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Abstract.

The accurate assessment of soil tillage quality may be pivotal when assessing soil health as part of a holistic process to ensure sustainable and profitable crop production practices. In this study, we focus on demonstrating methodologies for the spatial assessment of soil tillage quality as ground truth for assessing real-time soil tillage quality sensing technologies. The proposed methodologies for evaluating tillage quality involve the integration of the line transect method for residue distribution analysis. Soil aggregate is assessed by geometric mean diameter and mean weight diameter to describe aggregate size and distribution. These techniques offer valuable insights into crucial factors such as residue management, incorporation of organic matter, soil moisture conservation, seedbed preparation, and soil structure improvement, thereby contributing to improved crop emergence and growth. We seek to initiate a national dialog that moves the agricultural scientific community to develop assessment metrics as a means of elevating the soil tillage quality as an essential component of soil health assessment. Through literature review and existing field data collection protocols we aim to underscore the significance of reliable ground truth data for tillage quality mapping, tillage tool adjustment, and tillage tool automation. Findings from this study will provide valuable guidance as we seek to develop feedback sensing and automated control technologies to optimize tillage tool settings for producing the desired soil tillage outcomes.

Keywords.
Sensing, Soil Titlh, Tillage, Soil Health, Seedbed Preparation

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Development of Standard Protocols for Soil Tillage Quality Assessment as an Essential Component of Tillage Tool Automation and Improved Soil Health

The accurate assessment of soil tillage quality is pivotal for ensuring sustainable and profitable crop production practices, as it plays a critical role in maintaining soil health. In this study, we focus on demonstrating methodologies for the spatial assessment of soil tillage quality regarding seedbed preparation, serving as ground truth for evaluating real-time soil tillage quality sensing technologies. Ground truth data collection methods have been established such as assessing soil aggregates through geometric mean diameter and mean weight diameter and the line transect method for residue distribution analysis, we aim to provide valuable insights into crucial factors such as residue management, organic matter incorporation, soil moisture conservation, seedbed preparation, soil structure improvement, and tillage depth and levelness.

Our goal is to initiate a national dialogue that encourages the agricultural scientific community to develop assessment metrics that relate to sensing technology, elevating soil tillage quality as an essential component of soil health assessment. Through a comprehensive literature review and the application of existing field data collection protocols, we underscore the significance of reliable ground truth data for tailored conservation tillage and no-till approaches. The findings from this study will guide the development of feedback sensing and automated control technologies, optimizing tillage tool settings to achieve desired tillage outcomes.

This paper will discuss various aspects, including soil tilth, soil health quality metrics, ground truth data, soil health quality sensing techniques, viable real-time tillage sensing techniques and methods, , and the alignment of soil health quality metrics with sensing techniques for effective seedbed preparation. By addressing these topics, we aim to enhance our understanding and implementation of advanced soil tillage practices, contributing to improved crop emergence and growth.

Quantitative Soil Tilth and Soil Health Quality Metrics

Before environmental sensing or phenotyping can occur, relevant metrics need to be understood on a foundational level for seedbed creation. Soil tilth is a highly studied concept of soil health which encompasses properties in physical, chemical, and biological sciences (D. L. Karlen, 1990). As a review, soil tilth refers to the suitability of soil for planting and growing crops (Munkholm et al., 2019). Historical investigations on soil tilth will be used to outline current areas of sensing and future areas of interest for sensing soil tilth metrics for improvement of soil health. Munkolm et al. (2019) work to review soil tilth metrics establishes an extensive list of existing scientific publications documenting topics including ease of tillage, fitness of the seedbed, and impedance to seedling emergence and root penetration. These topics are related to quantifiable metrics for soil tilth.

The first important metric established by Yoder (1937) is to measure the aggregate size and distribution of the seedbed. Suh et al. (1977) incorporated metrics including soil texture, soil organic-matter content, bulk density/porosity, Atterberg's and Yoneda's consistency limits (water content), and a range of other soil-strength properties. Voorhees (1979) worked to quantify the effects of wheel traffic by measuring aggregate size and distribution, penetration resistance, bulk soil and clod bulk density, and tillage draft and wheel slip. Karlen et al. (1990) illustrated that soil tilth can be defined by bulk density, porosity, structure, roughness, and aggregate traits. Atkinson et al. (2007) measured aggregate size distribution, water content, and soil strength.

As a basis every researcher who has attempted to quantitatively assess soil health has interest in some or all these metrics. The metrics that are commonly agreed upon for measurement of soil tilth include aggregate size and distribution, residue incorporation, porosity, compaction, and moisture. Unfortunately, while much of the research has been quantifiable and worked well to assess soil health, it is rather time consuming to collect and assess these metrics and much of the assessment is done in a laboratory. This is of interest due to the desire to assess tillage in real time with metrics that are quantifiable.

Historic Techniques for Soil Health Measurement

As an interest to keep quantifiable metrics accurate and relatable a historic view of measurement techniques is important to relate sensing techniques to ground truth data. The historic soil health measurements of interest are those stated related to soil tilth such as aggregate size and distribution, residue coverage, soil moisture, and compaction.

Aggregate Size and Distribution

Aggregation refers to the association or grouping of soils in a hierarchal manner and the enclosed voids of differing sizes (Warkentin, 2008). Typical testing methods for soil aggregation include measures for stability, size, and distribution. Stability of an aggregate is a chemical function of whether cohesive forces between particles withstand applied forces. When measuring size and distribution of aggregates it is important to standardize the stability of the soil to have practical significance (Kemper & Rosenau, 1986). The most typical ways to assess soil aggregate size and distribution are those introduced by Kemper and Rosenau (1986) through a single parameter. The parameter is assessed through sieving techniques to give data on the amount of total mass for several size aggregate groupings. Typical aggregate size and distribution results are either assessed through mean weight diameter or geometric mean diameter (Kemper & Rosenau, 2008; Jensen et al., 2017; Bogrekci & Godwin, 2007a; Bogrekci & Godwin, 2007b).

The parameter, termed the mean weight diameter (MWD), is defined as the sum of products of (i) the mean diameter, x_i, of each size fraction and (ii) the proportion of the total sample weight, w_j, present in the corresponding size fraction. This summation spans across all n size fractions, including the one passing through the finest sieve. The MWD concept provides a comprehensive perspective on aggregate size distribution, considering both size and proportion in the evaluation process (Kemper & Rosenau, 1986).

$$MWD = \sum_{i=1}^{n} x_i w_i \tag{1}$$

The geometric mean diameter (GMD) is an index of the aggregate size distribution. The geometric mean diameter is calculated approximately by the equation:

$$GMD = \exp\left[\frac{\sum_{i=1}^{n} w_i log x_i}{\sum_{i=1}^{n} w_i}\right] \tag{2}$$

The use of the GMD over MWD is supported in most soils as it is approximately log-normal rather than normal. The GMD and the log standard deviation give a more complete description of the size distribution than the MWD. However, the MWD is easier to calculate and easier for most individuals to visualize (Kemper & Rosenau, 1986).

Residue Coverage

Ground truth measurements for residue include the line transect method, photo comparisons, and calculations. These methods provide estimates of the soil covered by residue. The line transect method covers a large area, 100 foot in length, and allows for estimates to be assessed at 100 points (Shelton & Jasa, 2009). The photo comparison method of estimating residue allows an individual to compare a field to a photo of a known amount of residue cover in a photo. The last method of estimating residue is by calculating an estimation of residue after harvest and throughout a year during farming operations. This is purely speculation based on averages evaluated in other studies. The line transect method is the most accurate way of estimating percent residue cover (Shelton & Jasa, 2009).

Soil Moisture

Ground truth measurements for soil moisture are the gravimetric or oven drying technique. This is the oldest method and reference for measuring moisture content in soil. The method ensures the measurement is independent of the soil type (Rasheed, et al., 2022). This method is limited by the time it takes to weigh and completely dry the sample and cannot be done in real time and must be removed from the soil to be analyzed in a laboratory.

Compaction

Compaction is the last metric of soil tilth to be discussed, has several components for consideration including soil bulk density, pore size and distribution, and dry specific volume. The components are the ground truth measurements for compaction (Hemmat & Adamchuk, 2008). Bulk density is the dry weight of soil divided by its volume and is typically measured using the cylindrical core method. The volume includes the volume of soil particles and of pores among the particles (Soil Quality Indicators). When particle density or specific gravity is known, the bulk density can be used to calculate porosity and void ratio. Porosity and void space both are volumetric ratios of bulk density divided by the particle density (ASTM D7263-21, 2021). Indirect measures can also be used such as mechanical impedance to measure soil strength or fluid permeability to measure pore spaces (Hemmat & Adamchuk, 2008).

Other Soil Health Considerations

While the metrics outlined previously historically represent soil tilth there is more to soil health as a holistic process to ensure sustainable and profitable crop production. Some other metrics to consider are outlined by the OSU extension where they also looked at total organic matter, permanganate oxidizable carbon (POXC), and aggregate stability (Culman et al., 2020). The study investigates the impact of these metrics as they vary with cation exchange capacity, soil depth, and management practices. The study found that the type of soil indicated by CEC has a major influence on soil health, depth of sampling maters, and on-farm management practices are critical (Culman et al., 2020)

Ground Truth Data Collection Protocol for Tillage Quality

The method that we will use is to collect samples from three locations per 300 m tillage pass and passes will be completed (fig 1). This method can be replicated for multiple tillage tool configurations and settings to express a range of aggregate sizes. The samples will begin one-fourth of the total pass distance from the ends and in the center of the pass to ensure the tractor is at speed and operating consistently. At each sample location (fig 2), 3 soil samples (9 per pass) will be collected, and 100 residue samples will be collected (300 per pass).

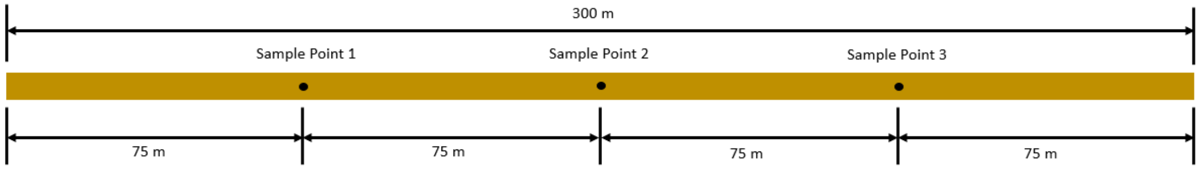
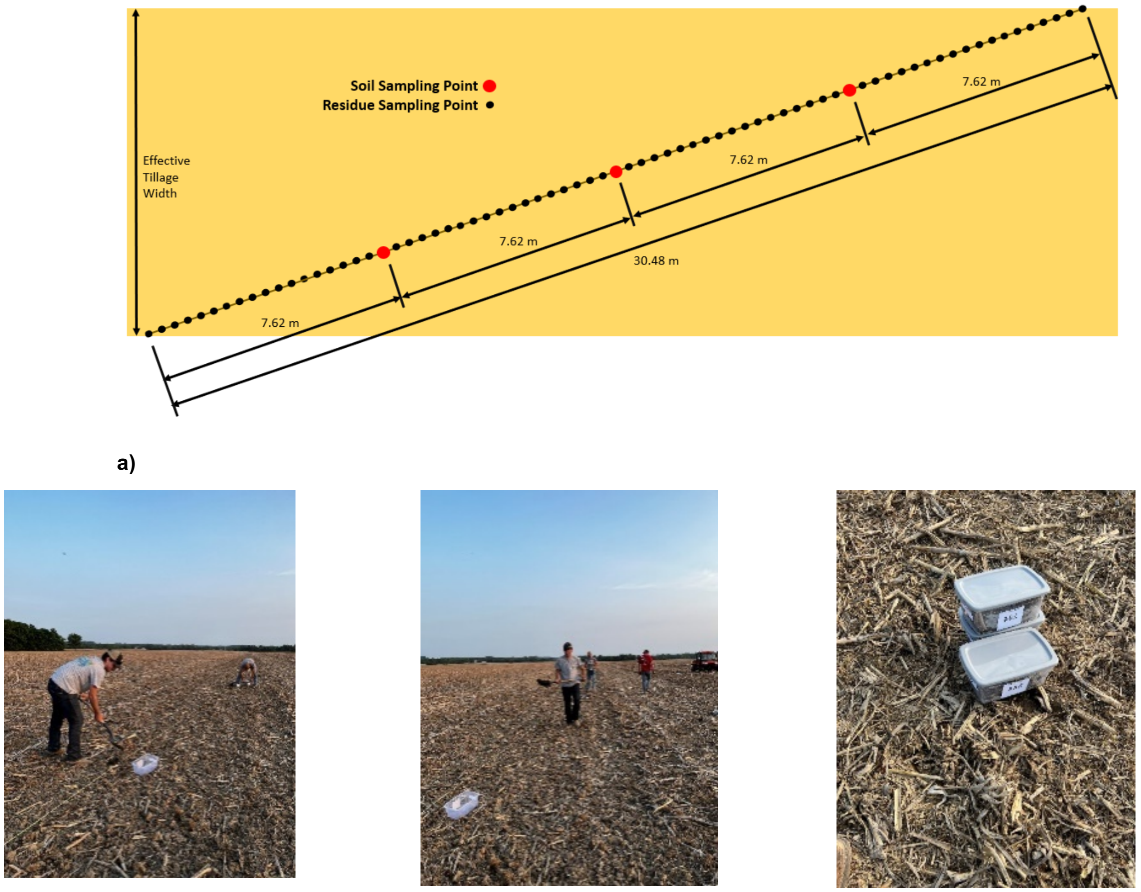


Fig. 1 Field sampling location layout along tillage pass.



a)

b)

c)

d)

Fig. 2 Field soil sampling and residue collection protocol; a) sampling point layout, b) collecting soil aggregate sample, c) residue covert sample collection and counting, and d) aggregate soil samples in collection containers.

Soil Aggregate and Distribution

Once field data samples were collected, they were moved to a lab and allowed to thoroughly air dry and stabilize for analysis. Natural air drying required up to two weeks depending on laboratory environmental conditions. In the process of aggregate separation, seven wire sieves were stacked in decreasing order of size, with dimensions ranging from 3 mm to 50 mm. The first step involves placing the sample from the collection bin onto the top separation sieve. Subsequently, loose residue is separated from the aggregate by shaking the grate up and down three times. Following this, the aggregate, along with the separation grate, is weighed, and the aggregate is transferred to the collection bin. The tare weight is subtracted from the total weight to obtain the net weight. These steps are repeated for each of the seven bins. The final step involves weighing the aggregate that measures less than the smallest grate of 3 mm. Once this is completed, the grates and catch pans are thoroughly cleaned, preparing the equipment for assessment of another sample. This procedure ensures accurate and consistent separation of aggregates for analysis.

a) **b)** **c)**

Fig 3. Soil sample sieving equipment in support of the protocol; a) seven sieve stack, b) aggregate screening and separation, and c) weight and tare of aggregate sieve.

From the field tests, aggregate size and distribution can be related to MWD bins, the bins are a range of MWD values, and each bin shows the breakdown from the seven sieves. This gives a feeling for the distribution of MWD calculation on a weight basis for each sieve. A larger MWD value relates to larger sized aggregates, while a smaller MWD value relates to smaller, more distributed aggregates.

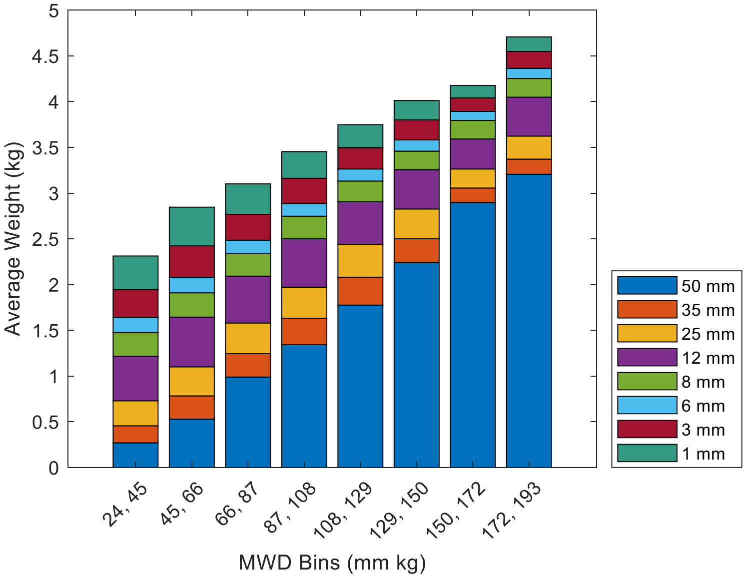


Fig 4. Average weight of soil sample vs. GMD bin calculation for tillage assessment.

a) GMD = 180 mm kg **b) GMD = 108 mm kg** **c) MWD = 24 mm kg**

Fig 5. Range of MWD sizes with respective soil sample.

Residue Coverage

The method which we used to collect residue samples are as follows, select an area that is representative of the whole field. This is three points along a tillage pass while avoiding end rows to ensure the tillage tool was up to speed and working consistently. The measurement was performed 30.5 m from each end and in the center of a pass. The rope was anchored at one end and stretched diagonally across the width of the implement. This allows for consistent measurements for each tillage tool setting (Fig 2a). Measurements were not taken parallel or perpendicular to crop rows. Determine residue cover by counting the number of marks that are directly over a piece of residue. To effectively reduce erosion, a piece of residue needs to be large enough to dissipate the energy of a raindrop during an intense storm. Consider a dot of 3/32 inch in diameter as the minimum size suggested for residue to be counted. When 100 points are observed, the number of marks that are directly over residue will be a direct measurement of the percent cover for that area of the field (Shelton & Jasa, 2009).

The assessment of residue cover will employ the line transect method, utilizing a 30.5 m rope marked at 30.5 cm intervals. The rope will be stretched diagonally across the effective tillage pass, with a minimum pass length of 300 m. This process will be replicated three times at ¼, ½, and ¾ of the total distance of the pass. Residues larger than 2.4 mm in diameter intersecting with the interval markings will be counted, and the intersection with the rope will be collected for size assessment. The size of residue will be determined by measuring the length, width, and depth of each particle.

Residue coverage bins were created to contrast how tillage tools and tools settings affect residue distribution on the soil surface. These data were collected using the line transect method and for an entire single pass with the same tillage tool and tool settings. In general, the more aggressive tillage tools and/or tool settings tended to bury more residue.

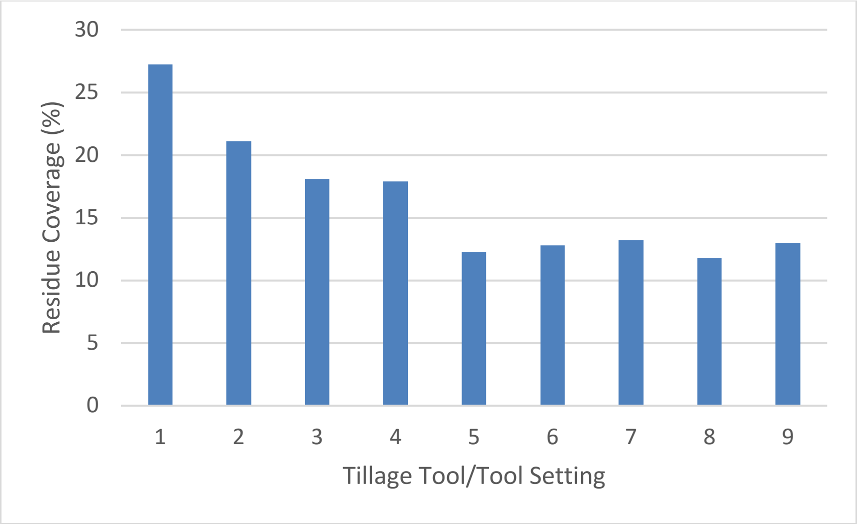


Fig. 6 Average plant residue cover for varying tillage tools/tool settings.

Tillage Quality and Soil Health Sensing Techniques

Several researchers have proposed solutions for measurement systems that investigate soil health including metrics of interest such as soil aggregate size and distribution, residue cover, soil moisture, and compaction. Various techniques and methodology have been applied and are of interest when it comes to sensing technologies especially those that can establish real time sensing for tillage applications. Techniques applied include in-situ, real-time, mechanical, and remote sensing types. While of the sensing methods attempted are practical for measuring the metric they may have limited value for real time sensing and control.

Aggregate Size and Distribution

Researchers have attempted to correlate sensing methods to aggregate size and distribution using different sensing techniques and analysis methods. Bogrekci and Godwin (2007) attempted several methods including the use of a real time spring tines for dynamic strain gauge analysis (2007a) and a static method through image processing of RGB images for correlation with GMD and MWD values (2007b). The use of strain gauge signal processing was used to correlate the signal of the force applied to a spring tine to traditional sieving techniques (Bogrekci & Godwin, Development of a mechanical transducer for real-time soil tilth sensing, 2007a). Bogrekci and Godwin (2007b) also attempted to develop an image-processing technique for soil tilth setting. Their research aimed at using computer vision as a non-contact measurement technique for clod/aggregate size distribution in the field. They used a classification method that would label soil as course, intermediate, and fine. Jensen et al. (2015, 2016, 2017) attempted several methods to correlate soil aggregate size to methods with seedbed quality including the use of 3D imagery and LiDAR scanners. Jensen et al. has attempted to use Gaussian curvature (2015), Fourier transforms and granulometry methods using a 3D imagery in situ and in real time for a field cultivator (2016 & 2017). Gaussian curvature was used to assess single aggregates in a laboratory and depth maps in a field setting to correlate to surface roughness under controlled conditions Jensen et al. (2015). When reassessing soil aggregate size and distribution using Fourier transforms and granulometry, Jensen et al. (2016) determined that granulometry was able to distinguish the soil samples collected far better than the Fourier transform method. Jensen et al. (2017) was able to produce results for full 3D surface images when used at a controlled pace but was not able to produce full images in real time at regular tillage speeds using granulometry. One study (Robichaud & Molnau, 1990) utilized a non-contact ultrasonic profiler to measure the soil surface roughness. The researchers were investigating evaluation methods for soil erosion. The instrumentation was used to determine the changes in random roughness as a function of tillage.

Residue Coverage

Image based methods have also been investigated for contrast transect residue estimation. The imagery estimation was element wise estimation of soil covered by residue (Lory, et al., 2021). Sensing techniques which have been studied relating to crop residue consist of spectral indices. A difficulty with sensing crop residue is that crop residue has similar spectral characteristics to the soil background, only the lignin and cellulose within the crop residues having strong absorption valleys around 2100 nm (Dong, et al., 2023). Indices that are typically used for crop residue estimation include cellulose absorption index (CAI), the normalized difference tillage index (NDTI), the simplest tillage index (STI), and the normalized difference residue index (NDRI). Research using these methods has been accomplished from satellite imagery as the most accessible form of SWIR data (Dong, et al., 2023).

Soil moisture

Sensing approaches for soil moisture including neutron scattering, gamma attenuation, time domain reflectometry, capacitance sensor and frequency domain reflectometry, resistive sensors, tensiometers, hygrometric techniques, ground penetrating radar, cosmic-ray neutron sensing, remote sensing techniques, and machine learning techniques (Rasheed, et al., 2022). Given a variety of challenges with these sensing techniques an ideal real-time sensor that provides accurate cost-effective results remains elusive. The most common method for measuring moisture is the dielectric techniques provided by TDR (Rasheed, et al., 2022).

Compaction

Compaction measuring devices have a much wider range of measuring metrics including those for soil strength, bulk density, dry specific volume, void ratio, and porosity; as such it has a large number of measurement devices to accompany the measurement of the state properties (Hemmat & Adamchuk, 2008). Hammet and Adamchuk (2008) reviewed systems that have been used to measure these metrics including water content sensors, soil strength sensors, and fluid permeability sensors. Soil strength sensors cover the broadest range of sensing strategies as they include sensing both vertically and horizontally actuated penetrometer readings of force for draft and profiling with tips and tines. Soil cone penetrometer measurements have become standardized for soil compaction, but they are limited to stationary profilers. Hammet and Adamchuk (2008) cover a handful of methods for on-the-go soil strength and bulk density measurements, but they prove difficult to correlate to the soil cone penetrometer measurement as the failure mode changes from vertical to horizontal.

As standard cone indices can provide information about the compaction layer of a soil, offering a profile of the force it takes a cone to move vertically through the soil. A soil cone penetrometer has been optimized to take two soil samples simultaneously (Figure 6). While soil cone measurements are limited by time, they can provide optimal information for circumstantial data including tillage results. As an example of circumstantial evidence un-trafficked and trafficked transects for tires. This was accomplished by measuring soil data at row intervals for an entire controlled trafficked field. The results are related to planter wheel traffic rows where the trafficked rows lead to a much higher cone index than the un-trafficked rows at the 50 to 150 mm of depth. The compaction layer for this controlled traffic field can be seen in the compaction layer over an average of 480 rows and 1920 sample locations. While not optimal for real-time measurements of soil tilth, soil cone indices provide a sensing method for ground truth data.

Fig 6. Dual soil cone penetrometer for data collection.

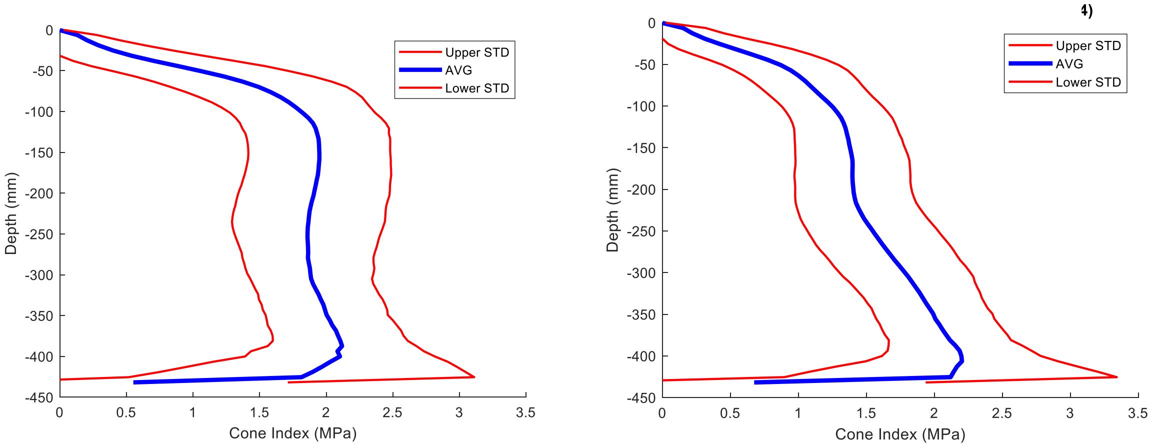


Fig 7. Soil cone penetrometer profiles for high (L) vs. low (R) GVW equipment traffic events.

Commercialized Soil Health and Tillage Quality Sensing Methods

Current cutting edge precision technology includes use of precision application methods of variable rate technology (VRT) applied with prescription mapping and sensor suites that describe the current setpoints of the machine. One method of controlling variability within the field is VRT, which allows the grower to apply the needed quantity of crop inputs at a precise location. Current VRT technology utilizes predefined rates within prescription maps that instruct the system to change rate in the desired location. Producers can vary tillage settings based on change soil types, field conditions, conservation practices and topography. The prescriptions can automatically adjust the implements settings as the tillage tool moves across the field (Bedord, 2022). Examples of this technology that is already available include VRT renegade, Salford Halo, and AFS soil connect. These machines allow operators monitor and adjust machine on the fly including gang angle, hitch control, tillage depth, gauge wheels, and wing and rolling basket down pressure (VRT Renegade, n.d.; Halo VRT, n.d.; AFS Soil Command, n.d.). AFS soil connect delivers real time feedback for seedbed preparation by making a level surface through control of tillage tool components and sections (AFS Soil Command, n.d.)

Sensing technologies are widely adapted to tillage implements including sensing technologies for tillage depth control such as TruSet Tillage produced by John Deere and Topcon Tillage Depth Control that compensate in real time for varying field conditions using ultrasonic sensors (Truset, n.d.; Topcon, 2023). Topcon claims their depth control feature offers improved, more accurate seedbed preparation, residue management, and land management (Topcon, 2023). Veris iScan TM uses a sensor suite of a soil EC array, infrared sensor, and moisture and temperature probes to measure organic matter, cation exchange capacity, soil moisture, and soil temperature in real time which probably provides the best feedback for tillage quality, it still lacks direct quantitative measurements of total tillage quality (iScan, n.d.).

While not specifically used for tillage health monitoring Solvita has created an in-situ sensor for detecting CO2 emissions called IRTH. This sensor measures biological decay and deterioration of soils, plant litter, and composts. The results provide valuable insights into carbon loss of the soil and stability index. IRTH reports the CO2 change and calculates overall decay rate in relation to the original sample rate (IRTH, 2024). Figure 11 highlights Solvita IRTH to compare the biodegradation of SOM for low vs high GVW agricultural equipment traffic. Soil under the low GVW traffic has slightly higher CO2 emissions which indicates a higher biodegradation – possibly from better soil aeration and higher soil moisture content.

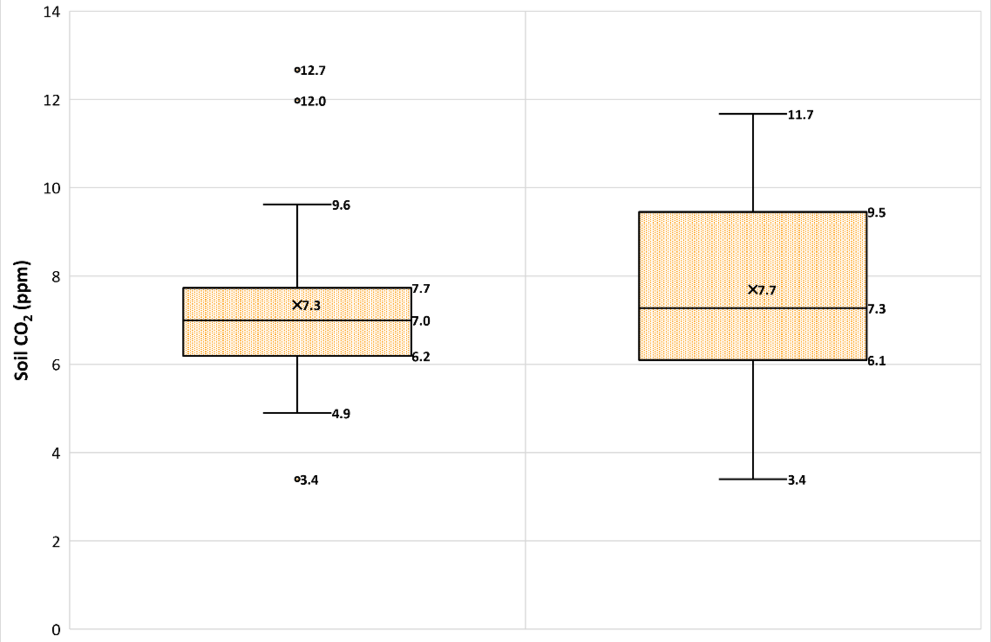
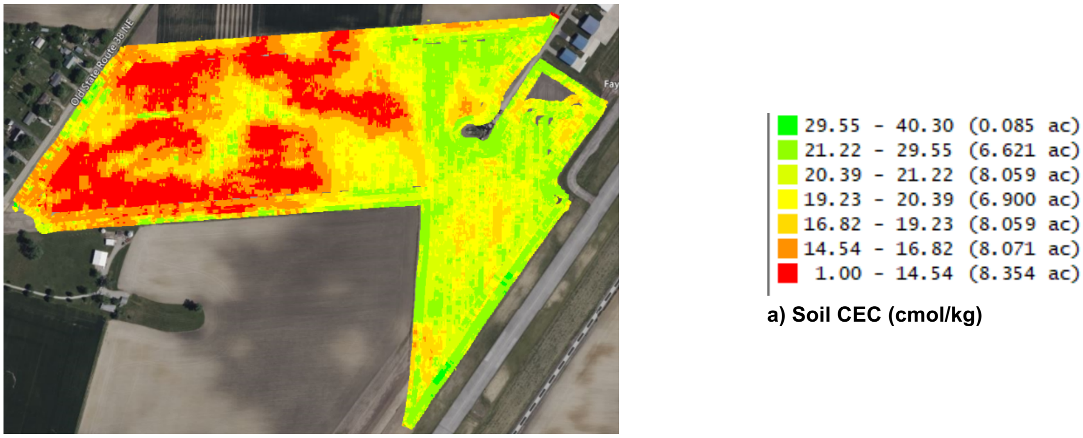


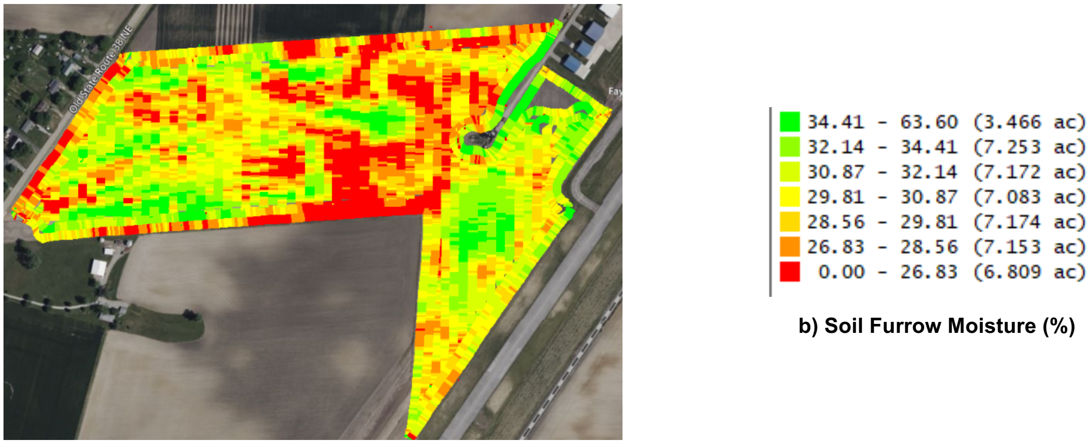
Fig 8. Soil $C0_2$ emissions for high (L) vs. low (R) GVW traffic events with Solvita IRTH test.

Another interesting sensor that is used for planting is created by Precision Planting. The Smart Firmer TM detects a range of metrics ranging from cation exchange capacity to soil moisture. Some of the desirable metrics for tillage are soil CEC, organic matter (OM), soil temperature, and moisture. The sensor operates and measures these metrics continuously throughout the field, indicating measurements for real time control. Typically, the Smart Firmer can control seeding, hybrid selection, insecticide rates, fertilizer rates, and planting depth (Smart Firmer, 2024). Example attribute maps are included to highlight data streams coming from the Smart Firmer.

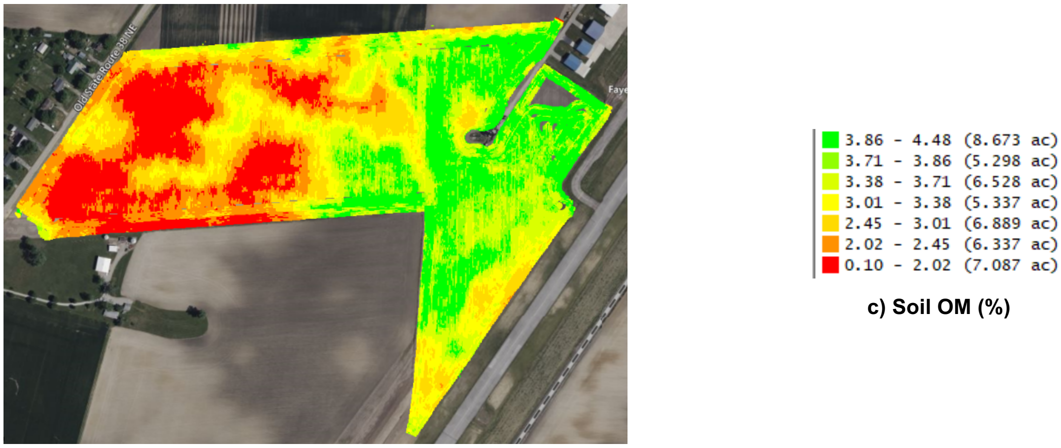
While currant tillage practices have adopted processes for controlling features of tillage systems and for sensing tillage tool component depth (e.g., component downforce, levelness, and indirect quality metrics), they fall short of sensing the overall quality of the tillage performed. They offer solutions with predefined settings before the grower even enters the field. While the operator can make changes to the system setpoints if the results do not look right, there is currently no way of quantifying the quality of the tillage, the changes are often made after the tillage is partly completed, and the operator will have to continually make changes given variability of the soil landscape including soil type, moisture, or residue cover.



a) Soil CEC (cmol/kg)



b) Soil Furrow Moisture (%)



c) Soil OM (%)

Fig 9. Precision Planting Smart Firmer continuous soil measurements for map-based planting quality.

Summary

The accurate assessment of soil tillage quality is crucial for sustainable and profitable crop production. This study has highlighted methodologies for spatial assessment of soil tillage quality which are foundational guiding crop managers in modification of the soil environment to enhance profitability and promote better soil health. By integrating the line transect method for residue distribution analysis and evaluating soil aggregates through GMD and WMD, we can begin conversations on soil tillage quality utilizing standard metrics of comparison.

Our goal is to stimulate a national dialogue within the agricultural scientific community to develop sensing technologies to quantify soil tillage quality which are vital to the ongoing assessment of soil health. By conducting a comprehensive literature review and applying existing field data collection protocols, we emphasize the significance of reliable ground truth data for quantification of various tillage practices. The findings from this study aim to guide the development of feedback sensing technologies, automated controls, and optimization of tool configuration and settings to achieve desired outcomes.

Despite the advancements in precision agriculture and the availability of technologies for real-time sensing and variable rate technology (VRT), there remains a gap in quantifying the overall quality of tillage. Current technologies fall short in providing comprehensive real-time feedback on tillage quality, which is necessary for ensuring consistent and desirable results. Future research should focus on identifying and quantifying the critical metrics for optimal seedbed creation, residue management, soil moisture conservation, and soil structure improvement. By addressing these gaps, we can enhance the implementation of advanced soil tillage practices, contributing to improved crop emergence and growth, and ultimately, sustainable agricultural practices.

Given this brief overview, a few questions have surfaced to spur on-going dialog: 1) Which parameters should be monitored to ensure desirable and consistent results? 2) What information needs to be assessed for best subsoil characterization? 3) What quantitative measurements need to be provided to equipment operators -- ideal seed to soil contact, soil pore size variation, aggregate size and distribution for varying soil types? 4) What quantitative measurements should be available to assess residue cover, residue incorporation/burial, soil organic carbon, and soil moisture content? 5) Which tillage tools and tool setting will produce the desired soil conditions for germination? And finally, 6) What actionable information should be made available for decisions making, tillage quality mapping, or closing the loop on real-time feedback adjustment of tillage too settings.

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