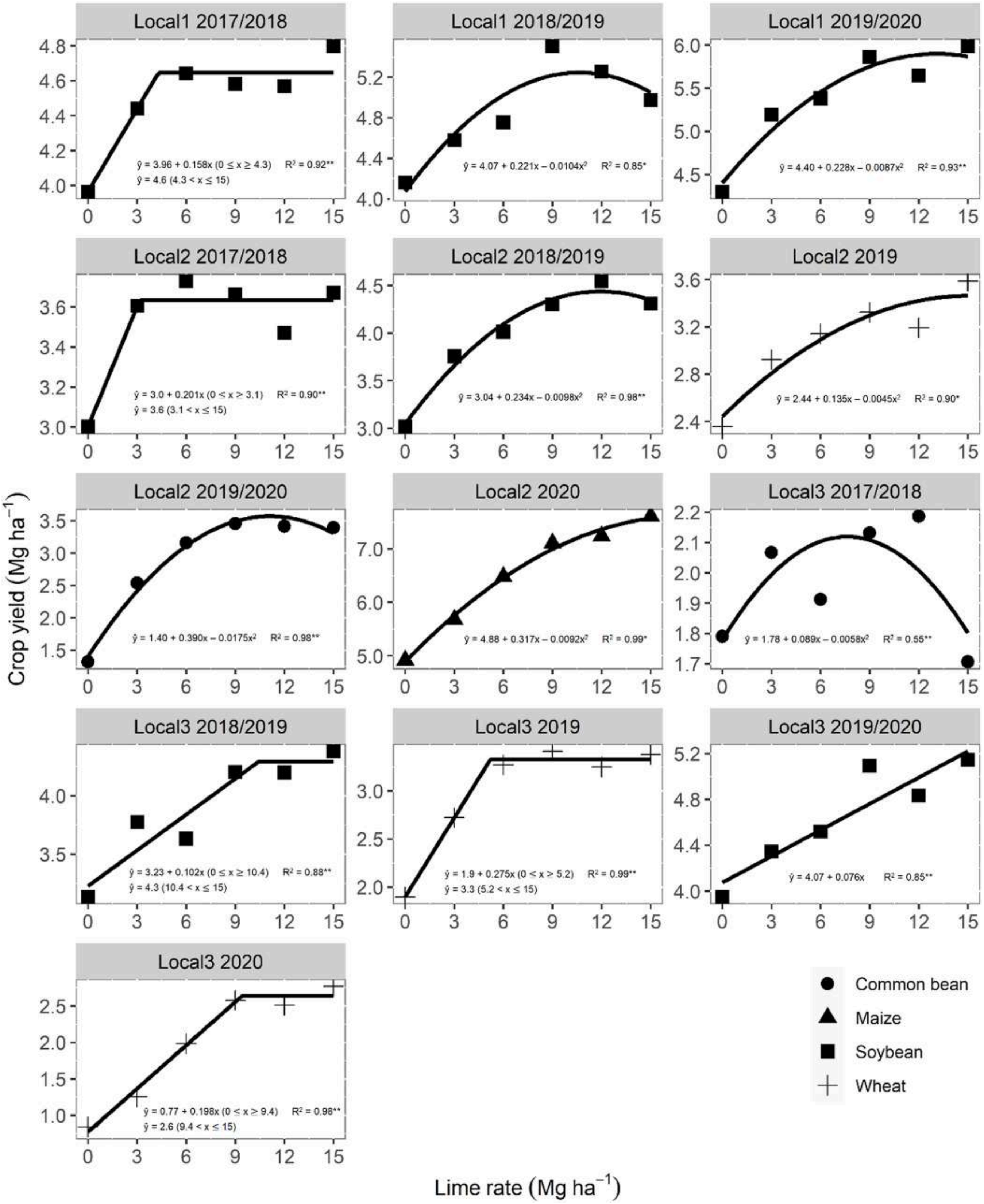

Fig. 10. Soybean, maize, common bean, and wheat yield as a function of the lime rate incorporated in the 0–40 cm layer in three sites (Local1, Local2, and Local3).

Fig. 11. Maize plants intercropped with Brachiaria as a function of limestone doses around 60 days after sowing. (1 = control; 2 = 6 Mg ha^{-1}; 3 = 12 Mg ha^{-1}).

the greatest positive impact; (iii) by increasing soil chemical condition to root development within the soil profile (0–60 cm), incorporating high doses of lime can improve crop yield resilience under water deficits in highly weathered tropical soils.

CRediT authorship contribution statement

F. A. de Moraes: Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **S. G. Moreira:** Supervision, Conceptualization, Funding acquisition, Writing – review & editing. **D. S. Peixoto:** Formal analysis, Visualization. **J. C. R. Silva:** Investigation, Resources. **J. R. Macedo:** Methodology, Investigation, Resources. **M. M. Silva:** Investigation, Resources. **B. M. Silva:** writing, Investigation, Resources. **P.A. Sanchez:** review & editing. **M. R. Nunes:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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