ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.27, n.6, p.480-486, 2023
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v27n6p480-486

Efficiency and quality of soil sampling according to a sampling tool[1]

Eficiência e qualidade da amostragem do solo de acordo com a ferramenta de amostragem

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HIGHLIGHTS:
The sampling devices under analysis showed a statistically significant difference between organic matter, K, Ca, and CEC.
There is a statistically significant difference between sampling depths for all nutrients except pH and S.
The automated hydraulic soil sampler had a more effective collection rate than the other equipment.

ABSTRACT: Soil sampling is a fundamental stage for recommending agricultural correctives and fertilizers, estimating the nutritional demands of plants, and consequently maximizing productivity. Therefore, this study aimed to assess the performance of three soil samplers in different management systems in terms of sample quality and operational efficiency. A completely randomized experimental design was used in a factorial scheme. Three samplers and two sampling depths (3 × 2) were used with four replicates. At each sampling location, eight single samples were taken at a varying sampling depth of 0.0-0.2 and 0.2-0.4 m, and the collection time was recorded. Samples were analyzed for chemical attributes and granulometry. Statistically significant differences were observed for specific attributes (organic matter, K, Ca, CEC, pH, and S). In terms of operational efficiency, the hydraulic sampler was more efficient than the other samplers, being three times faster than the combustion drill and six times faster than the manual probe. Thus, it is suitable and reliable for soil sampling purposes.

Key words: precision agriculture, soil sampling, automation

RESUMO: A amostragem de solo é uma etapa fundamental para a recomendação de corretivos e fertilizantes agrícolas, estimar demanda nutricional de plantas e consequentemente maximizar a produtividade. Por conseguinte, o objetivo deste estudo foi avaliar o desempenho de três amostradores de solo em áreas de diferentes sistemas de manejo no contexto de qualidade da amostra e eficiência operacional. Utilizou-se o delineamento experimental inteiramente casualizado em esquema fatorial 3 × 2 (três amostradores e duas profundidades de amostragem), com quatro repetições. Em cada ponto amostral, foram retiradas oito amostras simples em profundidade variável de coleta de 0,0-0,2 e 0,2-0,4 m, cronometrando-se o tempo de coleta. Foram avaliados atributos químicos e granulometria dos solos. Foram observadas diferenças estatísticas para atributos específicos (matéria orgânica, K, Ca, CEC, pH e S). Em termos de eficiência operacional, o amostrador hidráulico superou os demais amostradores, sendo três vezes mais rápido em comparação com o sistema a combustão e seis vezes em comparação com a sonda manual; sendo assim apto e recomendável para as operações de coleta de solo.

Palavras-chave: agricultura de precisão, amostragem de solo, automação

• Ref. 266160 – Received 19 May, 2022
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• Accepted 11 Jan, 2023 • Published 11 Feb, 2023
Editors: Geovani Soares de Lima & Carlos Alberto Vieira de Azevedo

Introduction

Understanding the spatial variability of soil physicochemical attributes is essential for sustainable planning of agricultural crop growth (AbdelRahman et al., 2020). Thompson et al. (2019) reported that only 66% of farmers conduct soil sampling at a density suitable for precision agriculture practices, and discussions on soil sampling tools have intensified, varying according to soil type, management, and fertilization (Pathak et al., 2019). Therefore, because of the density of sampling in precision agriculture, an analysis of the samplers available in the market is required to evaluate the most efficient and precise sampling methodology.

The most widely used samplers in Brazil are augers, Dutch augers, core-drill augers, and cutting shovels. Several studies indicate that the cutting shovel is the method of best representativeness considering the quality of the sample, since it mobilizes a greater content (volume) of soil, especially in no-till systems (Rosolem et al., 2010; Alvarez & Guarçoni, 2003).

The variability in fertility indices tends to increase according to the volume of soil collected; conversely, it is proportional (Guarçoni et al., 2019). Inadequate selection of the sampling system can alter the results of soil analysis and consequently the management strategies that can compromise agricultural productivity. According to a review by Bolinder et al. (2020), most studies consider only 20 cm soil samples, and almost never 30 cm samples are measured, in disagreement with the agricultural practices usually employed in Brazil (0-40 cm). An extensive study of sampling systems is justified considering the importance of reliable soil analysis in plant production processes. Therefore, the objective of this study was to evaluate the performance of three soil samplers in different management systems (conventional and no-till) in terms of sample quality and operational efficiency.

Material and Methods

The research was performed on the campus of the University of São Paulo, in Piracicaba, SP, Brazil (22° 42' 34" S and 47° 37' 55" W, altitude of 546 m), and the experimental sampling was conducted during the first fortnight of November 2021. Three sites with different percentages of clay in the soil were chosen because the texture could affect the stability of the aggregates and cause contamination of the sample. Areas under agricultural cultivation conditions were selected, with one being under the conventional system: Area 1, Oxisols soil (United States, 2014) which corresponds to a Latossolo Vermelho-Amarelo district (sandy texture) in the Brazilian Soil Classification System (EMBRAPA, 2018); two under the no-till system: Area 2, soil with the same classification as Area 1, but with higher clay content; and Area 3, Ultisols soil (United States, 2014) which corresponds to a Nitossolo Vermelho Eutroférrico in the Brazilian Soil Classification System (EMBRAPA, 2018).

The experimental design was entirely randomized in a 3 × 2 factorial scheme (three samplers and two sampling depths) with four replicates. Three types of soil samplers were evaluated as follows: A) manually driven probe, 20 mm in diameter; B) screw with one inch diameter (25.4 mm) and 3.4 mm pitch, driven by a combustion engine drill; and C) side-opening probe-type sampler, 26 mm in diameter, with a hydraulic drive and aided by a hydraulic hammer, mounted on an agricultural utility vehicle, for sampling up to a 0.6 m depth, allowing automated collection of two depths.

At each sampling point, eight single samples were taken at varying sampling depths of 0.0-0.2 and 0.2-0.4 m. Aiming to standardize the sampling with the three instruments, circles of approximately 2.5 m radius were defined, within which the subsamples were collected. At each point, all subsamples were initially collected with a hydraulic probe (C) to identify their location. Sampling was performed with a screw-type sampler (B) and a manual sampling probe (A). The subsamples obtained by each equipment were taken with a maximum proximity of 10 cm to obtain the minimum local variability between the subsamples and equipment. The subsamples were homogenized and packed in plastic bags, identified for each repetition and treatment, and sent to the laboratory for analysis, following the methodology of Teixeira et al. (2017).

To evaluate the operational performance of the activity, the total time spent collecting the subsamples was recorded using a digital stopwatch corresponding to each sampling device at both sampling depths in the three areas evaluated. The samples were collected during the first fortnight of November 2020, when the cumulative rainfall record for the last 30 days was only 27.4 mm (dry season).

The chemical attributes evaluated were pH (extracted by $CaCl_2$) (0.01 mol L^{-1}), phosphorus (P) in resin, exchangeable potassium (K^+), calcium (Ca^{+2}) and magnesium (Mg^{+2}), organic matter (OM), sulfur (S), cation exchange capacity (CeC), base saturation (V%), and micronutrients: boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). The particle size composition was determined by dispersion with NaOH (0.1 mol L^{-1}) and slow stirring for 16 hours, and the clay content was determined by the pipette method.

The assumptions of data normality were analyzed using Shapiro-Wilk's test, and homogeneity of variance was considered in Levene's test. The data were subjected to variance analysis, and when significant, the means of the treatments were compared using Tukey's test at $p \leq 0.05$, using R Studio software.

Results and Discussion

The assumptions of data normality (Shapiro-Wilk's test) and homogeneity of variance (Levene's test) were met for all attributes in Area 1 (conventional cultivation system), except for S content, which did not show residual normality, and potassium content, which did not show homogeneity of variances. Thus, for these nutrients, the data were transformed using the square root, which guaranteed the necessary assumptions for the analysis of variance.

Table 1 summarizes the analysis of variance for the variables evaluated in Area 1. The sampling equipment did not differ significantly for the chemical attributes P, pH, Mg, and S (Table 1), while significant differences were observed for OM, K, Ca, and CEC. There were significant differences in the sampling

Table 1. Analysis of variance F values for the chemical soil attributes in Area 1 (conventional cultivation)

Source of variation	DF	pH	P	OM	[1]K	Ca	Mg	CEC	[1]S
Equipment (E)	2	0.73^{ns}	0.86^{ns}	6.88*	5.26*	5.07*	3.49^{ns}	9.52*	2.91^{ns}
Depths (D)	1	0.31^{ns}	31.87*	69.00*	72.60*	28.16*	14.63*	38.62*	4.25^{ns}
E × D	2	0.94^{ns}	0.55^{ns}	1.99^{ns}	0.60^{ns}	0.11^{ns}	0.11^{ns}	0.68^{ns}	0.22^{ns}
CV (%)		4.06	34.09	12.44	28.49	10.42	17.04	6.50	25.81

* - Significant at $p \leq 0.05$, ns - Not significant, by F test; [1] Square-root-transformed data; DF - Degrees of freedom; CV - Coefficient of variation

depth for all attributes analyzed, except for pH and S. There was no interaction between the instruments and the sampling depth.

By conducting a comparative analysis in 15 different areas differing in management, soil, and fertility using five types of augers and cutting shovel, Rosolem et al. (2010) highlighted the statistical similarity for the values of pH, MO, and available P among all tools. However, divergence was identified between the augers and the cutting blade for Ca, Mg, and K content.

The lowest coefficients of variation (CV%) were observed for pH and CEC, indicating that these variables were the most homogeneous in the soil. Low CV values for pH are commonly found in soils (Oliveira et al., 2020; AbdelRahman et al., 2021; Gelain et al., 2021). The homogeneity of the pH is related to the subtle slope of the area and the parent material from which the soil is formed (AbdelRahman et al., 2021).

The results for P, K, and S showed coefficients of variation (CV%) greater than 20%. Evaluating different sampling arrangements, Gelain et al. (2021) observed that the increase in the dispersion of P and K is due to the successive application of fertilizers in the sowing furrow. This causes large variations in nutrient content over short distances, especially in the case of P, which is not very mobile in soil. Bolfarini et al. (2020) highlighted the lower uniformity of P distribution because tropical soils may have low P availability as P binds to clay minerals and forms poorly soluble compounds.

Table 2 shows the results of the comparison test of the means for the variables evaluated in Area 1. In general, the lowest average values were obtained with Probe A for the attributes analyzed in Area 1. The comparison of the averages of the results obtained with the different equipment revealed that the sampling carried out with the screw sampler (B) and hydraulic drive (C) were statistically similar for the OM and CEC contents, while they differed from the values of the manual drive (A).

The difference observed in the OM in relation to the equipment could be explained by the processes of cleaning the soil surface to remove the straw, as discussed by Mitchell (1960) regarding the care to be taken at the time of sampling. Nutrient levels from 0.0-0.2 m depth are higher for Auger B and Probe C than for Probe A. This is due to the rotation inherent in the downward movement of the equipment, obtaining the first centimeters of soil that were previously more fertilized. This effect does not occur with Probe A considering that the equipment is closed and does not execute any rotational movement. In sandy soil scenarios, this situation is more pronounced because of less structuring of the aggregates (Huang & Hartemink, 2020), which contributes to contamination owing to the rotation of the equipment.

On the other hand, for the K content, the values obtained with Probe C were intermediate and did not differ statistically from Probe A and Auger B. Regarding calcium content, Auger B showed similar behavior to Probes A and B, which differed from each other.

Evaluating the sampling depths (Table 2), there were significant differences among the attributes, except for pH and S, with higher values at the 0.0-0.2 m sampling depth due to routine chemical management to increase soil fertility. Several authors have observed that the physicochemical properties of soil change with increasing depth, indicating that depth influences the distribution and diversification of soil nutrients (Ali et al., 2019; Rahman et al., 2022).

In Area 2 (no-till), the assumptions of homogeneity of variance and normality of the data were met. The results of the analysis of variance are shown in Table 3. Significant differences between the sampling equipment were observed for OM, K, Ca, Mg, and CEC values. Similar results were observed for pH, P, and S data. In terms of sampling depth, the values were statistically different for all attributes, except for S. Additionally, a significant interaction between equipment and sampling depth was observed for the K data.

The results of the comparison test of the means are shown in Tables 4 and 5 (unfolding interaction for K data). For OM, Ca, Mg, and CEC, the values obtained with Auger B and Probe A were statistically different (regardless of sampling depth), whereas those obtained with Probe C were intermediate

Table 2. Results of the comparison test of the means for the evaluated variables of the chemical soil attributes in Area 1 (conventional cultivation)

Equipment	pH	P (mg dm^{-3})	OM (g dm^{-3})	[1]K	Ca	Mg	CEC	[1]S (mg dm^{-3})
				(mmol$_c$ dm^{-3})				
Probe A	5.3 a	6.1 a	7.9 b	0.8 b	14.5 b	8.5 a	39.5 b	2.5 a
Auger B	5.5 a	7.3 a	9.6 a	1.1 a	16.0 ab	10.0 a	43.1 a	2.8 a
Probe C	5.4 a	7.6 a	9.8 a	0.9 ab	17.1 a	10.6 a	45.5 a	2.8 a
Depths (m)	**pH**	**P (mg dm^{-3})**	**OM (g dm^{-3})**	**[1]K**	**Ca**	**Mg**	**CEC**	**[1]S (mg dm^{-3})**
				(mmol$_c$ dm^{-3})				
0.0-0.2	5.4 a	9.8 a	11.0 a	1.2 a	17.7 a	11.0 a	46.2 a	2.5 a
0.2-0.4	5.4 a	4.3 b	7.2 b	0.7 b	14.1 b	8.4 b	39.2 b	2.8 a

Means followed by the same letter in the columns do not differ significantly according to Tukey's test ($p \leq 0.05$); [1] Square-root-transformed data; Probe A: Manual probe; Probe C: Hydraulically driven probe

Table 3. Analysis of variance F values for the evaluated variables of the chemical soil attributes in Area 2 (no-till)

Source of variation	DF	pH	P	OM	K	Ca	Mg	CEC	S
Equipment (E)	2	1.11^{ns}	1.75ns	4.09*	7.79*	4.73*	6.22*	6.39*	1.37^{ns}
Depths (D)	1	6.94*	27.34*	73.98*	80.46*	21.18*	63.37*	33.35*	1.82^{ns}
E × D	2	0.25^{ns}	2.59^{ns}	0.50^{ns}	5.95*	0.99^{ns}	2.41^{ns}	0.89^{ns}	0.64^{ns}
CV (%)		2.47	30.16	10.28	26.83	8.68	11.78	7.32	21.34

* - Significant at p ≤ 0.05, ns - Not significant, by F test; DF - Degrees of freedom; CV - Coefficient of variation

Table 4. Results of the comparison test of the means for the evaluated variables of the chemical soil attributes in Area 2 (no-till)

Equipment	pH	P (mg dm^{-3})	OM (g dm^{-3})	Ca	Mg	CEC	S (mg dm^{-3})
					(mmol$_c$ dm^{-3})		
Probe A	5.6 a	12.3 a	18.3 b	36.5 b	17.3 b	74.1 b	7.8 a
Auger B	5.7 a	15.6 a	21.1 a	41.6 a	21.3 a	84.5 a	7.1 a
Probe C	5.6 a	16.0 a	19.5 ab	38.4 ab	19.6 ab	80.1 ab	8.5 a
Depths (m)	**pH**	**P (mg dm^{-3})**	**OM (g dm^{-3})**	**Ca**	**Mg**	**CEC**	**[1]S (mg dm^{-3})**
					(mmol$_c$ dm^{-3})		
0.0-0.2	5.7 a	19.3 a	23.2 a	42.0 a	23.1 a	86.5 a	7.3 a
0.2-0.4	5.6 b	9.9 b	16.1 b	35.7 b	15.7 b	72.7 b	8.3 a

Means followed by the same letter in the columns do not differ significantly according to Tukey's test (p ≤ 0.05); Probe A: Manual probe; Probe C: Hydraulically driven probe

Table 5. Results of the comparison test of the means for potassium (K) data in Area 2 (no-till)

Equipments	K (mmol$_c$ dm^{-3})	
	0.0-0.2 m	0.2-0.4 m
Probe A	1.7 bA	0.7 aB
Auger B	2.5 aA	1.1 aB
Probe C	3.3 aA	0.8 aB

Means followed by the same lowercase letter in the columns and uppercase letter in the row do not differ significantly according to Tukey's test (p ≤0.05); Probe A: Manual probe; Probe C: Hydraulically driven probe

between these two pieces of equipment, not statistically different from the other equipment.

For the K content at a depth of 0.0-0.2 m (Table 5), there were no differences between Auger B and Probe C, but they were different from those of Probe A, and in this sampling system, the lowest content of this element was observed. At a depth of 0.2-0.4 m, there was no difference between the sampling equipment for K.

Considering that for pH, P, and S, there were no differences between the three pieces of equipment tested, and that for OM, Ca, Mg, and CEC, there were no differences between Probe C and Probe A or Auger B, it can be confirmed that there were no significant differences when sampling was carried out with Probe C or the other two pieces of equipment. In addition, given the ease of sampling, Probe C can be very useful and efficient for intensive sampling, as in precision agriculture systems.

Area 2, as opposed to Area 1, had higher clay content in the soil. The nutrient concentration sampled by Probe A was similar to that of Auger B; this demonstrates that well-structured soil (with higher clay content) is less susceptible to contamination by nutrients at different depths. According to Molin et al. (2015), in precision agriculture scenarios, there is a demand for a large quantity of soil samples, especially when grid sampling is used. Although conventional sampling equipment can be employed (auger and probe, for example), there is a need to increase the performance of the operation through mechanized and automated sampling systems that are faster and more efficient.

The highest values of the soil chemical attributes were observed at a depth of 0.0-0.2 m. Soil acidity in the no-tillage system was corrected by limiting the soil surface without incorporation. However, in many cases, soil acidity improvement by lime application may be restricted to the first soil layer due to soil conditions and the low mobility of the reaction of lime products (Churka Blum et al., 2013). In addition to acidity correctives, fertilizers are also deposited on the surface or in lines, which cause a significant increase in nutrients in the surface layer of the soil. This causes a fertility gradient along the profile, resulting in differences in nutrient content, as observed in this study.

Alvarez & Guarçoni (2003) also observed that the direct application of fertilizers in the sowing row resulted in two distinct populations in terms of nutrient content: the superficial one with a high concentration and the other (subsurface) with a lower concentration of nutrients, especially those with little mobility in the soil. In addition, the greater occurrence of organic matter in the soil provides a fertility gradient.

In Area 3 (no-till), all analyzed attributes met the normality assumption, except for Mg even after data transformation. Likewise, all attributes showed homogeneity of variance, except for the data from S. Data transformation is not efficient in solving this problem. Table 6 summarizes the analysis of

Table 6. Analysis of variance F values and results of the comparison test of the means for the evaluated variables of the chemical soil attributes in Area 3 (no-till)

Source of variation	DF	pH	P	OM	K	Ca	[1]Mg	CEC	[1]S
Equipment (E)	2	1.58^{ns}	19.72*	14.35*	38.09*	20.85*	-	30.79*	-
Depths (D)	1	4.05^{ns}	244.02*	104.49*	279.31*	12.89*	-	98.49*	-
E × D	2	0.28^{ns}	4.47*	5.96*	17.82*	2.73^{ns}	-	5.17*	-
CV (%)		1.89	11.33	7.24	12.48	4.12	5.64	3.29	25.12

* - Significant at p ≤ 0.05, ns - Not significant, by F test; DF - Degrees of freedom; CV - Coefficient of variation; [1] Data did not meet the ANOVA assumptions

variance for the variables evaluated in Area 3. There were more interactions between the instruments and depth. Low CV values were observed for all attributes evaluated, except for S, which showed moderate variability.

Table 7 shows the mean values of the pH, calcium, magnesium and sulfur data in Area 3; for the latter two (Mg and S), the test of means was not performed because they did not meet the assumptions of analysis of variance. There were no significant differences in the pH between the equipment and sampling depth. There were no significant differences in Ca levels between Probe A and Probe C, which were lower than those obtained with Auger B. The highest values were observed at a depth of 0.0-0.2 m.

The test of means, after unfolding the interactions (Table 8), showed that there were no differences between Auger B and Probe C for the attributes P and CEC at the depth of 0.0-0.2 m, with the lowest values being obtained by Probe A, which differed from the others. However, this pattern changed at a depth of 0.2-0.4 m, with probes A and C presenting statistically similar values for P, K, and CEC. The values obtained with Auger B were much higher than those obtained with the other equipment in the 0.2-0.4 m layer.

The distribution of cations in the soil profile is greatly affected by the management system, with higher concentrations being observed on the surface in the no-till system, and a better distribution along the profile in the conventional system (Pavinato et al., 2009). As observed by Acqua et al. (2013), there was greater availability of nutrients in the first 5 cm of the soil profile in the no-tillage system, and the samples taken with the drill represented only the fertility indices of the layer in which there was a greater concentration of nutrients.

Differences in soil fertility were also observed by Silva et al. (2003), who indicated that the volume of soil collected by each piece of equipment may be the cause of this variation, especially in no-till systems, because of the irregular distribution of nutrients, such as P and K, when applied in the seeding line. Salet et al. (2005) verified the variability of fertility in the no-till farming system by comparing three areas with different fertility levels, cultures, and soils, comparing the Dutch auger to the cutting shovel. The authors reported that soil samplers that collect a small volume (auger) loosened more surface layers and consequently presented a higher coefficient of variation.

Evaluated sampling tools (Dutch auger and auger driven by electric drill) in 12 different no-till areas (2.5 and 10 years), Acqua et al. (2013) found that the sampling equipment influenced the results of soil analysis being that all macronutrients, except S, and all micronutrients showed high values when sampled with the auger driven by an electric drill.

The results of the analysis of variance and test of means for clay content are shown in Table 9. The data met the assumptions of normality and homogeneity of variance. There were no significant differences among the three types of equipment evaluated in the three areas studied. Regarding the depths, there were significant differences between Area 1 and Area 3, with the highest values being observed at a depth of 0.2-0.4 m.

The clay content data showed classical homogeneity, given by the coefficient of variation. Low CV values for clay content are commonly observed in the literature (Feitosa et al., 2019; Gelain et al., 2021) and are intrinsically linked to the source material of soil formation (AbdelRahman et al., 2021).

Regarding the time taken to collect samples (Table 10), there were significant differences between the three pieces of equipment. In all areas evaluated, the highest efficiency was observed for Probe C, with 3 min and 52 s per sample (composed of eight subsamples) at both depths in Area 1; 4 min and 37 s in Area 2; and 4 min and 51 s in Area 3.

The hydraulic sampler (Probe C) outperformed the other methodologies in all analyses. In Area 1, Probe A (22 min 12 s) underperformed both methodologies (12 min 25 s and 3 min 52 s for Auger B and Probe C, respectively). In Area 2, the operational efficiency of probe C was superior; however, there

Table 7. Means for the pH, calcium, magnesium, and sulfur data in Area 3 (no-till)

Equipment	pH	Ca (mmol$_c$ dm^{-3})	[1]Mg (mmol$_c$ dm^{-3})	[1]S (mg dm^{-3})
Probe A	5.3 a	46.4 b	19.4	17.15
Auger B	5.4 a	52.0 a	24.5	13.8
Probe C	5.4 a	46.5 b	21.9	13.3
Depths (m)	**pH**	**Ca (mmol$_c$ dm^{-3})**	**[1]Mg (mmol$_c$ dm^{-3})**	**[1]S (mg dm^{-3})**
0.0-0.2	5.4 a	49.8 a	25.7	12.6
0.2-0.4	5.4 a	46.8 b	18.2	16.9

Means followed by the same letter in the columns do not differ significantly according to Tukey's test ($p \leq 0.05$); [1] Data did not meet the ANOVA assumptions; Probe A: Manual probe; Probe C: Hydraulically driven probe

Table 9. Analysis of variance F values and results of the comparison test of the means for the clay contents (g kg^{-1}) in the three studied areas

Source of variation	DF	F values Area 1	Area 2	Area 3
Equipment (E)	2	3.35^{ns}	0.31^{ns}	0,95^{ns}
Depths (D)	1	9.12*	0.44^{ns}	5,20*
E × D	2	0.25^{ns}	2.98^{ns}	0,97^{ns}
CV (%)		15.12	10.81	9,42
Equipment		**Comparison test of means Area 1**	**Area 2**	**Area 3**
Probe A		106.5 a	225.3 a	418.4 a
Auger B		124.0 a	233.8 a	400.9 a
Probe C		128.8 a	233.9 a	392.4 a
Depths (m)		**Area 1**	**Area 2**	**Area 3**
0.0-0.2		108.5 b	227.6 a	386.3 b
0.2-0.4		130.9 a	234.3 a	421.7 a

* - Significant at $p \leq 0.05$, ns - Not significant, by F test; DF - Degrees of freedom; CV - Coefficient of variation; Means followed by the same letter in the columns do not differ significantly according to Tukey's test ($p \leq 0.05$)

Table 8. Results of the comparison test of the means for the evaluated variables of the chemical soil attributes in Area 3 (no-till)

Equipment	P (mg dm^{-3}) 0.0-0.2 m	P 0.2-0.4 m	OM (g dm^{-3}) 0.0-0.2 m	OM 0.2-0.4 m	K (mmol$_c$ dm^{-3}) 0.0-0.2 m	K 0.2-0.4 m	CEC (mmol$_c$ dm^{-3}) 0.0-0.2 m	CEC 0.2-0.4 m
Probe A	31.5 bA	13.0 bB	19.8 bA	16.0 aB	4.5 cA	1.9 bB	101.5 bA	88.8 bB
Auger B	39.8 aA	23.3 aB	24.3 aA	18.5 aB	7.1 bA	3.8 aB	111.9 aA	103.4 aB
Probe C	42.8 aA	17.3 bB	25.5 aA	16.8 aB	8.3 aA	2.4 bB	108.0 aA	89.0 bB

Means followed by the same lowercase letter in the columns and uppercase letter in the row do not differ significantly according to Tukey's test ($p \leq 0.05$); Probe A: Manual probe; Probe C: Hydraulically driven probe

Table 10. Analysis of variance F values and results of the comparison test of the means for soil sampling time with different equipment in the three studied areas

Source of variation	DF	F values		
		Area 1	Area 2	Area 3
Equipment (E)	2	507.0*	966.0*	848.0*
CV (%)		61.23	84.21	81.43
Equipments		Comparison test of means		
		Area 1	Area 2	Area 3
Probe A		22 min 12 s c	25 min 32 s b	32 min 31 s c
Auger B		12 min 25 s b	5 min 42 s a	9 min 23 s b
Probe C		3 min 52 s a	4 min 37 s a	4 min 51 s a

Means followed by the same letter in the column do not differ according to Tukey's test ($p \leq 0.05$)

was less disparity between Auger B (5 min 42 s) and Probe C (4 min 37 s), but there was still a significant difference compared to Probe A (25 min 32 s). In Area 3, an even greater disparity was observed when comparing Probe A (32 min 31 s) against Auger B (9 min 23 s) and Probe C (4 min 51 s). Sampling with Probe A was more labor-intensive and time-consuming and presented a much lower operational performance than the other equipment.

Regarding the total aggregated time, the sample collection time with Probe A (80 min 15 s) was approximately three times longer than that with Auger B (27 min 30 s) and six times longer than that with Probe C (13 min 20 s). When dealing with large areas, in which many sampling points are needed, the use of Probe A will demand a more intense sampling effort and a longer collection time.

According to Molin et al. (2015), in precision agriculture scenarios, there is a demand for a large quantity of soil samples, especially when grid sampling is used. Although conventional sampling equipment can be employed (auger and probe, for example), there is a need to increase the performance of the operation through mechanized and automated sampling systems that are faster and more efficient.

Conclusions

1. There were no statistical differences in the physical attributes; therefore, all the equipment under study was suitable for textural analysis. For the chemical attributes, probes A and C were more efficient in terms of sample quality, having a more stable nutrient concentration in deep layers (20-40 cm) than Auger B, thus being significantly less contaminated.

2. Probe C showed greater efficiency in terms of sampling time, being at least two times faster than that of Auger B and six times faster than that of Probe A, considering the total collection time. Furthermore, Probe C was at least 1 min faster than Auger B and at least 18 min faster than Probe A in every field. Thus, its use increases sampling efficiency in large areas and with a high sampling density.

Acknowledgments

We use this opportunity to express special thanks to Wintex, which provided the side-opening probe-type sampler, and to IBRA Lab for the soil laboratory analysis.

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