Laboratory Evaluation of an Electro-Pneumatic Sampling Method for Real-Time Soil Sensing

S. Yildirim, S. J. Birrell, J. W. Hummel

Abstract. *An automated electro-pneumatic soil sampling method based on pressurized air for real-time soil analysis was developed and tested under laboratory conditions. Pressurized air was applied for 36 ms across a 2.5 cm diameter cylinder to cut a sample from a soil column and convey the sample along a delivery pipe into a container. An electro-pneumatic regulator valve was used to regulate the air pressure at 550, 690, and 830 kPa (80, 100, and 120 psi) using an analog electrical signal. A two-position solenoid valve controlled by a stand-alone microprocessor was used to control pulse duration. Laboratory tests were conducted to determine the effectiveness of positive high-pressure air as a cutting force for different soil conditions. The effects of air pressure level, soil moisture content, soil compaction, and soil type on the quantity of soil sample obtained were investigated. Moisture content and air pressure level were the most significant factors, while compaction was not significant (α = 0.05) in terms of mass of soil obtained. Laboratory test results proved that pressurized air was effective in cutting and transporting a soil sample in a short time period (36 ms) for all different soils studied in this experiment. The electro-pneumatic method was also capable of obtaining a consistent amount of soil sample with a coefficient of variation of less than 20% for any individual treatments in the experimental design. The electro-pneumatic soil sampling method is a viable candidate as a soil sampling system for on-the-go soil analysis.*

Keywords. *Precision agriculture, Real-time sensors, Soil sampling, Soil sensing.*

In the early part of the 20th century, scholars recognized the importance of variability in soil properties such as nutrient status and organic matter levels (Waynick and Sharp, 1919) and were advising farmers to map soil acidity and vary application rates of lime accordingly (Linsley and Bauer, 1929). Although over the next 50 years researchers continued to report on soil and yield variability (James and Dow, 1972), the mechanization of agriculture and the trend to larger implements led agricultural production in the opposite direction, with larger and larger areas being treated as a single unit. Within the last few decades, technological advances and the pressure of environmental concerns have revitalized the idea of defining smaller management units based on the individual characteristics of those units. Today, low-cost computers, real-time controllers, navigational systems, and developments in sensors have combined to provide the technology to make site-specific management a reality (Auernhammer et al., 1991).

However, the success of site-specific crop management depends on the ability to accurately characterize variability within fields. This characterization requires automated systems that will collect important soil, crop, and pest data. Nitrate ion selective field-effect transistors (ISFETs) have shown promise as a convenient and fast method for on-the-go soil nutrient measurements. The rapid response and low sample volumes requirement by the multi-sensor ISFET/FIA system make it a strong candidate for use in real-time soil nitrate sensing (Birrell and Hummel, 2000; 2001). The automation of real-time soil measurement based on ISFET sensors requires a rapid and precise soil sampling method.

This article reports on the initial development of an automated pneumatic soil sampling method based on pressurized air to sample and transport a consistent mass of soil for analysis. A pneumatic system could have some advantages over a mechanical sampling system, including simplicity, fast response, digital controllability, and accuracy in terms of collecting a precise mass of soil.

Literature Review

Several soil samplers have been developed by scientists to study not only soil properties, such as bulk density, porosity, nutrient content, moisture content, and organic matter content, but also other phenomena such as rooting characteristics of a soil profile, and soil classification. The samplers were either hand operated or powered by an energy source. Although many different soil collection methods for various soil conditions have been developed, most soil samplers are based on a soil coring tube. Several different insertion methods to force the tube into the soil have been developed, including manual insertion, hammering by weights, hydraulic, and other insertion methods (Powel, 1926; Buchele, 1961; Karahashi et al., 1987).

Coring tube samplers operate in a static mode and are not suitable for continuous soil sampling. Vertical augers are

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similar to coring tubes except that an auger is used to convey the soil sample to the surface (Sneath et al., 1992; Shapiro and Kranz, 1992; Wild et al., 2002). Auger samplers can be operated at various depths with less power than coring tubes and can provide an accurate sample volume. However, highly cohesive soils including wet clays may not part readily from the auger, and soils with large stones below the surface can lead to excessive damage to the machine (Sneath et al., 1989). These types of samplers are not suitable for continuous soil sampling.

Johnson (1981) invented a soil sampler based on a shank that rotated to engage the soil surface, collecting the soil in the internal slots. The sampler consisted of a hydraulic ram, a shank, baffles (initial catch bins), a secondary compartment, and a primary compartment (storage unit). To collect soil, the sampling device was forced into the sampling position by retracting a hydraulic ram. The shank then gouged out soil, with the soil been thrown through an aperture above the shank and falling between baffles. The hydraulic ram was then extended, tipping the soil into the secondary compartment. When the hydraulic ram was retracted again to collect the next sample, the first sample fell from the secondary compartment into the storage unit. When sufficient soil had been collected, it was transported into a bucket. This system operated as a discreet sampler since samples were not collected while the shank rotated up for unloading. It is unlikely that this soil sampler would work in clay soils, which are either wet and sticky, or dry and hard (Sneath et al., 1989). Another shank sampler invented by Behringer (1982) had a conveyer system, which was housed in an internal cavity, and continuously cut through the soil. A back plate, mounted behind the shank and slightly wider than the shank, moved the soil into an internal cavity. The conveyor transported the soil sample to the top of the device where the samples were collected for analysis. The sampling depth (0-90 cm) was controlled by moving the sampling plate, or adjusting the shank for different depths. It was also possible to estimate sample volume by monitoring the amount of soil conveyed by the conveyor. However, this device also may not be suitable for some soil conditions, particularly clay soils.

Rotating soil samplers are suitable for real-time soil sampling. Sneath et al. (1989) described a slotted single-disk cutter system where a horizontally mounted disk was driven into the ground and then rotated to obtain samples. A slot in the disk caught the soil sample, which was removed later for analysis. This system could be modified for high-frequency discrete sampling. Sneath et al. (1989) outlined a double-disk cutter system, which was contained within two disk openers running side by side to open a slot of several centimeters width in the soil. A horizontal ramp with a sharpened edge was placed between the disks at an angle to the soil surface. When the sampler was drawn forward, slices of soil were elevated over the ramp and then returned to the ground. A plunger system cut portions of the soil slice at a particular interval. The system was capable of sampling to a depth of 30 cm below the surface.

Slot cutters employ a moving wheel or a chain that is used to cut a slot in the ground. Adsett et al. (1999) tested a slot-cutter sampler based on a chain saw, in combination with a real-time nitrate sensing system. The sampler was capable of delivering a soil sample in 3 seconds. The consistency of the sample varied with soil type, forward speed, soil compaction, and water content. In some tests, the soil being conveyed was not completely released from the teeth of the slot cutter chain. Adamchuk et al. (1999) reported on the development of an automated soil sampling system for rapid determination of soil pH. The system consisted of a lever situated below a soil shank, which collected soil and then rotated to press the soil slurry against the surface of a pH electrode. They reported that the automated soil sampling system had lower analysis accuracy than standard laboratory methods for analysis of soil acidity. However, the system had the potential to improve soil map quality due to the higher sampling intensity.

The mechanical soil samplers discussed above operated either in quasi-static or dynamic mode and were generally unsuitable for continuous soil sampling due to problems related to soil conditions and/or the complexity of the sampling mechanisms and sampling speed restrictions. The interaction between the soil and the sampler devices caused several problems, including inconsistency of soil sample flow and clogging of soil within the sampling unit. Unfortunately, no research has been reported investigating the effects of soil type, soil moisture content, and soil compaction on the accuracy and precision of the mass of sample collected by the samplers. There is a need to develop a soil sampling system that can operate in various soil types and conditions to automate real-time soil analysis.

Objectives

The overall objective of this work is the development of an automated soil sampling system for integration into a real-time soil nutrient analysis system. An automated soil sampler must meet certain criteria for successful real-time soil analysis. First, the sampler must be able to collect a consistent sample mass or volume of soil at a known depth. The mass of soil must be known for calculation of the *in situ* soil nutrient levels from the measured concentrations in the soil extracts. Secondly, the sampler should be able to obtain a sample within 1 to 2 seconds. The sampling period should be small to minimize the time lag between obtaining a soil sample and determination of the final measurement result. The time lag is critical if the nutrient analysis system is utilized for real-time control of fertilizer applications. If the real-time soil nutrient analysis system is used for nutrient mapping only, then the time lag is not critical. Finally, the sampler should be able to operate in different soil types and conditions (soil moisture content, compaction level) and provide continuous sampling.

The present work focuses on the development of an automated electro-pneumatic (EP) soil sampling system. The primary objective of this laboratory study was to investigate the feasibility of an electro-pneumatic system as a sampling unit for real-time soil analysis. The specific objectives were:

- Investigate the effectiveness of positive air pressure as a cutting force through a soil column.
- Evaluate the effect of air pressure and pulse duration on the quantity of soil sample obtained.
- Determine the effects of soil moisture content, soil compaction level, and soil type on the quantity of soil sample obtained.

The eventual goal of this work is to integrate the EP system into a shank, and development of the Real-Time Electro-Pneumatic Sampler (REPS) for continuous soil sampling under dynamic field conditions.

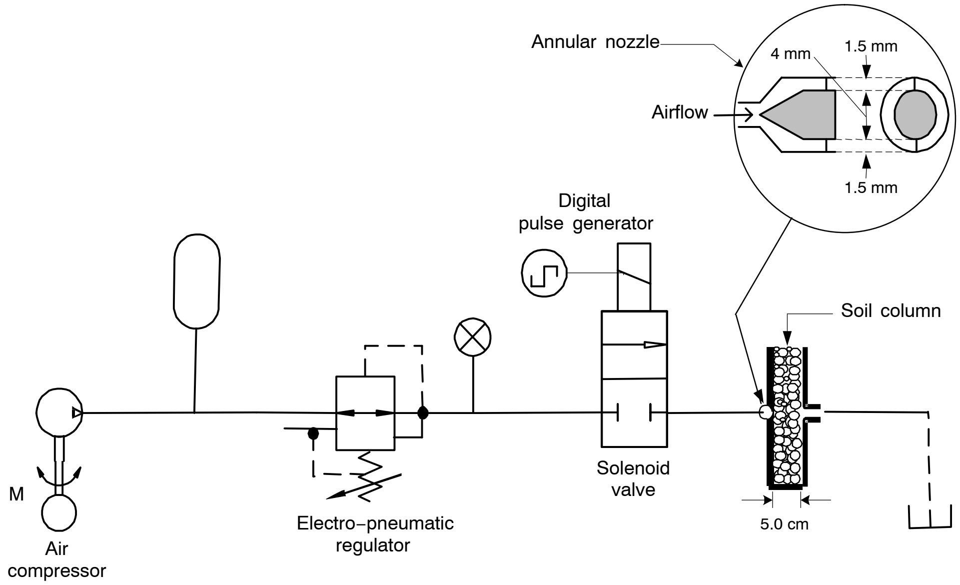

Figure 1. Diagram of the test apparatus for pneumatic soil sampling.

Equipment

A schematic diagram of the laboratory test setup of the pneumatic soil sampling system is shown in figure 1. A digitally controlled solenoid valve generated a high-pressure air pulse to cut through the soil placed in a 5 cm cylinder, and conveyed the sample along the delivery pipe into the container. An electro-pneumatic regulator (EPR) valve (ITV3000 series, SMC Corp., Indianapolis, Ind.) was used to regulate system air pressure. The valve was capable of regulating the pressure from 5 to 900 kPa in proportion to an analog electrical signal. A BASIC Stamp microcontroller controlled a two-position solenoid valve (SV) (two-port, direct operated, normally closed; VX22 series, SMC Corp., Indianapolis, Ind.) to direct a high-pressure pulse of known duration to the soil column. The high-pressure air was applied to the soil column through an annular nozzle (fig. 1). The annular nozzle directed the air to the outer edges of the nozzle for precise and effective cutting of the soil column.

Methodology and Experimental Design

The randomized, complete block experimental design included three soil types, three moisture content levels (10%, 18%, and 26%), three levels of compaction (low, medium, and high), and three levels of air pressure (550, 690, and 830 kPa). Therefore, 81 different treatments were tested, with five replicates of each treatment. The air pulse duration was 36 ms for all treatments.

Homogenous, ground, and sieved samples of three representative Iowa soils (Clarion, Nicollet, and Monona) and their respective physical properties (table 1) were obtained from the Iowa State University Agronomy Department. These soil series are taxonomically defined as fine-loamy, mixed, superactive, mesic Aquic Hapludolls. The Monona soil is a sandy clay loam soil, bordering on a sandy loam soil. The Clarion soil is a loam soil. Nicollet is also classified as a loam soil but is very close to a clay loam.

Three levels of moisture (10%, 18%, and 26% gravimetric moisture content) for all soils were prepared to investigate the effect of moisture content on soil sample mass. The gravimetric moisture content of the soil samples was determined using the oven drying method (Gardner, 1986). To obtain the desired moisture content, all soil samples were oven dried for 24 h at 103°C and water was added to obtain the desired gravimetric moisture level. Three levels of air pressure (550, 690, and 830 kPa) were used to determine the effect of air pressure on the mass of sample obtained.

In order to study soil compaction effects, three different pressures (18.1, 45.3, 87.1 kN/m^2) were applied on the surface of the soil samples within the cylinder (60 s duration). Therefore, three compaction levels (low, medium, and high) for each soil and moisture content level were produced. The dry bulk density for each treatment was measured and recorded. As the applied compaction force increased, the corresponding dry bulk density also increased for all soils. The dry bulk densities for the Monona, Clarion, and Nicollet soils at different moisture contents are shown in table 2.

To determine the significance of each variable involved in the experimental design (soil type, air pressure, moisture content, and compaction level) on the measured soil sample, an analysis of variance was performed using PROC ANOVA (SAS, 1999) for each soil individually and then repeated for the pooled soil data. For the individual soil analysis, air pressure, moisture content, and compaction level were the independent variables, with sample mass as the response (dependent) variable. In the pooled analysis, soil type was included as an independent variable.

For real-time nutrient measurement using ion-selective field-effect transistors (ISFETs), it is important that the soil/extractant ratio be constant, or that this ratio can be accurately determined. Any variation in the ratio, due to inaccurate determination of either soil or extractant amount, will affect the estimate of *in situ* soil nitrate concentration. The amount of soil obtained during the laboratory tests was

Table 1. Physical properties of Monona, Clarion, and Nicollet soils.

Soil Type	Sand (g/kg)	Clay (g/kg)	Silt (g/kg)
Monona sandy clay loam	580	210	210
Clarion loam	384	196	420
Nicollet loam	316	254	430

Table 2. Bulk densities of three different compaction levels for all treatments.

Moisture Content (%)	Soil Type	Bulk Density (g/cm^3), dry basis		
		Low Compaction	Medium Compaction	High Compaction
10	Monona	1.32	1.35	1.39
	Clarion	1.31	1.36	1.4
	Nicollet	1.36	1.4	1.50
18	Monona	1.38	1.53	1.61
	Clarion	1.36	1.44	1.64
	Nicollet	1.54	1.62	1.79
26	Monona	1.15	1.24	1.31
	Clarion	1.16	1.19	1.32
	Nicollet	1.21	1.29	1.34

affected by the air pressure and moisture content. If the significance and weight of these variables can be determined, this information can be used to correct for their effects. Therefore, the PROC REG procedure (SAS, 1999) was used to model the relationship between the sample mass and the independent variables (air pressure, moisture content, and compaction) for each soil type and for the pooled soil data. All statistically significant (α = 0.05) main variables and their interactions were included in the final regression model.

Results and Discussion

Preliminary tests were conducted to determine the effectiveness of high-pressure air as a cutting force. The minimum air pressure required for cutting and transporting the soil sample through the soil profile was 100 kPa (15 psi) for all soil types and conditions (data not shown). Additional tests were performed to determine the minimum pulse duration. Tested pulse durations ranged from 18 ms to 1 s. Longer pulse durations resulted in soil erosion and collapse of the soil into the center of the sample channel, whereas at shorter pulse durations, the diameter of sample channel remained constant. These preliminary trials provided the basis for the selection of the pressure range (550 to 830 kPa) and pulse duration time (36 ms) for the experimental tests. The laboratory tests were conducted to investigate the effect and significance of air pressure, soil moisture content, soil compaction, and soil type on the quantity of soil sample obtained.

The mass of soil transported to the container during a single air pulse was measured and recorded for all soil conditions. The mean sample mass and standard deviations for all treatments studied in this experiment are given in table 3. Mean soil sample mass varied from 7.28 to 15.4 g for the Monona soil, depending on soil moisture content, soil compaction level, and air pressure. The standard deviation varied from 0.27 to 1.76 g, and the coefficient of variation (CV) varied from 1.74% to 15.2%. For the Clarion soil, the mean soil mass varied from 8.4 to 11.8 g, with standard deviations of 0.25 to 2.19 g and CVs ranging from 2.45% to 18.6%. Similarly, mean soil sample mass varied from 7.36 to 12.8 g for the Nicollet soil (standard deviation of 0.11 to 2.29 g and CV of 1.38% to 12.6%) depending on soil moisture content, soil compaction level, and applied air pressure.

Analysis of variance was performed to determine significance of each independent variable (air pressure, moisture content, and compaction) on the sample mass collected for each soil type. For all three soils, the effects of moisture content and air pressure on sample mass were highly significant (α = 0.05), while compaction level was not significant. When all soil data were pooled, the effects of soil type, air pressure, and moisture content on sample mass were all highly significant, while compaction was still not significant.

Effect of Air Pressure on Sample Mass

The ANOVA showed that air pressure had a significant effect (α = 0.05) on the sample mass for all soil types. The mean mass values at different air pressures for each soil type and for the pooled data are shown in figure 2. An increase in air pressure level yielded a corresponding increase in the sample mass for all soil types. The standard deviations (shown by the error bars) represent the overall standard deviation. This included the variance due to the difference in treatment means (soil moisture content and compaction level for fig. 2) and random error. Therefore, the standard deviations shown in figures 2 through 5 are conservative. If variance due to treatment effects were excluded, the standard deviations would generally be less than 50% of the values shown. In general, the standard deviations were not greatly affected by air pressure. Mean sample mass varied from 9.86 to 11.99 g, depending on soil type and air pressure level.

Table 3. Mean sample mass (g) and standard deviation (in parentheses) for all laboratory test treatments.

Moisture Content (%)	550 kPa Applied Air Pressure			690 kPa Applied Air Pressure			830 kPa Applied Air Pressure		
	Low Compaction	Medium Compaction	High Compaction	Low Compaction	Medium Compaction	High Compaction	Low Compaction	Medium Compaction	High Compaction
Monona soil									
10	13.50 (0.45)	13.80 (1.37)	11.70 (1.06)	12.40 (1.30)	12.70 (1.76)	11.40 (0.36)	14.00 (1.19)	15.40 (0.27)	13.40 (0.83)
18	8.42 (0.76)	8.50 (0.56)	7.28 (0.97)	8.44 (1.06)	8.34 (0.32)	8.16 (1.24)	9.14 (0.75)	10.40 (1.33)	9.28 (1.07)
26	10.70 (0.74)	10.20 (0.69)	11.90 (1.29)	10.70 (1.04)	10.90 (0.91)	12.50 (1.07)	11.20 (0.61)	12.10 (1.15)	13.00 (1.45)
Clarion soil									
10	10.40 (0.87)	9.50 (0.1)	10.30 (0.85)	10.10 (1.06)	9.12 (0.65)	11.80 (2.19)	11.40 (1.78)	11.00 (0.95)	11.50 (1.30)
18	9.20 (0.55)	10.00 (1.29)	8.40 (1.01)	10.10 (1.06)	9.12 (0.65)	11.80 (2.19)	10.20 (0.25)	11.00 (0.63)	10.80 (0.56)
26	11.30 (0.80)	11.00 (0.91)	9.68 (0.83)	12.80 (0.88)	10.50 (0.69)	10.50 (1.68)	12.20 (0.99)	11.60 (1.20)	11.30 (1.17)
Nicollet soil									
10	10.70 (0.79)	10.90 (0.19)	10.40 (0.40)	10.50 (0.41)	12.00 (1.23)	12.80 (2.29)	10.50 (0.73)	13.00 (1.24)	12.30 (0.66)
18	8.46 (0.54)	9.46 (1.04)	8.24 (0.11)	8.74 (0.67)	7.36 (0.74)	7.54 (0.63)	9.74 (0.89)	7.88 (0.98)	8.38 (1.01)
26	10.00 (0.48)	10.30 (0.62)	10.40 (1.31)	11.10 (0.93)	10.50 (1.13)	12.00 (1.21)	10.70 (0.55)	11.00 (0.70)	12.30 (1.61)
Pooled data									
10	11.51 (1.60)	11.41 (2.07)	10.79 (0.99)	11.04 (1.39)	11.27 (2.00)	12.02 (1.81)	11.97 (1.94)	13.14 (2.03)	12.37 (1.22)
18	10.67 (0.83)	10.49 (0.78)	10.64 (1.43)	11.54 (1.29)	10.64 (0.88)	11.69 (1.52)	11.37 (0.96)	11.57 (1.07)	12.19 (1.50)
26	8.69 (0.69)	9.33 (1.14)	7.97 (0.91)	9.11 (1.17)	8.27 (0.93)	9.17 (2.39)	9.69 (0.77)	9.75 (1.68)	9.49 (1.33)

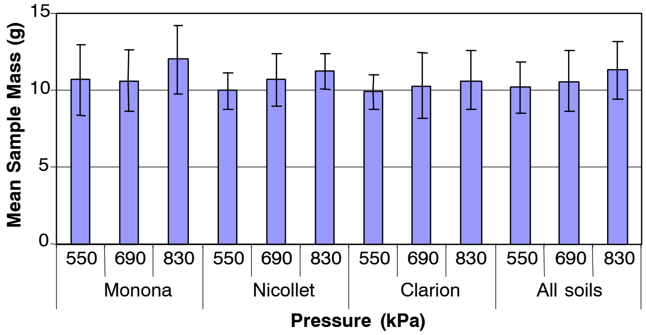

Figure 2. Air pressure effect on soil sample mass for different soils (45 samples at different moisture contents and compaction levels) and for all soils (135 samples). Error bars represent standard deviations.

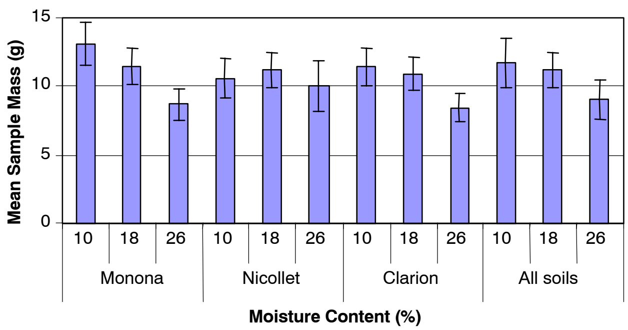

Figure 3. Effect of soil moisture on soil sample mass for different soils (45 samples at different pressures and compaction levels) and for all soils (135 samples). Error bars represent standard deviations.

Effect of Moisture Content on Sample Mass

Moisture content also had a significant effect (α = 0.05) on the sample mass for all soils. The effects of moisture content on the mean sample mass for each soil and for all soils are shown in figure 3. There was a significant decrease in the mean soil sample mass with an increase in moisture content for the Monona and Clarion soils, but not for the Nicollet soil or for the pooled soil data. Mean sample mass varied from 8.42 to 13.14 g depending on soil type and moisture content level. Although there was a reduction in the standard deviations for the pooled data as moisture content increased, the standard deviations were not greatly affected by moisture content for individual soil types.

During laboratory tests, soil accumulated around the outlet port of the cylinder. While the airflow through the orifice cut through the soil column within the cylinder, it also pushed some soil around the outlet port. The outlet port consisted of a circular orifice in the cylinder wall directly opposite the air inlet nozzle. The orifice was connected to an outlet tube. This soil accumulation reduced the outlet passage area into the collection container and reduced the mass of soil samples at high moisture contents. Soil cohesion increased soil accumulation around the outlet port at higher moisture contents, which decreased collected sample mass.

Effect of Compaction on Sample Mass

Surprisingly, compaction did not have a significant effect (α = 0.05) on the mass of soil samples for either the individual soils or the pooled soil data (fig. 4). There was very little difference in the mean sample mass at different compaction levels. However, the standard deviations and coefficients of variance increased slightly as the compaction level increased. Mean sample mass varied from 10.05 to 11.38 g depending on soil type and compaction level. There was an increase in standard deviation as compaction level increased for the pooled soil data and for the individual soils, except for the Nicollet soil.

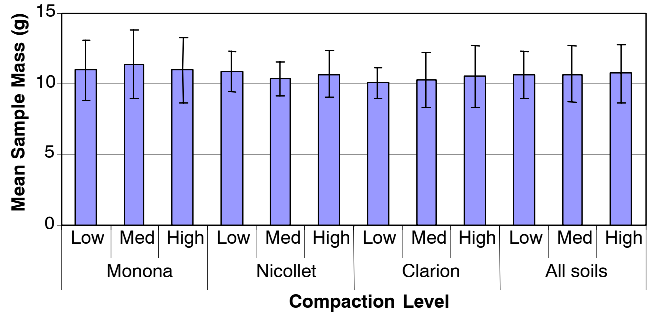

Figure 4. Effect of compaction on soil sample mass for different soils (45 samples at different pressures and compaction levels) and for all soils (135 samples). Error bars represent standard deviations.

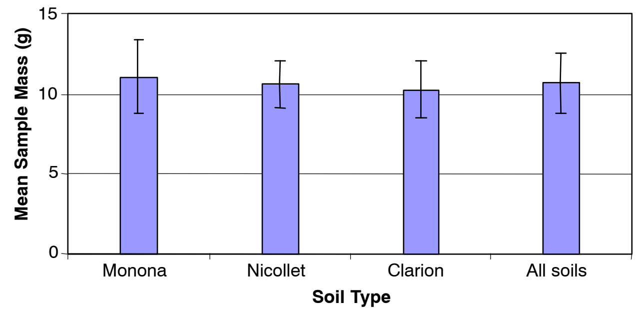

Figure 5. Effect of soil type on soil sample mass (each soil contains 135 samples at different moisture contents, compaction levels, and air pressure levels). Error bars represent standard deviations.

Effect of Soil Type on Sample Mass

When all treatments were pooled, soil type significantly affected the mean sample mass, as expected (fig. 5). Monona, the lightest soil and with less clay, had the highest sample mass standard deviation and coefficient of variance. On the other hand, Nicollet, the heaviest soil, had the smallest sample mass standard deviation and coefficient of variance. This was most likely a result of soil particle size differences between the light and heavy soils. Mean sample masses were 11.69 g, 10.69 g, and 10.27 g for the Monona, Nicollet, and Clarion soils, respectively.

Calibration for Soil Moisture Correction

Regression analysis (PROG REG) was used to develop calibration models for prediction of sample mass for each soil type (and pooled data) at different moisture contents, air pressure levels, compaction levels, and soil type (pooled data only), and their interactions. The final models only included parameters that were significant at the 5% level. The calibration model results for the Monona, Nicollet, and Clarion soils are shown in table 4.

In the case of the pooled data, soil type, moisture content, and air pressure were significant. The model root mean square error (RMSE) was 1.45 g (mean sample mass = 10.66 g), and the correlation coefficient was 0.42. The linear calibration model for the pooled data is as follows:

$$M = 11.705 - 0.412ST - 0.167MC + 0.02785P \quad (1)$$

where

M = sample mass (g)
ST = soil type (1, 2, 3)
MC = moisture content (%)
P = air pressure (kPa).

Table 4. Calibration model results for prediction of soil sample mass for the Monona, Nicollet, and Clarion soils.

Soil Type	R^2	RMSE (g)	Mean Mass (g)	Model Parameters[a]
Monona sand clay loam	0.70	1.25	11.09	Moisture content, air pressure
Nicollet loam	0.12	1.36	10.61	Air pressure
Clarion loam	0.51	1.26	10.27	Moisture content, air pressure

[a] The final models only included parameters significant at the 5% level.

Moisture content and air pressure were included in both the Monona and Clarion prediction models, while air pressure was the only significant predictor for the Nicollet soil. The predictive capability of regression was relatively good for the Monona (RMSE = 1.25 g, R^2 = 0.70) and Clarion soils (RMSE = 1.26 g, R^2 = 0.51), while it was very poor for the Nicollet soil (RMSE = 1.36, R^2 = 0.12). Moisture content and air pressure level provided a good prediction of soil sample mass for all soils except Nicollet. The high clay content of the Nicollet soil (clay/sand ratio of 0.80) may have affected soil sample mass prediction. The Monona soil had a wider range in soil sample mass as compared to the other two soils.

The coefficients of determination (R^2) reported above are for individual treatment replications. If treatment means, instead of individual replications are used, the R^2 values increase to 0.84, 0.81, and 0.89 for Monona, Clarion, and pooled soil data, respectively. However, the R^2 for the Nicollet soil is not substantially changed.

The regression analysis showed that moisture content and air pressure could be used to predict the expected sample mass. This dependency on two variables provides the flexibility to maintain a consistent soil/extractant ratio by changing air pressure as soil moisture content varies, or more likely, using the regression analysis to calculate the actual soil/extractant ratio under different conditions. Moisture content and air pressure level provided a fairly good prediction of sample mass for all soils except the Nicollet soil, which had the highest clay/sand ratio. For the Monona and Clarion soils, it is possible to make corrections for different moisture contents based on the information from linear regression analysis, although this could not be justified for the Nicollet soil.

Conclusions

An automated electro-pneumatic soil sampling method (EP) utilizing pressurized air for sample collection was developed and tested in a laboratory setting. Preliminary laboratory results suggest that pressurized air was effective in cutting and transporting soil samples for all soils studied in this experiment. In laboratory tests, the EP method was capable of obtaining a relatively consistent soil sample mass regardless of soil type and compaction level at fixed moisture contents. The electro-pneumatic soil sampling system was capable of obtaining a soil sample within 36 ms with a coefficient of variation of less than 30% for all treatments in the experimental design. The effects of soil type, moisture content, and applied air pressure on the mass of sample collected were highly significant (α = 0.05), while the effect of compaction was not significant. The regression results showed that moisture content and air pressure level provided a relatively good prediction of the sample mass. Therefore, correction factors are possible to account for different soil moisture contents. The electro-pneumatic soil sampling method has the potential to be used in a real-time soil nutrient analysis system.

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