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The Development of a Procedure for the PXRF Analysis of Soil Cation Exchange Capacity in Collaboration with Colorado Farmers

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The Development of a Procedure for the PXRF Analysis of Soil Cation Exchange Capacity in Collaboration with Colorado Farmers

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Submitted in partial fulfillment of the requirements
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at the College of Wooster

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Cover photo by Werner Slocum/NREL, 2020, Longmont, Colorado.

Abstract

Discrepancies between farmers' and scientists' knowledge systems and experiences have long prevented the success and mutual beneficiality of collaborative research efforts between these two groups. The development of agricultural technologies, such as portable X-ray fluorescence (PXRF) for the analysis of soil cation exchange capacity in the field, creates a promising overlap point for farmers and scientists to cooperatively study issues within their sociocultural context and with access to institutional resources. In this study, the generation of an in-field PXRF method in collaboration with Colorado farmers helps to provide a prospective model for scientists and farmers looking to use collaborative research to move toward a more holistic and all-encompassing understanding of agriculture.

Acknowledgments

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I would like to thank the community of farmers who helped to make this research possible by so generously giving me access to their time, energy, and space during the summer and fall of 2020. They truly are the bedrock of the science I want to conduct in my life, and the people I look to as I grow into my aspirations of becoming a farmer and steward of the soil.

Most of all, I must thank Dr. Meagen Pollock for being the first person to look me in the eye and tell me that I could become a scientist, which at one time was far beyond what I could imagine for myself. Her leadership, guidance, and friendship have been one of the most formative forces in my life, and I hope to use the skills and traits she has helped me develop for years upon years to come. She is emblematic of all things possible for educators and women in STEM everywhere.

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Introduction

Collaborative research by scientists and farmers, if realized in its full capacity, has the potential to greatly further the productivity, sustainability, and well-roundedness of agriculture as a field. Yet while this type of research has gained increasing traction over the last several decades, existing discrepancies between the two involved groups—such as little use of the complementary relationship between scientists' and farmers' knowledge systems and skills, inadequate incorporation of local cultural understanding into scientific research, and inherent biases created by the dominant scientific epistemology—are critical obstacles that prevent the growth and progress of cooperative efforts that could benefit scientists, farmers, and their associated and shared communities (Hoffmann et al., 2007).

The development of agricultural technologies, when applied appropriately, have the capacity to generate a fruitful overlap point for scientists and farmers to conduct research together and directly benefit the farmers using them. Portable X-ray fluorescence (PXRF) is a potential example of a technology whose in-situ application to soils directly on farmland could provide farmers with more rapid, readily available results than those from an external lab. The lack of existing literature on a consistent and reliable method for PXRF on soils in the field indicates a gap where both scientific and farmer knowledge could be useful when combined. The portability of the machine creates greater opportunities for scientists to experience and better understand the cultural context in which they are working, and for farmers to share localized and specialized expertise pertaining to their own farms.

Farmers' tacit knowledge regarding the land use history of their own farms gives them a unique perspective on soil health. Farmers bring specific contexts of culture, values, ideas about farming, and science and technology to the table, generating a unique framework in which dominant, mainstream concepts of scientific research are not only challenged but enhanced by the contributions of the farmers for whom the research is being conducted. Developing an in-field method for PXRF application to soils with cooperation from the farmers who will use it themselves will not only improve the quality of the scientific discoveries that result from the study but will also help to broaden and diversify our understanding of what science means in different communities and how it can best serve those who have not always been included as part of the conversation.

Collaborative research between farmers and scientists

Collaborative research between farmers and scientists presents an important opportunity for the holistic advancement of agriculture. Farmers' knowledge pertaining to their own farms provides both parties with a greater sense of farm environments as interconnected, multipart systems. Traditional scientific questions and experimentation tend to focus on singular aspects of agricultural operations, such as individual crops, animals, or climatic factors, such as wind or water—all components that never truly exist independently from one another due to the deeply interrelated nature of agroecosystems. Simultaneously, scientists' localized, empirically tested ideas help establish a framework for farmers to ask questions pertaining to their own experiences (Stuiver et al., 2002; Hoffmann et al., 2007).

The occurrence of either of these forms of expertise without the other creates significant dissonance between scientists and farmers that has defined their research relationship for the last several decades. Perceptions of progress in modern agriculture tend to follow a "linear model of innovation," in which scientists are the primary actors responsible for producing discoveries that correlate directly with advancement, while farmers simply fulfill the application of these discoveries to their own practices without providing any direct input to their development or refinement. Scientific knowledge is produced under very specific, carefully dictated circumstances to standardize measurements in places like labs or extension facilities; however, once these conclusions are transferred to farmers for implementation, these conditions can be difficult to replicate, and were not previously accounted for due to lack of farmer input in the research process (Stuiver et al., 2002).

At their root, discrepancies between farmers' and scientists' knowledge stem from the dominant epistemology that creates the hierarchy of expertise we associate with most research conducted today. The dominant epistemology associated with science "... is one based on the proposition that one needs to 'reduce' complex wholes to their component parts ... by focusing on the individual parts, and the relations between isolated variables, one can understand the functioning of the complex whole" (Stuiver et al., 2002). The segregation of each aspect of a farming environment for study purposes separates not only their connection to other parts of the agroecosystem but also their relationships with the broader social, cultural, and economic contexts surrounding the farm itself. Because farmer knowledge is based on cohesive understanding of how all these pieces work together and influence one another, and not necessarily expertise in the particular area of an isolated variable, it has never been afforded the same weight as scientific knowledge derived from the dominant epistemology (Stuiver et al., 2002; Hoffmann et al., 2007).

The dominant scientific epistemology must be broadened and diversified to accommodate the perspectives and knowledge of farmers who play an essential role in holistic agricultural research. The development of farming technology—which requires both the resources of scientists and their associated institutions and the informal, firsthand experiences and innovations of farmers—has great potential as an overlap point to explore this relationship. Together, farmers and scientists can define research questions that account for the complexities of an agroecosystem (including its cultural, social, and economic contexts), identify the technological mechanisms that are best for guiding research toward these questions, and ultimately disseminate their results through community connections that could not be realized by traditional work in a lab (Hoffmann et al., 2007).

The "farmer-back-to-farmer" (FB2F) approach, pioneered by Rhoades and Booth in the 1980s, proposes an alternative to the "... piecemeal, multidisciplinary approach [of the dominant epistemology] ... an interdisciplinary perspective which rejects the fragmented, staggered roles of several specialists in favour of on-going, dialoguing, and totally involved research teams working together towards the identification, design, generation and evaluation of acceptable agricultural technology" (Rhoades and Booth, 1981: 128). Research using this approach should begin and end with the perspective of the farmer, socially situating technical problems throughout the research process so that the resulting technology can be best evaluated, adapted, and integrated to the needs of the involved farming community (Crane, 2014) (Figure 1). In this case, technology and its development cannot be separated into isolated parts or variables as it traditionally might in a study conducted in congruence with the reductionist ideologies of the dominant scientific epistemology. It must account for the multifaceted realities of farmers' lives and perspectives by expanding what it means to conduct scientific research. "Rather than essentialize 'science' as a monolith, we should construe it as a dynamic and heterogeneous cultural institution of which we are a part and can thus change" (Crane, 2014: 52).

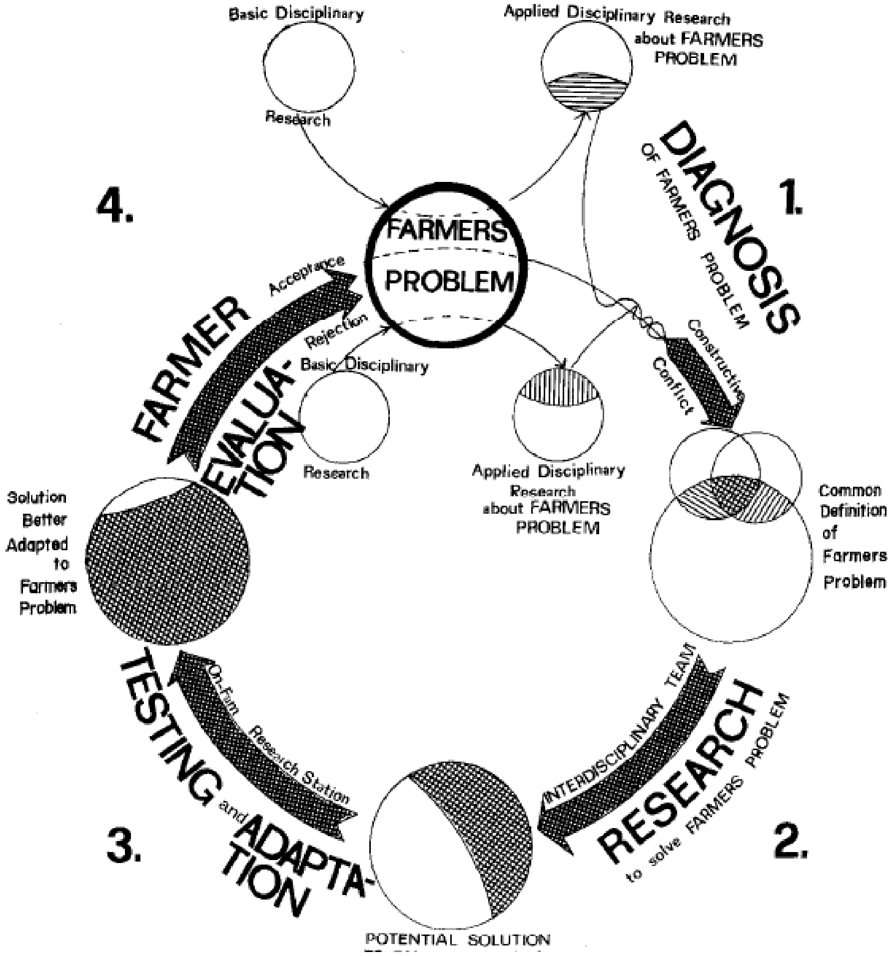


Figure 1. Visual conception of the Farmer-back-to-farmer model (Rhoades and Booth, 1981).

Importance of soil health and cation exchange capacity to agriculture

Soil health is an essential aspect of our understanding and development of sustainable farming practices. As a concept, soil health can be defined as “the state of the soil being in sound physical, chemical, and biological condition, having the capability to sustain the growth and development of land plants,” with particular emphasis on the ecosystem services that soil provides for plants and animals, water and air quality, habitat preservation, and nutrient cycling (Idowu et al., 2019). All these services rely on the balanced and interconnected functioning of the soil’s physical, biological, and chemical components. Physical properties of the soil include texture (the proportion of sand, silt, and clay particles), bulk density (measurement of soil compaction), and structure (distribution and stability of soil aggregates). The state of these three properties determines important realities of the soil system, including water infiltration, retention and movement, resistance to erosion, and efficiency of nutrient cycling. Biologically, the soil supports an incredible variety of living organisms associated with plants and organic matter that in turn support the wider services of the soil system.

For the purposes of this study, the focus is the measurement of soil cation exchange capacity (CEC) in the context of soil physical properties. CEC measures “the moles of positive or negative charges per unit mass of soil that relates to exchange of cations or anions occurring on the surface of colloidal fractions of inorganic or organic soil particles (primarily clay and humus)” (Al-Kaisi and Lowery, 2017). It is determined by the relative amounts of different colloids in the soil sample and the specific CEC of each of those colloids. In and of itself, CEC is an interplay process between the physical and chemical characteristics of the soil, meaning that one component cannot be studied separately from the other when making a measurement. Calculating CEC can provide farmers with critical information regarding types and amounts of soil amendments to apply in order to improve soil quality, how to engineer and design fields to maximize the benefits of the physical soil type, and even what kind of crops to grow.

The chemical properties of soil are most directly related to plant growth; land plants generally require 17 nutrient elements, which are divided into three categories. Primary nutrients—nitrogen, phosphorus, and potassium—are those needed by plants in the largest proportions. Secondary nutrients—calcium, magnesium, and sulfur—are needed in relatively substantial amounts, and micronutrients—zinc, manganese, boron, copper, chlorine, iron, nickel, and molybdenum—are required in the smallest amounts. However, the categorical separation of these critical soil nutrients should not be viewed as a hierarchy that places the universal importance of one element over another. Instead, the necessity of soil nutrients must be determined on a case-by-case basis according to type of land use, plants grown, and preexisting soil conditions within the agroecosystem. Widespread emphasis during the last several decades on nitrogen, phosphorus, and potassium as the only essential nutrient elements, assuming that secondary and micronutrients would naturally follow, have led to greater degradation of worldwide soil health than improvement (Keesstra et al., 2016; Kinsey, 2013; Gliessman, 2015). Sustainable farming methods, in an effort to reverse the negative effects of these narrow-minded approaches to soil health and chemistry, contrastingly focus on soil systems holistically and examine the importance of each individual element in addition to the broader role it plays in relation to other nutrients (Idowu et al., 2019).

Soil health can be evaluated using the analysis of these different properties, which then serves as the basis for recommendations about management practices that will help to maintain or improve the condition of the soil. Soil chemistry specifically can be analyzed in a variety of ways: electrical measurements, which are primarily used to determine pH; titration, for soil acidity and organic matter content; extraction, which physically separates nutrient elements of interest from the larger soil structure; spectroscopy, which uses X-rays to interact with matter; and chromatographic methods that separate compounds into stationary and mobile phases (Conklin, 2005). Most of these procedures must be conducted in labs with access to resources, technology, and scientists trained in the specifics of these analyses.

The development of these procedures in external labs and the requirement of particular personnel and equipment act as significant barriers to farmers who are interested in measuring soil health on their own farms. Generally, farmers send soil samples away to labs at academic institutions, extension facilities, or private establishments where they are separately analyzed before the results are returned. These methods were not created with in-field, on-farm measurements in mind, and therefore also little consideration of farmers' contexts, needs, and questions. However, modified versions of these technologies for increased portability present opportunities to bridge this gap by bringing measurements of soil health directly to the on-farm environment. This study will focus specifically on portable X-ray fluorescence technology as a potential point of this collaborative development.

Portable X-ray fluorescence (PXRF)

X-ray fluorescence (XRF) is a form of spectroscopy in which elements exposed to a spectrum of X-rays eject electrons from their inner shells when atoms absorb some of the X-rays. Electrons from the outer shells fall into these inner vacancies and emit an X-ray photon of a specific wavelength as a result of their higher energy state. These wavelengths can then be analyzed to identify the element characteristic of that photon (Conklin, 2005; EPA, 2007). XRF technology to perform this analysis is available in two forms: laboratory size and a portable handheld instrument (PXRF). The smaller size and faster processing time of the handheld instrument makes it the ideal option to bring into a field context and enable a successful FB2F approach.

PXRF use on soils can be performed in intrusive and in-situ procedures. Intrusive methods involve the collection and preparation of soil in a sample cup that is placed on the instrument window for analysis. In-situ methods see the placement of the instrument window directly on the soil surface, or of a representative loose sample on a piece of protective film placed over the instrument window. The samples in each procedure are then exposed to radiation from the instrument source, and the resulting fluorescent X-rays are converted into electric pulses by a detector that can be measured proportionally to the energy of characteristic X-rays. Most PXRF instruments are run using external software that process the data from these measurements (EPA, 2007).

The PXRF instrument presents clear advantages over other analytical laboratory methods in that its associated methods are faster, more cost-effective, and less destructive of samples than most wet laboratory procedures (Ravansari et al., 2020). The portability of the PXRF instrument also improves the ability of scientists to bring technology directly to the field and better incorporate farmers' knowledge and experience into their conduct of actual analyses, while simultaneously increasing the exposure of farmers to technology and breaking down hierarchical obstacles that exist in traditional scientific research.

However, there are several barriers to the effective use of PXRF in-situ on agricultural soils stemming from both the limitations of the instrument and the variability of the in-field context. Complications due to the instrument itself include thickness of analytical sample films, external interferences and detector resolution, consistency in X-ray energy and intensity, power source fluctuations, and instrumental drift over time. Such issues can be solved according to the specifications of the instrument and the procedure developed for its use.

Obstacles presented by in-field measurements occur primarily because of complexities and contamination in the observed area, such as presence of organic matter, soil water content, and sample heterogeneity and geometry (Ravansari et al., 2020; Conklin, 2005). Additionally, PXRF use in direct soil analysis can primarily detect only surface elements and heavier elements, limiting the scope of nutrients identified in a particular soil sample (Conklin, 2005). Many of these barriers can be remedied by sample preparation that homogenizes sample particle size and structure through sieving and drying, yet a balance must be struck between maintaining the time- and cost-effectiveness of in-situ PXRF methods and preserving the integrity and accuracy of the soil sample.

Methods: Social

Early iterations of this project focused on Amish farmers in central Ohio and their conceptions of science and soil health. The research questions at the center of those interviews focused more on testing overall soil nutrients using PXRF technology, but it was through these conversations that farmer interest in CEC repeatedly arose as a key tool in small farmers' understanding of soil health. The original intent to collaborate with Amish farmers had to be abandoned due to the pandemic. The project was revised to focus on Colorado farmers.

For this study, IRB approval was obtained from the College of Wooster Human Subjects Research Council (HSRC) in March 2020, and a second revised application was approved in September 2020. The Colorado farmers were interviewed in-person or on the phone following onsite sample collection at their farms. Interviews were recorded with permission and transcribed for use in this paper. Questions included:

1. What do you know about your farm's land use/geologic history?
2. How do you use science/partner with scientists on your farm?
3. How do you identify areas on your farm to perform soil tests on?
4. How could scientists you have worked with better conduct research in collaboration with farmers?
5. What motivates you to learn more about your farm?
6. What does the scientific process mean to you? In what ways are you interested in being involved in this process?
7. What would your ideal research process look like?
8. What does research mean to you?
9. How do you understand cation exchange capacity?
10. What other questions do you have about the health of your soil?
11. Where do you get your scientific information?

Methods: Scientific

Sample Collection

A representative soil sample of approximately two cups was collected at each site using an 18-inch soil probe. Cores were taken in at least five locations across the field or bed of interest to a depth of six inches and then homogenized using a clean field knife or trowel. Beyond these specific parameters, the farmer at each site was asked to collect the soil sample as they saw fit. Any rocks or plant debris were removed from the sample before it was placed in a clean plastic sample bag and labeled with the corresponding sample ID.

Sample Analysis by PXRF

Samples were analyzed using a Bruker Tracer III-SD. Prior to sample analysis, USGS Standard Reference Material soil standards 2710a (Montana I), 2711a (Montana II), 2706 (New Jersey), and 2709a (San Joaquin) were pressed into pellets and analyzed directly on the detector window for 90 seconds using S1PXRF software on the Lenovo tablet in order to establish a data baseline. Each data file was saved in .pdz format. Sample analysis followed the same procedure, with each sample bag placed directly on the detector window and analyzed for 90 seconds and subsequently saved as a .pdz file.

Following initial data collection, the corresponding .pdz file for each soil standard and sample was analyzed using Bayesian Deconvolution in the S1PXRF program to identify each element present. Spectral peaks were labeled with the appropriate elements, and the resulting intensity data for each standard and sample was exported from the program into an Excel spreadsheet. The intensity data for the standards and the standard concentration data provided by the USGS standard reference material certificates were used to create a calibration curve for each element of interest. The corresponding equation for each calibration curve was used to identify the intensity of each element present in the soil samples.

Sample External Lab Analysis

Six tablespoons of each sample were reserved for the purposes of maintaining a sample archive; the remaining soil was sent to the University of Massachusetts Amherst Soil and Plant Nutrient Testing Laboratory (hereby referred to as “UMass”) for textural analysis and chemical composition, including an overall nutrient element profile, proportion of organic matter, and a calculated CEC value. More information about the specific methods of the UMass lab can be found on their website at https://ag.umass.edu/services/soil-plant-nutrient-testing-laboratory.

Results

Soil samples were collected from farm locations across Colorado (Figure 2). Each sample site is described below, followed by a summary of the soil chemistry results.

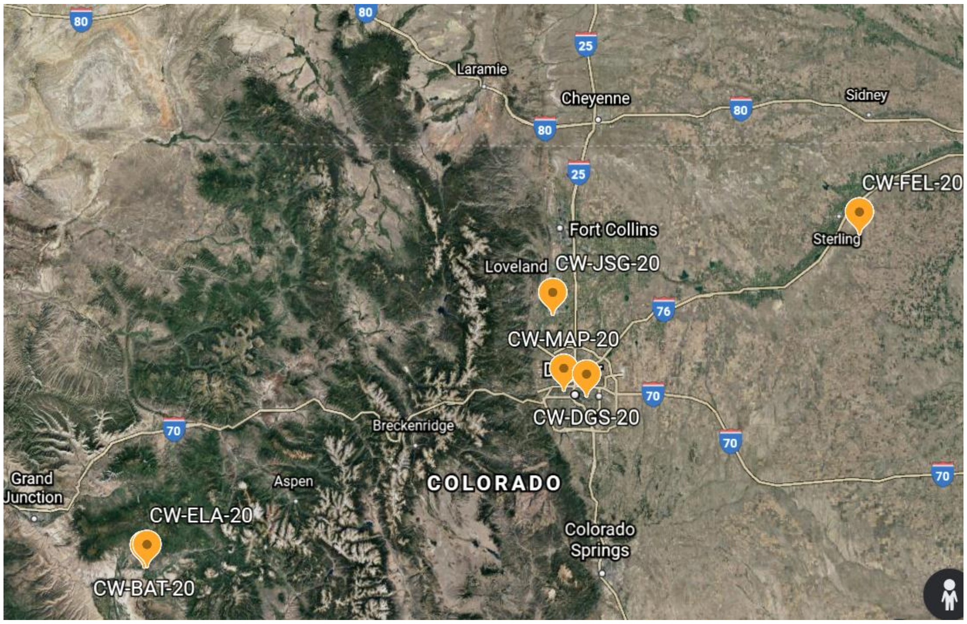


Figure 2. Map of sample locations across Colorado.

BAT-CW-20

Sample site BAT-CW-20 is in southwestern Colorado, near the town of Hotchkiss, where the geology is defined by proximity to the surface-level shales of the North Fork Gunnison River, placement within the Fifth Gunnison River Terrace, and the ancient lava flow deposits of the Colorado Grand Mesa. The property lines of BAT-CW-20 encompass both features; the upper level of the farm, where the soil sample was taken, is described by the farmer as "... the nice flat upper section that has been turned into more of an agricultural space [that transitions into] a hillside with a permanently flowing stream ... the water hits the soil coming down from the Grand Mesa, [penetrates the shale deposit], and runs out of the ground to create the permanent stream [on the lower portion of the property]." The sample was taken from the eight-acre, conventionally maintained, historically irrigated upper portion of the farm, where the previous property owners have grown winter wheat for the past 13 years.

The farmer recently purchased and moved to the BAT-CW-20 location to start her agricultural career. She expressed significant interest in utilizing the expertise of area extension officers and other scientific information specific to her property to guide her designs and plans for her farm. She identifies her motivation to incorporate such knowledge into her practice as "... [wanting to] create a space that is human-centric but also follows nature. I like diversification and seeing things grow, and I guess the reason I want to know all this information is so I can make better choices about how to progress that way in the best possible manner, the most water efficient, and keep the natural beauty of the area ..."

When asked about science and research specifically, the farmer pointed to the traditional scientific method as an ideal model for constant evolution in practices and knowledge in an agroecosystem. "By viewing it that way, you're constantly evolving and trying to get to a better solution with each iteration. I think that process will be constant on the farm—not that I'll be writing a hypothesis to test every time, but that everything will always be an experiment. Something works, it doesn't work, so you change the scale, or start over entirely. I think even in permaculture that's a huge thing—make changes, always question the answers, assume you're wrong until you're proven right, or [at least] getting closer to what you want."

Where does the farmer fit into this scientific method process? "...Maybe there's an aspect of science that the farmer isn't thinking about, or an aspect of farming that the scientist isn't thinking about, and a collaboration is good. Ultimately the farmer knows the land better than the scientist ... the best way to try to ameliorate that would be to get the scientists out on the farms more consistently, talking with people, I really do think a boots-on-the-ground approach is the best way to work with farmers."

ELA-CW-20

Sample site ELA-CW-20 is a fourth-generation, 90-acre organic fruit farm also located near the town of Hotchkiss, approximately one mile east of site BAT-CW-20. The orchards sit atop an alluvial fan extending downward from Grand Mesa, and rocky particles ranging from cobbles to more angular sediments influence the soil catena across the property. Since the 1910s, the farm has cultivated over 55 types of organic fruit trees, with increasing peach production in recent years, and annually provides fruit for farmers markets, restaurants, and grocery stores across the state.

Professionally trained in soil science, the farmer at ELA-CW-20 uses science on his farm to understand everything from pest and disease control to the nuanced complexities of perennial crop soils–a reality he identifies as a big obstacle to better research. "… We have those trees in the ground for 20 years ... And because we're dealing with those long-term systems, research needs to be done for three years at a very minimum, but five to 10 years would be ideal and that's just incredibly difficult to get funding for. Because you are not turning the soil over with tillage, and the perennial cover crops change themselves over the years, and we just don't have good documentation of what happens. That may change with every soil and climate type or even different tree varieties. So people haven't had the time or money to tune into this complex system."

The farmer views collaboration between farmers and scientists as a potential opportunity to remedy this issue by conducting experiments driven by real farmer questions on research plots, because the plots are better able to accept the risk of a crop loss over a longer period of years than a regular farm that is dependent on annual income. He emphasizes the value of farmer-determined questions in these research processes: "In some cases it's just basic research trying to understand a system or look for things that might help our system, without trying for a particular outcome. And the applied research is really answering questions farmers are asking and understanding whether that [fits] an application or the timing is right or if something is effective or not. We need both of those. And having farmers involved, especially in applied research, is important because we *are* short of time and money, and farmers can prioritize what questions they most need answered, because I've certainly seen researchers do great projects where I'm like, 'Yeah, that's cool! But it doesn't really help me.'"

MAP-CW-20

MAP-CW-20 is situated in a public park in Lakewood, near central Denver. The one-acre land plot was formerly tennis and basketball courts, fully demolished in 2014 and infilled with soil and compost for the purpose of establishing the working urban farm. The farm crew at MAP-CW-20 still frequently finds chunks of asphalt and other industrial debris in the vegetable and flower beds of the farm—a reflection of the intensely urban surroundings, which includes apartment buildings, processing plants, and a public transportation train track. The farm produces approximately 10,000 pounds of organic produce annually, which is distributed through community supported agriculture (CSA) and food access programs, and is worked regularly by two dedicated farm managers, a cohort of interns, and regular volunteers.

The industrial context of MAP-CW-20 creates a specific set of problems, particularly with water drainage resulting from the severe soil compaction caused by the historical presence of pavement. When asked how scientists could help the farm identify solutions to these issues, the farm manager described personal experiences in which people in academics "... [have] their own curiosity they're trying to explore, and they're trying to find that one place where they can explore that instead of being more open-minded to problems that might already exist. I think it goes back to the question of whether they're trying to serve their own curiosity or are they trying to serve a larger need? If somebody is trying to serve a larger need, you go to the community and you ask them what they need."

In the case of MAP-CW-20, the community is the farm and the surrounding residents, and the manager says they are her primary motivation behind wanting to learn more about the farm. "Feeding the community. That's the end of the day. In general, this country has an issue with our health, and our wellness, and a disconnect from the land, and I think farming solves a lot of those problems. I mean, small-scale farms can't fix everything. This community around the farm is a low-income community. Learning how to best serve this land so that it provides nutrition and health for the surrounding community, so the community can take it back—that's my main motivation. I know that probably won't happen in my time at this farm, but it's my hope."

DGS-CW-20

DGS-CW-20 is the sister farm to MAP-CW-20 and located in central Denver. It is a vegetable operation encompassed on a one-acre portion of a K–8 public school campus. Prior to the farm's construction, the site consisted of pea gravel cover, and then a brief period of low-mow, low-irrigation turf mix before the site was fully transitioned to crop production in 2010. Today, the farm distributes 10,000 pounds of food annually through CSA and access programs and supports on-farm education for the school and surrounding community.

The founder and former manager of DGS-CW-20 highlights difficulty finding the time and money to participate in scientific research as major barriers to keeping up with the constant change and evolution of the farm. “Everything is changing all the time and even at [DGS-CW-20] 10 years in we’re still learning about the soil structure and how to best work with it, so the fact that every year is different means that we constantly have to try to be in touch and gather the data we need to make management decisions. I want to say that we’ve learned a lot about the soil over the years and we know what we’re doing, but I don’t really think that’s ever the case!” She notes that the high cost of lab soil tests severely limits the amount of information the farm crew can gather and synthesize to identify patterns in soil health and plant growth. Access to regular soil tests and assessments of ecosystem pressures, such as pests and disease, with guidance from outside experts would better help the farmers to stay on top of factors affecting crop yields and the agroecosystem overall, rather than “[having] to backpedal a lot and tread water to try to keep up with it, which is really intense and causes a lot of burnout [for farmers].”

JSG-CW-20

In Longmont, north of Denver and about 10 minutes northeast of Boulder, JSG-CW-20 is in the process of transitioning from several decades of conventionally farmed alfalfa to an experimental, research-based organic vegetable and agrivoltaics operation. The five-acre property consists of unirrigated grasses and alfalfa grown in industrially levelled land. A large-scale array of 3,200 solar panels has been installed to provide energy for over 300 homes and businesses. Beneath the array are research plots for soil scientists, biologists, and ecologists interested in the effects of solar panels on ecosystem and growing conditions. The vegetable production operation will launch in 2021.

The owner at JSG-CW-20 does not identify himself as a farmer or scientist but is interested in providing space for farmers and researchers to work together at the intersection of agrivoltaics to “… create an example. It’s an educational project, it’s my livelihood and the farm’s livelihood, and I like having a lot of people on the land. Whatever you decide to do, it’s so much easier if you can find people to do work with you. 100 percent. And there’s always going to be somebody out there, it’s just a matter of taking the time to find them.”

He articulates the lack of collaboration between farmers and scientists as a problem of communication. “I bet most farmers would be interested in having more science done on their farms, and that a lot of scientists would think farmers would be more resistant to that idea ... if researchers were looking at Google maps and found the perfect farms they wanted to study, they should just drive out and talk to the farmer, and whatever they're asking should start out as very noninvasive, like measuring things that could help the farmer get a better sense of what's going on before engaging in a more intensive activity. Just sitting down and talking to people makes it a hell of a lot easier to learn than trying to call or email or trying to contact the local politician to find their favorite farmer. Just look at the map, start talking to people, and see who says yes."

FEL-CW-20

FEL-CW-20 identifies a sample taken from one small field in the vast context of a 5,500-acre farm located outside of Sterling, on Colorado's eastern plains. The farmer describes the geologic history as "... [once] completely underwater, which created the limestone formations you see out here, and it's been native grass ever since. We sit up upon sand dunes [outside of an ancient river valley] ... and the limestone is what creates the cliffs and high ground that we sit on at an elevation 500 feet above the valley. And then the soil really varies [because of historical sediment shifting]—sand, caliche, loam—but there's not very much topsoil anywhere in this part of the state." The farm is a fourth-generation, conventional operation focused on dryland crop production, such as wheat, milo (sorghum), millet, sunflowers, corn, and hay, in addition to grazing a midsize herd of cattle.

Compared to the other farmers I spoke with, who all run smaller operations, the farmer at FEL-CW-20 conducts research and engages with science on a scale more conducive to her large operation. She relies heavily on guidance from nearby research stations and extension offices and frequently attends conferences and seminars about certain crops or soil health; however, she must be particular about what methods she chooses to implement simply because one solution does not perfectly fit all 5,500 individual acres of her farm. "I think part of the problem is getting the science to trickle down [to farmers] ... How do you take what the ag schools are researching and finding out and a) make it appropriate for where we are—research in Kansas isn't the same as eastern Colorado, and b) how do you make it something we can digest? To be honest, I'm not going to go read the journals, but where can I find those quick briefs on what's happening? The magazines try to do it, but they aren't always specific enough, but that's where we can learn about different grazing patterns or different seeds we haven't used before. Yet they tend to be more topical ... I think it would be cool if more direct research and communication was available. We haven't figured out how to tap into that yet."

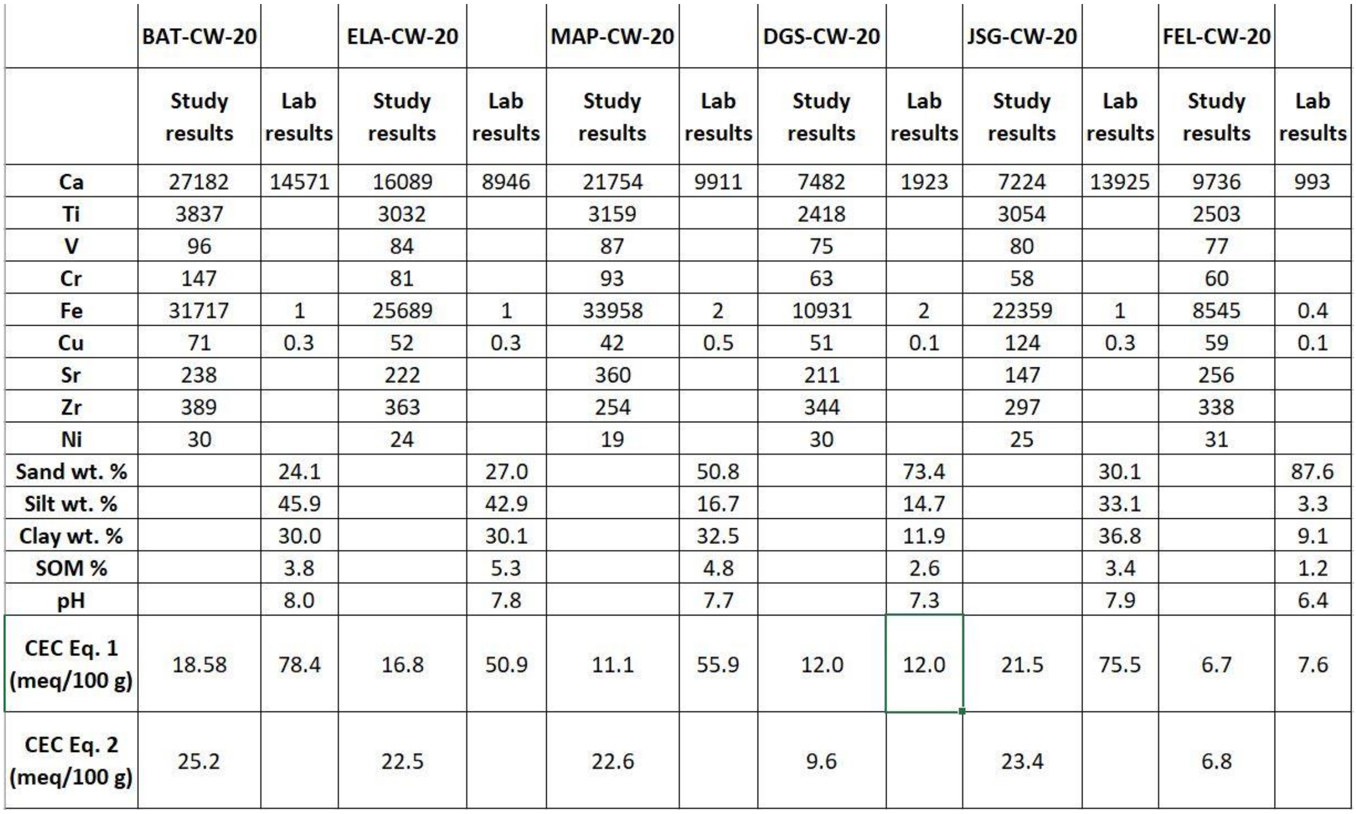
Soil Chemistry Results

Equations for converting from measured intensity to element concentration derived from the calibration curves are found in Table 1. The equations for strontium and nickel were chosen based on the removal of outliers that skewed the standard data. All R^2 values are above 0.95 except for iron. For all other elements, vanadium, nickel, and chromium display the greatest uncertainty with the lowest R^2 values. Copper, zirconium, and titanium show the greatest certainty based on their R^2 values, although Cu shows a standard error of slightly above 40 percent when standards are run as unknowns. The Appendix contains more information on how these equations were selected.

Element	Average standard error in percent	Equation for concentration calculation	R^2
Ca	16.8	.0748x + 633.45	0.973
Ti	6.2	.0304x	0.995
V	20.2	.0018x	0.957
Cr	13.1	.0146x - 501.73	0.955
Fe	6.3	.0184x - 9472.6	0.868
Cu	41.2	.0129x - 654.38	0.999
Sr	15.5	.007x - 366.93	0.984
Zr	2.4	.003x	0.999
Ni	25.8	.0009x - 59.183	0.965

Table 1. Equations for converting from measured intensity (x) to concentration of each element of interest in ppm.

Table 2 depicts the results when calculating element concentrations present in each soil sample using the equations from Table 1. All samples consistently have elevated concentrations for iron, calcium, and titanium.



	BAT-CW-20		ELA-CW-20		MAP-CW-20		DGS-CW-20		JSG-CW-20		FEL-CW-20	
	Study results	Lab results	Study results	Lab results	Study results	Lab results	Study results	Lab results	Study results	Lab results	Study results	Lab results
Ca	27182	14571	16089	8946	21754	9911	7482	1923	7224	13925	9736	993
Ti	3837		3032		3159		2418		3054		2503	
V	96		84		87		75		80		77	
Cr	147		81		93		63		58		60	
Fe	31717	1	25689	1	33958	2	10931	2	22359	1	8545	0.4
Cu	71	0.3	52	0.3	42	0.5	51	0.1	124	0.3	59	0.1
Sr	238		222		360		211		147		256	
Zr	389		363		254		344		297		338	
Ni	30		24		19		30		25		31	
Sand wt. %		24.1		27.0		50.8		73.4		30.1		87.6
Silt wt. %		45.9		42.9		16.7		14.7		33.1		3.3
Clay wt. %		30.0		30.1		32.5		11.9		36.8		9.1
SOM %		3.8		5.3		4.8		2.6		3.4		1.2
pH		8.0		7.8		7.7		7.3		7.9		6.4
CEC Eq. 1 (meq/100 g)	18.58	78.4	16.8	50.9	11.1	55.9	12.0	12.0	21.5	75.5	6.7	7.6
CEC Eq. 2 (meq/100 g)	25.2		22.5		22.6		9.6		23.4		6.8	

Table 2. Soil test results from this study and from the UMass lab for each sample. Element concentrations in ppm. CEC Equation 1 and Equation 2 calculated following Sharma et al. (2014).

The results from the UMass lab are also included in Table 2. Soil texture results from the UMass lab are plotted on a soil ternary diagram (Figure 3). Four of the samples are a variety of clay loams, and two of the samples are of a sandier texture. In general, a correlation exists between higher clay content of the soil sample and a higher CEC value, and a higher sand content and a lower CEC value.

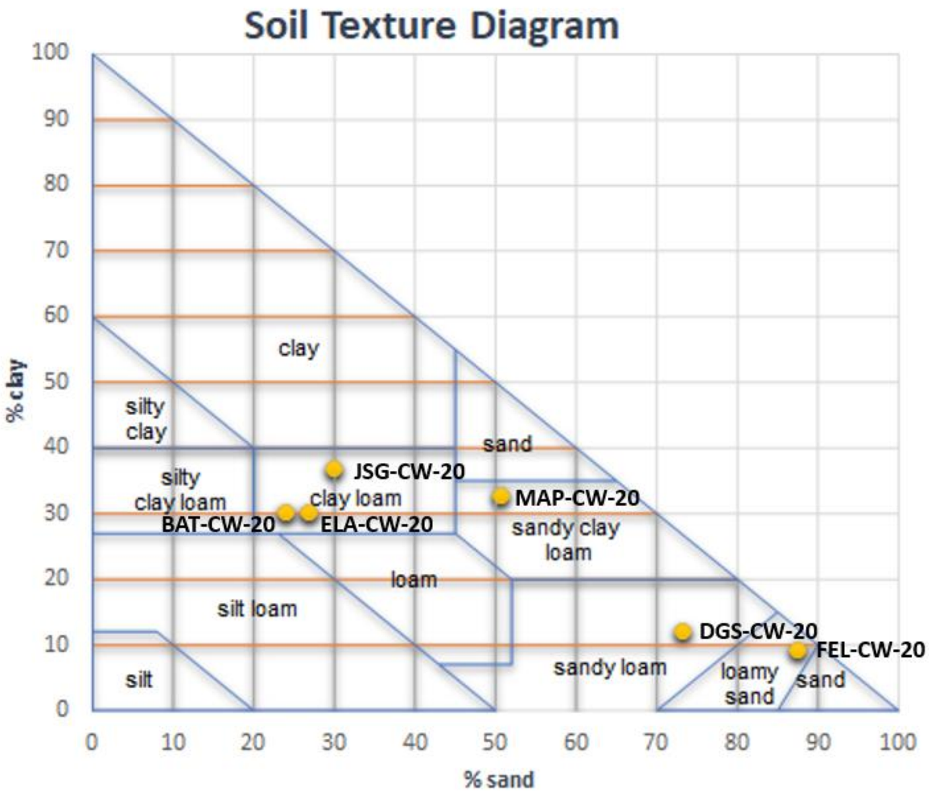


Figure 3. Study samples plotted by soil texture type (Gerakis and Baer, 2000).

Based on the results in Table 2, there is a correlation between higher pH and higher lab calculated CEC values (Figure 4).

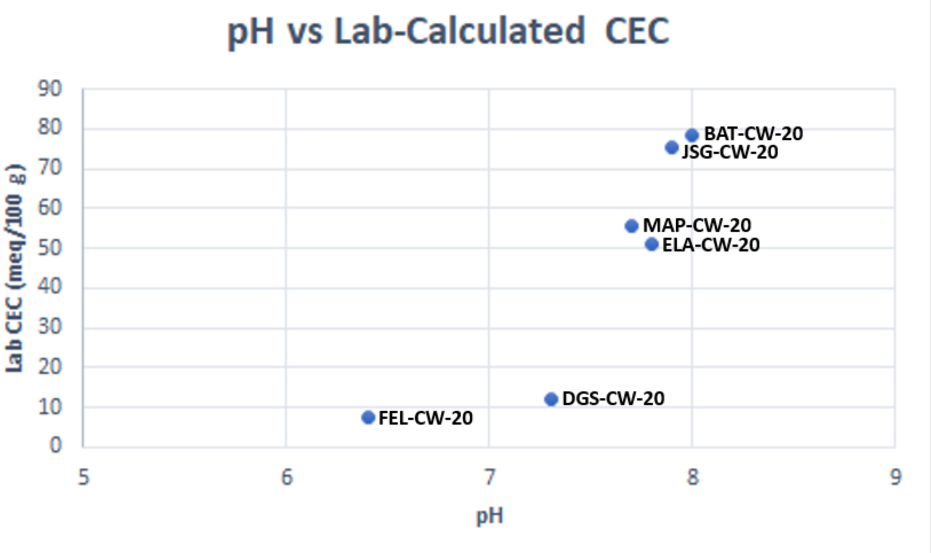


Figure 4. Graph depicting the relationship between lab-calculated CEC values and sample pH.

For the purposes of this study, CEC was calculated using two different equations from Sharma et al., 2014. Equation 1 uses solely elemental data collected using the PXRF, while Equation 2 uses some elemental data collected from the PXRF combined with soil textural data from the UMass lab. The CEC values calculated for this study using both Equation 1 and Equation 2 are lower than the lab CEC values for four of the samples, while CEC calculations for two of the samples resulted in comparable values with the UMass lab data (Table 2 and Figure 5).

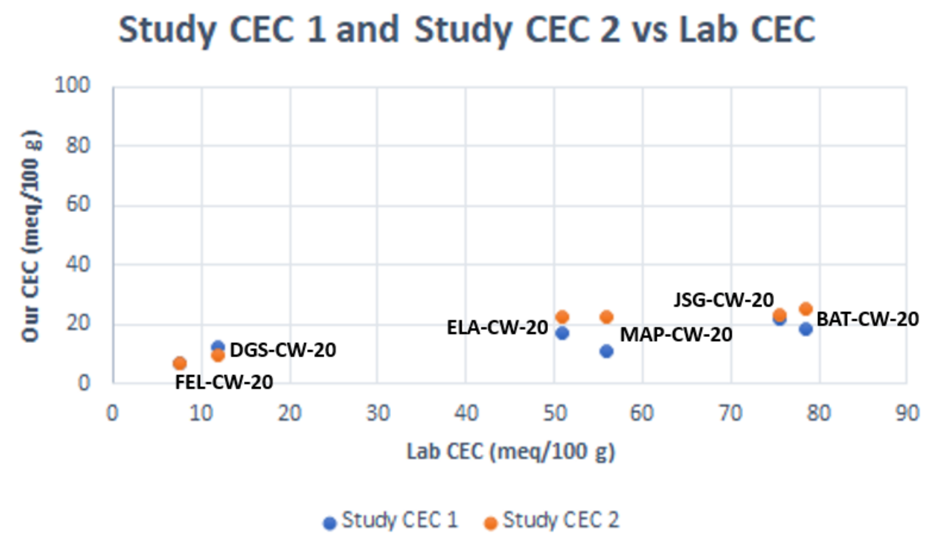


Figure 5. Comparison of study CEC values calculated using Equation 1 and Equation 2 and lab-calculated CEC values.

To test the sensitivity of the CEC equations using data from the PXRF instrument, the average standard error in percent for the concentration of the element copper (41 percent) was used to determine the upper and lower boundaries of the concentration range, which were then used to calculate CEC using Equation 1 (Table 3). Copper was chosen because it has the largest margin of error (Table 1) of the elements of interest and has a significant effect on the results of Equation 1 because of its coefficient and exponent. Based on these calculations using the maximum and minimum possible concentration values for copper, CEC varies from 10.9 to 11.4, which is not a major difference.

	Calculated concentration	Concentration at top of error range	Concentration at bottom of error range
Cu	42	59	25
CEC Eq. 1 (meq/100 g)	11.1	11.4	10.9

Table 3. Instrument sensitivity test calculations for the element copper.

Discussion

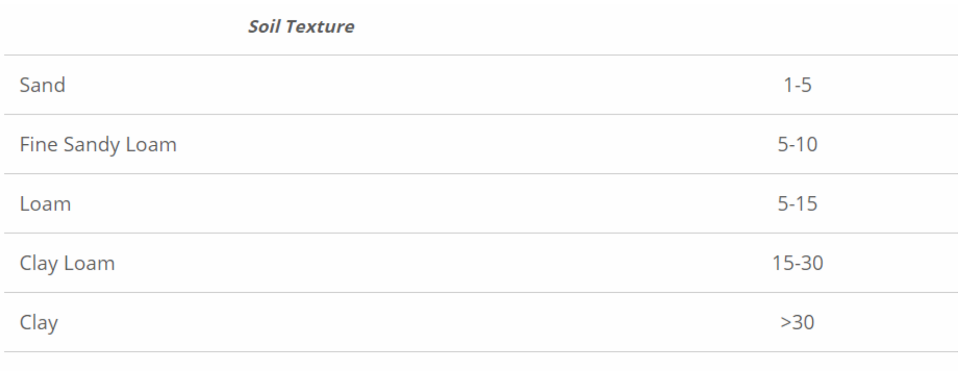
Calculation of CEC

Equation 1 is the best option for calculating soil CEC values with PXRF data because it yields, on average, values closer to external lab measurements (see Table 1) and requires only elemental data for the calculation, whereas Equation 2 requires soil texture and organic matter data that cannot be collected quickly or accurately in-field and must be provided by a lab. The calculation of CEC is not very sensitive to the accuracy of the PXRF-derived concentrations; as long as the PXRF measures within the “ballpark” of the actual concentration, the equation is effective for calculating usable CEC values. Small variations between the upper and lower thresholds of possible CEC values for a given concentration, as in the error calculation for the element copper, will not make a significant difference in how a farmer will use CEC data in their soil health plan.

Effect of pH and soil texture on CEC

Soil cation exchange capacity varies considerably with soil pH and is therefore most commonly measured at a soil pH of 7.0, because CEC measurements taken from soil with a pH greater than 7.0 are often overestimated (Sonon et al., 2017). CEC values calculated for this study were closest to the lab measurements for samples DGS-CW-20 and FEL-CW-20, each with a pH of 7.3 and 6.4, respectively (Table 1 and Figure 3). UMass lab results were provided with the disclaimer that CEC values could be overestimated for samples with a greater pH than 6.8.

More accurate CEC values for a given soil correspond directly with soil texture, which can give us an idea of how much lab-measured soil CEC may have been affected by soil pH. Because of the direct relationship between soil texture and CEC, an appropriate range of values for CEC exists depending on that soil texture, which can be found in Table 4.



Soil Texture	
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	>30

Table 4. Appropriate range of CEC values for soil texture types measured at a pH of 7.0 (Sonon et al., 2017).

For samples with a pH greater than 7.3 in this study, the CEC values calculated using Equation 1 fall within the range of appropriate values for the corresponding soil texture, while the CEC values calculated in the UMass lab fall far outside the range of expected values. Therefore, PXRF measurement of soil CEC yields more accurate results that correlate with appropriate CEC values for a given soil texture compared to lab measurement methods.

Effectiveness of PXRF vs. Lab

PXRF calculation of CEC is a more effective method than lab measurements for several reasons. Based on the test calculation using the element copper in Table 3, PXRF does not require a high degree of instrumental precision to receive accurate results that are useful to farmers. A one- or two-digit difference in a CEC value will not drastically impact the resulting steps a farmer might take to improve their soil health, and instead gives them an accurate idea of where their soil stands in terms of exchange capacity. PXRF calculation of CEC is not impacted by other chemical characteristics such as pH, which can cause traditional lab method results to be overestimated and provide an inaccurate portrayal of soil CEC. Finally, the PXRF method is an easily replicable, understandable process that is more cost-effective for farmers than sending soil samples to an external lab and has the potential to yield immediate results farmers can use right away to make decisions about soil health on their farms, rather than having to wait several days or weeks for data that may no longer be applicable to the rapidly changing agroecosystem.

PXRF technology as a solution for farmers

In-field use of PXRF technology for the measurement of CEC and other soil health factors creates an essential opportunity for scientists and farmers to resolve many of the discrepancies present in their research relationship. Farmers interviewed for this study highlighted the need for an increased “boots-on-the-ground ” approach by scientists, in which they visit with farmers in their agroecosystemic context to better understand issues they face and questions they might have. Then, farmers and scientists can develop a research process together to overcome many of the time and cost obstacles that discourage farmers from frequently participating in traditional scientific research. Conducting research in this “farmer-back-to-farmer" format also provides scientists with more direct circumstances in which to present and communicate their conclusions in ways that are relevant to the communities they impact, and effectively disperse these results so they might be applied and used more widely than they would otherwise.

PXRF can act as a catalytic form of technology for these relationships by creating an overlap point for scientists to meet farmers where they are. The portability of PXRF makes it easy to bring the technology into the field and encourage conversation between scientists and farmers regarding practices and environmental factors that might influence study results that scientists may not be aware of by simply analyzing samples in a closed lab setting. The replicability of the PXRF procedure and immediacy with which data can be obtained also proves to be more cost- and time-effective for farmers than collecting and mailing samples to an external lab for processing. Farmers can choose where and how to collect soil samples based on their own methods because the sampling process does not drastically impact the effectiveness of PXRF measurements. The capacity of the PXRF to analyze more than one sample also means the farmer is no longer limited by cost for multiple samples or by the number of areas they can have analyzed.

Future Work

Future work to elaborate on the results of this study should be two-fold: increasing the number of soil samples analyzed by the PXRF and used to calculate CEC, and specifically focusing on the analysis of soils with a pH at or less than 7.0 in order to further test the ability of the PXRF to accurately calculate soil CEC without the influence of outstanding chemical characteristics that cause overestimation by traditional lab methods.

Conclusion

Differences in knowledge systems, professional experiences, and practical concerns such as time and cost can create obstacles to successful collaborative research between farmers and scientists. The development of agricultural technology presents a potential overlap point for the improvement and maximization of these relationships. Successful use of portable X-ray fluorescence instruments for the accurate analysis of soil cation exchange capacity, though only a recently studied phenomenon, is one such technology. The creation of an in-field PXRF method helps to close the gap between farmers and scientific procedures associated with their farms, more directly benefit the farmers involved, and provide scientists with opportunities to better understand the social and cultural context in which the results of their research will be used.

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Appendix

A detailed account of the methods used in this study, raw data files, original spreadsheets used for calculations, and supplemental materials are available as an electronic supplement stored with Dr. Meagen Pollock at the College of Wooster.