AN ON-THE-GO SOIL SAMPLER FOR AN AUTOMATED SOIL NITRATE MAPPING SYSTEM

K. J. Sibley, J. F. Adsett, P. C. Struik

ABSTRACT: An automated on-the-go soil sampler was developed as part of a soil nitrate mapping system that collects data for precisely analyzing small-scale variation in soil NO$_3$-N. An essential requirement of the sampler is the ability to reliably collect a soil sample of known “weight” (mass). It was hypothesized that if a uniform bulk density sample could be collected in a device of fixed volume, then the mass of the sample would be known and constant. The sampler employs a woodsaw blade to cut a 15 cm deep slot in the soil at a sampling location as it travels forward and to throw a spray of finely chopped soil into a fixed-volume pocket milled into the surface of an automatically positioned flat-belt transfer conveyer. Performance testing of the sampler was conducted in five fields. Coefficient of uniformity (CU) for sample bulk density was 92.9%, which produced less than a 5.5% deviation in sample delivered weight (DW) in 83.6% of the cases. Mean DW error was 10.9% and DW CU was 82.0%, mostly due to localized high clay content in three of the fields. Mean pocket fullness (PF) was 89.9%, and PF CU was 83.6%. Pocket fullness was linearly correlated with DW ($R^2 = 0.979$, $n = 140$). It was concluded that the sampler’s “uniform bulk density” design principle was validated for all intents and purposes of field use. Delivered weight uniformity, particularly when sampling in clayey soils, should be increased by further improving the design.

Keywords. Ion-selective electrode, Precision agriculture, Rapid soil sampling, Soil bulk density, Soil nitrate measuring.

Precision agriculture offers an exciting opportunity to use highly advanced technology for better agriculture. The ultimate goal of such technology is to enable farmers to more intensely and precisely analyze variations in field conditions throughout the growing season, in correlation with environmental and crop response data, in order to make the most sound and site-specific management decisions possible. This ability is offering new production efficiencies to farmers, while at the same time offering assurances to the public that agricultural practices are being conducted in the most environmentally friendly way.

A soil nitrate mapping system (SNMS) (fig. 1) will be one such technology that can contribute to precision agriculture as it provides a way to collect the data necessary to analyze the variation in soil NO$_3$-N. The SNMS consists of six sub-assemblies (as labeled in fig. 1): (1) soil sampler sub-assembly, (2) soil metering and conveying sub-assembly, (3) nitrate extraction and measurement sub-assembly, (4) auto-calibration sub-assembly, (5) control sub-assembly, (6) GPS sub-assembly. The system automatically collects a soil sample at a depth of 0 to 15 cm, mixes it with water, and directly analyzes it electrochemically for nitrate concentration in real-time (6 s) using a nitrate ion-selective electrode (NO$_3$-ISE) as the analysis instrument. Additionally, global positioning system (GPS) geo-referenced data are simultaneously recorded at each sampling location to enable a nitrate map to be created for the field. The system can be used to analyze soil samples automatically while on-the-go, or manually while stationary by hand-placing samples into the nitrate extraction and measurement sub-assembly. It is envisioned that the SNMS will eventually be used in practice as (1) a tractor-mounted version (fig. 1) and (2) a “suitcase” version comprising a portable and modified combination of the nitrate extraction and measurement sub-assembly, auto-calibration sub-assembly, and control sub-assembly used in combination with a back-pack GPS (not shown).

From its beginnings as a first prototype (Adsett, 1990; Adsett and Zoerb, 1991), the SNMS has undergone several developmental iterations. The use of an NO$_3$-ISE in this type of application has been extensively tested in the laboratory (Thottan et al., 1994; Thottan, 1995; Brothers et al., 1997). Development and preliminary field testing of the five initial sub-assemblies and their integration into one complete system followed (Thottan, 1995; Adsett et al., 1999). In 2001, a completely new electronics and control system that incorporated the GPS sub-assembly was added.

Although the “soil sampler” (combination of sub-assemblies 1 and 2) was first reported by Thottan (1995) and Adsett et al. (1999), detailed descriptions of the design principle, its development and operation, and preliminary field-testing in 1994 were never reported, nor was it ever subjected to comprehensive field testing. At that time, the focus was only on getting it to the point where it worked well enough to enable development of the other sub-assemblies of the SNMS, which were experiencing difficulties, to continue. In 2006, the next step in the soil sampler’s development was undertaken as comprehensive field performance testing, which is the work reported in this article.
Many vehicle-mounted soil sampling devices are mentioned in the literature, all having varying degrees of success. Most are based on the traditional soil coring concept. Schickendanz et al. (1973), Ginn et al. (1978), Chandler and Savage (1979), and White (1982) all describe hydraulically activated coring devices mounted to either the front, side, or rear of a tractor. These devices all collect undisturbed individual core samples, but the tractor must be stopped, their sampling rates are low, and they often eject incomplete cores. Wrenn et al. (1982) describes a tractor-mounted sampler that collects a core and releases it on the ground for manual collection. None of the devices have any mechanism for automatically transferring the samples onward for analysis, as is required for automated on-the-go soil analysis.

Devices for collecting continuous samples consist of rotating tines (Johnson, 1981), subsoiler-type blades with elevators (Behringer, 1982), slotted disks and powered augers (Sneath et al., 1989), and chain cutters (Sneath et al., 1989; Adsett, 1990). These devices generally sample the 30 to 100 cm zone, have high draft requirements (45 to 75 kW), have problems with clogging in wet and clayey soils, are susceptible to stone damage, are subject to jamming due to silicates glazing from heat generation during sampling, or have problems coping with surface trash.

Lüttingen (2000) developed a GPS-equipped, auger-type system that enables automatic control of precise depth under varying field conditions when collecting soil samples. The system was reported to work well. However, like the coring devices, it must also stop at each sampling location, and soil is collected in a container for later analysis.

As part of an investigation into the feasibility of an on-the-go soil K and NO$_3$-N mapping system, Adamchuk et al. (2002a) performed laboratory tests on four commercially available NO$_3$-ISEs to simulate the direct soil measurement technique of an automated soil pH measurement system developed by Adamchuk et al. (1999, 2002b). The soil pH measurement system uses a toolbar-mounted shank with an attached sampling mechanism to scoop soil (approx. 5 to 10 g at a 10 cm depth) and bring it into firm contact with the sensing membrane of the electrode being used for analysis. During sampling, the mechanism is positioned 5 mm below the shank to enable soil collection while leaving a small gap to reduce interference by large soil particles and small rocks. A GPS is used to geo-reference the sampling location. In the laboratory, Adamchuk et al. (2002a) manually re-moistened previously air-dried soil samples and pressed them into contact with the sensing membrane of each NO$_3$-ISE to determine NO$_3$-N concentration (liquid basis of mg L$^{-1}$ reported as ppm). These results were compared to a standard cadmium reduction laboratory analysis technique to give an indication of the accuracy of the NO$_3$-ISEs. For individual soil samples, $R^2$ values ranging from 0.38 to 0.63 were obtained, depending on the ISE, while averaging of three repeated measurements yielded $R^2$ values ranging from 0.57 to 0.86. It was concluded that it is feasible to use an NO$_3$-ISE for measuring soluble nitrate concentration of naturally moist soil samples, but one of the main limitations of the proposed method reported was difficulty in maintaining high-quality contact between soil and electrode. We note as well that use of the proposed method in the field in combination with the pH measurement system’s soil sampling mechanism would not enable the NO$_3$-N content (mg kg$^{-1}$) of the sample to be directly computed since the “weight” (mass) of the soil sample would not be known.

Kataoka et al. (2004) developed and laboratory-tested an on-the-go soil sampling system that consists of three parts: (1) roto-tiller, (2) soil transport conveyor, and (3) soil can collection apparatus. As the tractor moves forward, the roto-tiller throws pulverized soil rearward onto a flighted plastic soil-transport conveyor, which subsequently dumps the soil into cans being moved transversely beneath its outlet end with a typical canning factory-type round-belt conveyor. Sampling depth is up to 20 cm. Sampling location is recorded with a GPS mounted on the tractor. The system was reported to have good performance in generating pulverized soil. However, there were issues with the soil conveyor becoming blocked because too much soil was thrown onto the conveyor.
to be adequately handled at certain conveyor speeds. The system was only tested in a soil bin containing pre-roto-tilled silt-loam soil having a moisture content of 21.1% and a wet density of 1.32 g cm⁻¹. The study was conducted to understand the performance of the system at various combinations of forward travel speeds, roto-tiller rotational speeds, and transport conveyor speeds. The ability and performance of the soil can collection apparatus to collect soil was not reported. In addition, the system does not mass the samples, and the samples are intended to be taken to a laboratory for analysis.

**DESIGN PRINCIPLE OF THE SOIL SAMPLER**

An essential requirement of the SNMS is the ability to reliably collect a soil sample of known “weight” (mass) for analysis while on-the-go. This is the job of the soil sampler. During calculation of NO₃-N content (mg kg⁻¹) of a soil sample analyzed by the SNMS, a constant soil to extractant (water) ratio representing the dilution factor during nitrate extraction and concentration measurement is used (Thottan, 1995). Thus, it is required to know the mass of the soil sample in addition to the volume of the extractant. Directly massing (weighing) a very small soil sample in the range 10 to 15 g accurately on-the-go is extremely difficult, if not virtually impossible. Therefore, it was decided to utilize the simple physics relationship between mass, volume, and density (eq. 1) in order to estimate the mass of a sample:

\[ m_s = \rho_s \cdot V_s \]  

where \( m_s \) is the sample mass (g), \( \rho_s \) is the sample bulk density (g cm⁻³ w.b.), and \( V_s \) is the sample volume (cm⁻³).

It was hypothesized that if a uniform bulk density sample could be collected in a device of fixed volume, then the mass of the sample would be known and constant. This is the principle upon which the design of the SNMS’s soil sampler was based.

**DESIGN CONCEPTS AND DESCRIPTION OF THE SOIL SAMPLER**

To overcome many potential mechanical complexities during construction and operation of the soil sampler, two design concepts were conceived: (1) breaking the sampling cycle into three linear processing steps (chop, collect, transfer), and (2) mechanically separating soil engagement from collection and transfer.

The sampler (fig. 2a), originally reported by Thottan (1995) and Adsett et al. (1999), employs a woodsaw blade powered by a hydraulic motor. The blade is mounted on a frame that can be hydraulically raised and lowered automatically and intermittently while on-the-go for sampling. During sampling, the blade is lowered into the soil and the frame is allowed to float to follow ground contours while the blade is allowed to swivel horizontally up to ±10° to accommodate slight deviations in travel path. A travel distance of approximately 0.5 m is required to collect a sample. The blade cuts a 15 cm deep slot as it travels forward, and throws a spray of finely chopped soil onto the head-end area of an automatically positioned flat-belt transfer conveyer (fig. 2b). This action is intended to create finely ground particles that allow samples having uniform bulk density be collected. The fine-ground particles also facilitate the subsequent nitrate extraction and measurement process. The conveyor belt has an oblong fixed-volume pocket milled into its surface to collect a sample from the soil particles landing on the conveyor. A specially designed scraper placed above the belt levels the soil sample in the pocket without compaction and removes excess soil from the belt as the belt moves to deliver the soil sample to the nitrate extraction and measurement sub-assembly of the SNMS. During delivery of the sample, the pocket stretches lengthwise as it passes around the conveyor’s tail-end roller to facilitate complete emptying of the pocket (like emptying an ice-cube tray). The GPS antenna is mounted directly above the blade on a mast. The operation of the sampler is controlled via an electronic control system.

The sampler can be operated in either fully automatic or semi-automatic mode. While operating in fully automatic mode, the distance between sampling locations is determined by a pulse counter mounted to the tractor’s front-right wheel hub. The operator sets the desired distance by adjusting the electronic control system. In this mode, the minimum distance between sampling points is governed by the travel speed in combination with the sample processing speed. While operating in semi-automatic mode, the operator drives to a desired sampling location and manually activates the control system to take a sample.

In this study, field testing of the SNMS’ soil sampler was conducted with the objectives of determining (1) the validity of the sampler’s “uniform bulk density” design principle, (2) the uniformity of pocket fullness, (3) the relationship between pocket fullness and delivered “weight” (mass), and (4) the uniformity of delivered weight. The scope of this study was limited to testing in five locally available field conditions, as described below.

**Figure 2. Soil sample collection procedure:** (a) soil sample collection apparatus setup, (b) soil sampler in action, and (c) delivered soil sample being collected into plastic bag for weighing.
Table 1. Field-specific conditions at time of sampling.

<table>
<thead>
<tr>
<th>Date</th>
<th>Field</th>
<th>Soil Group[a]</th>
<th>Crop</th>
<th>Surface Condition</th>
<th>Moisture Content[b] (w.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Oct</td>
<td>Banting</td>
<td>PGW52</td>
<td>Fallow</td>
<td>Bare to slightly weedy</td>
<td>13.3 to 17.2</td>
</tr>
<tr>
<td>17 Oct</td>
<td>F207S</td>
<td>DRT22, PGW52</td>
<td>Wheat</td>
<td>Stubble, high residue</td>
<td>20.1 to 27.6</td>
</tr>
<tr>
<td>18 Oct</td>
<td>F207N</td>
<td>PGW52</td>
<td>Wheat</td>
<td>Stubble, high residue</td>
<td>20.9 to 22.9</td>
</tr>
<tr>
<td>31 Oct</td>
<td>F206</td>
<td>TUO52</td>
<td>Switchgrass</td>
<td>Fresh plowed, disked</td>
<td>21.2 to 23.2</td>
</tr>
<tr>
<td>5 Nov</td>
<td>F102</td>
<td>PGW52</td>
<td>Rye</td>
<td>Bare, newly planted</td>
<td>16.3 to 20.3</td>
</tr>
</tbody>
</table>

[a] PGW52 = Pugwash 52; DRT22 = Debert 22; TUO52 = Truro 52.
[b] Moisture content range at sampling locations for 0-15 cm depth.

MATERIALS AND METHODS

FIELD SITES

In late fall of 2006, field testing was conducted in five fields on the Nova Scotia Agricultural College (NSAC) farm, Truro, Nova Scotia, Canada (45° 22′ N, 63° 16′ W). These fields were Banting field (Banting), field 207 south (F207S), field 207 north (F207N), field 206 (F206), and field 102 (F102). There were three soils groups, Pugwash 52 (PGW52), Debert 22 (DRT22), and Truro 52 (TUO52), present in these fields. The PGW52 soil group is a well to moderately well drained soil having 50 to 80 cm of friable, coarse loamy solum over firm, coarse‐loamy lower subsoil material with an average in‐situ bulk density of 1.25 g cm−3 in the Ap horizon. The DRT22 soil group is an imperfectly drained soil having 20 to 50 cm of friable, coarse loamy solum over firm, coarse‐loamy lower subsoil material with an average in‐situ bulk density of 1.41 g cm−3 in the Ap horizon. The TUO52 soil group is a well drained soil having 50 to 80 cm of friable, coarse‐loamy solum over loose, fine‐sandy lower soil material with an in‐situ bulk density of 1.50 g cm−3 in the Ap horizon. Full descriptions of these soils are well documented by Webb and Langille (1996).

The surface conditions of the fields at the time of sampling ranged from fresh plowed and disked to high‐residue wheat stubble. Moisture content (0 to 15 cm depth) in the fields ranged between 13.3% and 27.6% w.b. The field‐specific conditions are shown in table 1.

SOIL SAMPLING STRATEGY AND ANALYSES

It was planned to sample at five random locations in each of the five fields, with six repeated samples at each location, for a total 150 samples. However, only 140 samples were collected and analyzed. F207S had one bad sample due to a data processing error. In F207N, seven samples were not collected due to mechanical breakage of the PTO shaft driving the sampler’s hydraulic system, and two samples collected for weighing were inadvertently lost.

Two subsamples were collected simultaneously at each sampling location: one for bulk density and moisture content analyses, and the other to determine delivered weight. A special apparatus was designed and installed immediately above the conveyor pocket to hold one standard 125.5 mL aluminum gravimetric moisture analysis can (fig. 2a). During subsample collection, the sampling blade was run through the soil, creating a spray of finely chopped soil particles landing on the conveyor in the pocket area and filling the can (fig. 2b). A sample collected in the can was hand‐leveled off without compression using a flat wooden stick, and then sealed with the can’s cover. These samples were transported to the laboratory, immediately weighed, and then placed into a drying oven at 105°C for 24 h. Bulk density (BD) and moisture content (MC) were determined from these samples. A sample collected in the conveyor pocket was dumped through a plastic tube into a plastic bag and then sealed with the bag’s zip‐lock feature (fig. 2c). These samples were transported to the laboratory and immediately weighed to determine delivered weight (DW).

POCKET FULLNESS ASSESSMENT

To assess pocket fullness (PF), digital photographs were taken of each sample collected in the conveyor pocket. As the conveyor moved to deliver a sample, it was stopped by manually tripping the position switch. The photograph was then taken manually, holding the camera square to the conveyor surface. A typical photograph is shown in figure 3a. Each
photograph was then cropped close around the pocket, enlarged, enhanced (brightness and contrast) using photo editing software (Camedia Master 4.1, Olympus America, Inc., Center Valley, Pa.) to improve visual clarity, and then saved and printed in color on high-brightness white paper (fig. 3b). Each photo was then analyzed visually to determine PF according to equation 2:

\[
PF = \frac{[V_{pc} + V_{bc} + V_{pof} - V_{puf}]}{V_p} \times 100\% \tag{2}
\]

where

- \(V_p\) = unit volume of pocket
- \(V_{pc}\) = unit volume of pocket filled with soil
- \(V_{bc}\) = unit volume of belt area covered with soil
- \(V_{puf}\) = unit volume of pocket underfilled with soil
- \(V_{pof}\) = unit volume of pocket overfilled with soil

Individually, each cropped photo was overlaid with a 1.0 cm² grid-embossed transparent film (fig. 3c). Each grid on the film contained 100 units (1 mm² block). Measures of pocket area (\(A_p\)), pocket cover area (\(A_{pc}\)), belt cover area (\(A_{bc}\)), pocket underfilled area (\(A_{puf}\)), and pocket overfilled area (\(A_{pof}\)) on a unit basis were then made by manually counting and summing the number of blocks corresponding to each area. Each unit area was then multiplied by a corresponding estimated number of unit-layers of depth (\(D_i\)) to determine unit volume according to equation 3:

\[
V_x = A_x \cdot D_i \tag{3}
\]

where subscript \(x\) = \(p, pc, bc, pof,\) or \(puf\).

It was assumed that the pocket was four unit-layers deep (\(D_i = 4\)), soil on the belt was one unit-layer deep (\(D_i = 1\)), and overfilled areas were one unit-layer deep (\(D_i = 1\)). Underfilled areas had estimates of 1, 2, 3, or 4 unit-layers of depth (\(D_i = 1, 2, 3, 4\)) as visually assessed.

**STATISTICS AND DATA ANALYSES**

Description and quantification of the levels and distribution of BD, DW, and PF was performed using exploratory data analysis (EDA) techniques, and Minitab (Ver. 15.0, Minitab, Inc., State College, Pa.) and Excel (Ver. Prof. Ed. 2003, Microsoft Corp., Redmond, Wash.) software.

Descriptive statistics of interest were computed: mean, standard error of the mean (SEM), standard deviation (SD), coefficient of uniformity (CU), minimum (min), and maximum (max). The coefficient of uniformity was used to assess the consistency of performance, since in this study uniformity was contextually of more interest than variation, as described by the coefficient of variation (CV).

The distribution characteristics of the data sets were computed, and distribution goodness-of-fit was determined based on a combined analysis of data by probability plot and test statistic (D’Agostino et al., 1990) using the Anderson-Darling test in Minitab. Potential outliers identified from the histograms and probability plots were checked for data processing errors and possible sources of sampling error.

Correlation between variables was determined using Pearson’s correlation analysis. Sensitivity analyses were performed using deviation frequency plots, regression plots, and error calculations. For each regression, the validity of normal distribution and constant variance of the error terms assumptions were verified by examining the residuals, as described by Montgomery (2005).

All tests of significance were made at the 5% probability level unless otherwise noted.

**RESULTS AND DISCUSSION**

**EXPLORATORY DATA ANALYSES**

Histograms of the raw data sets (fig. 4) and probability plots (not shown) revealed that BD, DW, and PF had normal distributions. Several extreme values (potential outliers) residing in tails of the normal distribution plots were identified and investigated for data processing errors and possible sources of sampling error. No errors were found.

Descriptive statistics were then computed, as shown in table 2. The potential of trimming the data sets (at 10%) in order to reduce susceptibility of the results to the effects of the extreme values was investigated. Descriptive statistical values of the trimmed data sets were not substantially different from those of the raw data sets. The means were virtually identical, and the CUs were only between 1.7 and 3.7 percentage points higher. In the interest of being conservative in the assessment of sampler performance, all final analyses were completed using the raw data sets.

The degree of correlation between BD, DW, and PF is shown in table 3. The potential influence of soil moisture content (MC) on the other variables was also investigated by including it as an additional variable in the correlation analysis.

The correlation values indicate that a moderate influence (\(r \approx 0.6\)) of MC on BD, DW, and PF was evident, while a weak influence (\(r \approx 0.4\)) of BD on DW and PF was evident. However, with the correlation values for MC and BD being virtually the same as the other factors, columnwise respectively, and the fact that DW and PF are very highly correlated (\(r = 0.989\)), as expected, it is likely that the influence was more from autocorrelation (interdependence) than from independent influence. To investigate this possibility, a stepwise regression analysis was performed sequentially fitting linear additive models of PF, BD, and MC to DW. It was
Table 2. Descriptive statistics summary for bulk density, delivered weight, and pocket fullness.

<table>
<thead>
<tr>
<th>Field</th>
<th>Statistic</th>
<th>Bulk Density (g cm⁻³ w.b.)</th>
<th>Delivered Weight (g)</th>
<th>Pocket Fullness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banting</td>
<td>Mean</td>
<td>0.833</td>
<td>15.9</td>
<td>100.8</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>0.008</td>
<td>0.4</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.045</td>
<td>2.3</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>CU[¹]</td>
<td>94.7</td>
<td>85.4</td>
<td>88.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.759</td>
<td>9.3</td>
<td>67.3</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.944</td>
<td>19.3</td>
<td>117.3</td>
</tr>
<tr>
<td>F207S</td>
<td>Mean</td>
<td>0.726</td>
<td>12.4</td>
<td>80.9</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>0.008</td>
<td>0.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.041</td>
<td>2.5</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>CU</td>
<td>94.3</td>
<td>80.3</td>
<td>81.3</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.655</td>
<td>7.9</td>
<td>51.4</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.812</td>
<td>19.3</td>
<td>110.5</td>
</tr>
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<td>F207N</td>
<td>Mean</td>
<td>0.720</td>
<td>13.0</td>
<td>84.2</td>
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<tr>
<td></td>
<td>SEM</td>
<td>0.008</td>
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<tr>
<td></td>
<td>SD</td>
<td>0.036</td>
<td>1.7</td>
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<td></td>
<td>CU</td>
<td>94.9</td>
<td>86.6</td>
<td>88.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.614</td>
<td>9.3</td>
<td>62.1</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.776</td>
<td>16.3</td>
<td>98.9</td>
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<td>F206</td>
<td>Mean</td>
<td>0.790</td>
<td>12.8</td>
<td>83.2</td>
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<tr>
<td></td>
<td>SEM</td>
<td>0.005</td>
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<td>F102</td>
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<td></td>
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<td>0.030</td>
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</tr>
<tr>
<td></td>
<td>CU</td>
<td>96.1</td>
<td>89.3</td>
<td>90.1</td>
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<td></td>
<td>Min</td>
<td>0.692</td>
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<td>77.7</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.828</td>
<td>18.7</td>
<td>119.0</td>
</tr>
<tr>
<td>All data combined</td>
<td>Mean</td>
<td>0.769</td>
<td>13.9</td>
<td>89.9</td>
</tr>
<tr>
<td></td>
<td>SEM</td>
<td>0.005</td>
<td>0.2</td>
<td>1.2</td>
</tr>
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<td>SD</td>
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<td>14.7</td>
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<td>92.9</td>
<td>82.0</td>
<td>83.6</td>
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<td>119.0</td>
</tr>
</tbody>
</table>

Table 3. Pearson correlation values (*r*, *n* = 140) between bulk density, pocket fullness, delivered weight, and soil moisture content. All correlation values were significant at the 0.1% probability level.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Moisture Content</th>
<th>Bulk Density</th>
<th>Delivered Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>-0.666</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivered weight</td>
<td>-0.641</td>
<td>0.413</td>
<td></td>
</tr>
<tr>
<td>Pocket fullness</td>
<td>-0.645</td>
<td>0.375</td>
<td>0.989</td>
</tr>
</tbody>
</table>

found that PF explained 97.9% of the variation in DW, while BD and MC explained only an additional 0.2% and 0.1%, respectively. Therefore, it was concluded that BD and MC independently had very little influence on DW. This was expected due to the fine-chopping action of the blade mechanism and further confirms the validity of the sampler’s design principle.

**Bulk Density Uniformity**

As shown in table 2, the CUs among fields for soil sample BD ranged between 94.3% and 96.9%. Overall, the CU was 92.9% for all data combined. To determine whether this amount of variation had any practical effect on DW, a sensitivity analysis was conducted. First, the relationship between BD and DW was determined through regression analysis to be linear: \( DW = -0.591 + 18.868 \cdot BD; R^2 = 0.171, n = 140. \) This low \( R^2 \) value indicates that only a very weak relationship existed for all field conditions tested, and in practical terms the variation that did occur had less than a 5.5% deviation effect on DW most of the time. It was concluded that the sampler’s design principle was validated for all field conditions tested, and in practical terms the variation that did occur had less than a 5.5% deviation effect on DW most of the time. It was concluded that the sampler’s main design principle of “uniform bulk density” was validated for all intents and purposes of field use.

**Pocket Fullness Uniformity**

As shown in table 2, among fields, the PF means ranged between 80.9% and 100.8% and the CUs ranged between 81.3% and 90.1%. For all data combined, the mean PF was 89.9% and the CU was 90.1%. These results indicate good performance overall; however, the relatively large range in means and CUs among fields suggests that the level of performance was field-condition specific. As such, the results for the individual fields were examined more closely. Two of the fields, Banting and F102, had excellent performance, with means of 100.8% and 98.3% and CUs of 88.1% and 90.1%, respectively. The other three fields had only fair performance, with means and CUs among fields suggests that the level of performance was field-condition specific. As such, the results for the individual fields were examined more closely. Two of the fields, Banting and F102, had excellent performance, with means of 100.8% and 98.3% and CUs of 88.1% and 90.1%, respectively. The other three fields had only fair performance, with means and CUs ranging between 80.9% and 83.2% and 88.1% and 90.1% respectively. Therefore, it was concluded that BD and MC independently had very little influence on DW. This was expected due to the fine-chopping action of the blade mechanism and further confirms the validity of the sampler’s design principle.
content of soil, and (2) plant residue. Both issues caused “gouging out” of soil collected in the pocket to occur in varying degrees, as seen in figures 6 and 7. These figures show the lowest and highest, respectively, PF (DW) samples of the six samples at each location in F207S, the field where PF performance was observed to be the worst. “Gouging out” would occur when “blocky” soil particles or plant residue, whichever the case, caught on the scraper as the pocket traveled beneath it to level off the sample.

Localized high clay content (visual and feel-test assessed) was evident at several of the sampling locations in these three fields (particularly in F107S), despite being reported as having a friable, coarse loamy solum (Webb and Langille, 1996). This is not unusual, given the relatively large scale of soil classification maps (D. Langille, 2007, personal communication). When high clay content was encountered while sampling, it was observed that soil being thrown onto the pocket area of the belt by the blade tended to have a “blocky” versus “finely chopped” granulation (table 4). The varying degrees of blocky granulation are shown in figure 8.

Occasionally in fields F207S and F207N, a relatively long (3 to 5 cm) piece of plant residue would get thrown into the pocket with the soil (figs. 6b and 6d). However, most of the time any plant residue being thrown in was relatively finely chopped (fig. 8). In contrast to the worst range of performance, as presented for F207S in figures 6 and 7, it should be noted that figures 3b, 7a, and 7b are typical of the better range of performance observed in the other four fields (additional sets of figures not shown in the interests of brevity).
Table 5. Relationships between pocket fullness and delivered weight for the test fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Regression Equation[(^a)]</th>
<th>(R^2)</th>
<th>Delivered Weight([b])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banting</td>
<td>(DW = -3.3 + 19.0 \cdot PF)</td>
<td>0.975</td>
<td>15.7</td>
</tr>
<tr>
<td>F207S</td>
<td>(DW = -0.6 + 16.1 \cdot PF)</td>
<td>0.987</td>
<td>15.5</td>
</tr>
<tr>
<td>F207N</td>
<td>(DW = -1.2 + 16.9 \cdot PF)</td>
<td>0.955</td>
<td>15.6</td>
</tr>
<tr>
<td>F206</td>
<td>(DW = -0.9 + 16.5 \cdot PF)</td>
<td>0.971</td>
<td>15.6</td>
</tr>
<tr>
<td>F102</td>
<td>(DW = -0.9 + 16.3 \cdot PF)</td>
<td>0.969</td>
<td>15.4</td>
</tr>
<tr>
<td>All data combined</td>
<td>(DW = -1.2 + 16.8 \cdot PF)</td>
<td>0.979</td>
<td>15.6</td>
</tr>
</tbody>
</table>

\([a]\) Predicted delivered weight (g) at 100% pocket fullness.

\([b]\) Banting \(n = 30\); F207S \(n = 29\); F207N \(n = 23\); F206 \(n = 30\); F102 \(n = 30\); all data combined \(n = 140\). \(DW\) = delivered weight (g), and PF = pocket fullness (%).

POCKET FULLNESS AND DELIVERED WEIGHT RELATIONSHIP

The relationships between PF and DW for each field and all data combined were determined through regression analysis (table 5). All regression equations were linear, had very high \(R^2\) values, and the predicted delivered weights (DW) at 100% pocket fullness were nearly the same for each field. The equation for Banting looked to be somewhat different from the rest (\(I = -3.3\), \(S = 19.0\)), but in reality it was very close as the predicted DW at 100% PF was 15.7 g. A 0.1 g difference in DW from 15.6 g (all data combined predicted DW at 100% PF) results in an error of 0.6%, while a 0.2 g maximum difference (15.6 to 15.4 g) for F102 results in an error of 1.3%. These results indicate that DW was very highly correlated to PF and that the relationship was consistent over all field conditions tested.

DELIVERED WEIGHT UNIFORMITY

As shown in table 2, among fields, the DW means ranged between 12.4 to 15.9 g and the CUs ranged between 80.3% and 89.3%. For all data combined, the mean DW was 13.9 g and the CU was 82.0%. These results indicate good performance overall, and because of the very high degree of correlation between DW and PF, it can be concluded that the DW and PF results were highly similar. Therefore, the performance issues as discussed above for PF were the same for DW, and they do not require any further discussion here.

To determine the practical effects that this level of performance in DW would have on SNMS soil NO\(_3\)-N measurements, a sensitivity analysis was conducted. First, a mathematical calculation of potential error in NO\(_3\)-N measurement that could result from error in DW was made. It was determined that changes in NO\(_3\)-N measurement are directly proportional to changes in DW. Based on a full pocket having a DW of 15.6 g (from all data combined regression equation above), the mean DW of 13.9 g would result in a mean theoretical error in NO\(_3\)-N measurement of 10.9%.

Second, to determine how often it is likely that various degrees of error could occur, a frequency plot of the measured DW deviations from full pocket weight (15.6 g) was prepared, as shown in figure 9. It was found that the sampler delivered within \(\pm 10\%\) of full weight in 37.9% of the cases, within \(\pm 20\%\) of full weight in 70.8% of the cases, and deviations greater than 20% occurred in 29.3% of the cases.

A mean DW error of 10.9% is likely acceptable for most practical field use situations; however, a CU of 82.0% is not. These results clearly indicate that the DW uniformity of the sampler, particularly in clayey soil conditions, should be increased by improving the design.

SUMMARY AND CONCLUSIONS

An automated on-the-go soil sampler was developed as part of a soil nitrate mapping system that collects data for precisely analyzing small-scale variation in soil NO\(_3\)-N. An essential requirement of the sampler is the ability to reliably collect a soil sample of known “weight” (mass). It was hypothesized that if a uniform bulk density sample could be collected in a device of fixed volume, then the mass of the sample would be known and constant. The sampler employs a wood saw blade to cut a 15 cm deep slot in the soil at a sampling location as it travels forward and to throw a spray of finely chopped soil into a fixed-volume pocket milled into the surface of an automatically positioned flat-belt transfer conveyor. The field performance of the sampler was tested in five field conditions to determine the validity of the sampler’s “uniform bulk density” design principle, the uniformity of pocket fullness, the relationship between pocket fullness and delivered “weight” (mass), and the uniformity of delivered weight. Based on the results of this study, the following conclusions were made:

**Bulk Density Uniformity:** The overall uniformity in BD of 92.9% for all field conditions tested was excellent, and in practical terms the variation that occurred over all field conditions had less than a 5.5% deviation effect on DW in 83.6% of the cases. The sampler’s main design principle of “uniform bulk density” was validated for all intents and purposes of field use.

**Pocket Fullness Uniformity:** Among fields, PF means ranged between 80.9% and 100.8% and the CUs ranged between 81.3% and 90.1%. For all field conditions data combined, the mean PF was 89.9% and the CU was 83.6%. Pocket fullness uniformity was found to be field-condition specific, related mostly to localized high clay content at several sampling locations in three of the fields.

**Pocket Fullness and Delivered Weight Relationship:** Delivered weight was consistently very highly correlated to

The debate with the current design, then, would be whether design improvements should strive to obtain a consistently delivered known “weight” (mass) of soil at some percentage of pocket fullness (i.e., a not quite full pocket) or a consistently full pocket of known weight. In either case, it does not really matter what the relative magnitude of the weight is as long as it is known and consistent.

Therefore, it is important that the current design of the sampler be improved to either (1) ensure better consistency in DW if the “uniform bulk density” design principle is continued to be used, or (2) incorporate a method of “weighing” individual samples as they are being delivered.
Delivered Weight Uniformity: Overall, the sampler had a mean DW error of 10.9% and a CU of 82.0%. Delivered weight uniformity was found to be field-condition specific, related mostly to localized high clay content at several sampling locations in three of the fields. Delivered weight uniformity of the sampler, particularly when used in clayey soils, should be increased by improving the design.

Acknowledgements

Funding in 1993-1994 for Development of a Tractor Mounted Soil Sampler was provided by the Nova Scotia Department of Agriculture and Marketing under their Research and Innovative Demonstration Program. Thanks are extended to Doug Burris, Grant Terry, and Fred Hampton (research technicians), and Steven Creelman, Brian Verboom, and Jacob Thottan (research assistants) with the former Agricultural Engineering Department of the Nova Scotia Agricultural College for their technical assistance during the early work. Funding for this study, Field Testing and Application of a Soil Nitrate Mapping System, in 2006-2007 was provided by the Nova Scotia Department of Agriculture under their Technology Development Program. A special thank you is given to Scott Read and Daryl Hayes, research technicians with the current Engineering Department of the Nova Scotia Agricultural College, for their help with construction of test apparatus, and collection and analysis of soil samples during this later field work.

References


Nomenclature

\[ NO_3^- = \text{nitrte nitrogen} \]
\[ DW = \text{delivered sample weight (g)} \]
\[ PF = \text{conveyor pocket fullness (\%)} \]
\[ SNMS = \text{soil nitrate mapping system} \]
\[ NO_3^- - \text{ISE} = \text{nitrte ion-selective electrode} \]
\[ GPS = \text{global positioning system} \]
\[ m_s = \text{mass of sample (g)} \]
\[ \rho_s = \text{bulk density of sample (g cm}^{-3} \text{w.b.)} \]
\[ V_s = \text{volume of sample (cm}^{-3} \text{)} \]
\[ \text{Banting} = \text{Banting field} \]
\[ \text{F207S} = \text{field 207 south} \]
\[ \text{F207N} = \text{field 207 north} \]
\[ \text{F206} = \text{field 206} \]
\[ \text{F102} = \text{field 102} \]
\[ \text{PGW52} = \text{Pugwash 52 soil group} \]
\[ \text{DRT22} = \text{Debert 22 soil group} \]
\[ \text{TUO 52} = \text{Truro 52 soil group} \]
\[ \text{MC} = \text{moisture content (\% w.b.)} \]
\[ \text{BD} = \text{bulk density (g cm}^{-3} \text{w.b.)} \]
\[ V_p = \text{unit volume of conveyor pocket} \]
\[ V_{pc} = \text{unit volume of conveyor pocket filled with soil} \]
\[ V_{bc} = \text{unit volume of conveyor belt area covered with soil} \]
\[ V_{puf} = \text{unit volume of conveyor pocket underfilled with soil} \]
\[ V_{pof} = \text{unit volume of conveyor pocket overfilled with soil} \]
\( A_p \) = unit conveyor pocket area
\( A_{pc} \) = unit conveyor pocket area covered with soil
\( A_{bc} \) = unit conveyor belt area covered with soil
\( A_{puf} \) = unit conveyor pocket underfilled area
\( A_{pof} \) = unit conveyor pocket overfilled area
\( D_i \) = unit-layer of conveyor pocket depth