Soil Variability and Fertility Management

6

D.W. Franzen*

Chapter Purpose

Among the numerous challenges of crop production is the management of soil nutrients, soil moisture content and crop and soil variability. One of the first problems that was addressed in precision agriculture was site-specific nutrient management (Pierce and Nowak, 1999). Since then, advancements have been made in the creation of mathematical approaches that can be used to help match fertilizer recommendations to soil and crop productivity. This chapter will review sources of soil variability and current management tools and techniques to help growers manage soil variability.

Sources of Soil Variability

Variability can result from many factors, including those from inherent differences produced during soil development, the result of erosion following tillage, and systematic errors from uneven application of fertilizers and manures (Franzen, 2011). Variability is discussed in more detail in Chapter 2 (Kitchen and Clay, 2018).

General Soil Sampling Basics

Soil sampling is variable in three dimensions (Van Meirvenne et al., 2003). There is two-dimensional variability that is most often considered: forward, backward, and side to side. But there is also vertical variability. The importance of vertical variability has changed with me. For example, when a plow was used to prepare a seed bed. Soil was mixed relatively uniformly vertically, whereas conservation tillage concentrate many of the nutrients in the surface two inches. The nutrient recommendations are based on a specific depth within region, state, province, country, so it is important for the sampler to know where the recommendations will be made and on what depth the recommendation is based (Franzen and Cihacek, 1998; Reisenauer, 1978; Sikora and Moore, 2014; Dairy One, 2017). An extensive discussion of the strengths and limitations of different models that can be used to site N management is available in Morris et al. (2018).

A complication in soil sampling is the use of a banded fertilizer phosphate (P) and potassium (K) application by many farmers (Kitchen et al., 1990; Mahler, 1990; Tewolde et al., 2013). A banded application is a reduced width, concentrated fertilizer application made in the same furrow with the seed, or spread laterally at a reduced width relative to row spacing along each side of the seed furrow, or applied at the soil surface over the row, or near the row, or to the side and below the seed in a separate furrow. These applications could be made every year, or in random years. These bands can complicate collecting representative soil samples for many years. If previous bands are suspected, appropriate sampling protocols should be followed (Fig. 6.1). In this case, multiple soil cores should be

D.W. Franzen, North Dakota State University, Soils Department, P.O. Box 6050, Fargo, ND. * Corresponding author (david.franzen@ndsu.edu).
doi:10.2134/precisionagbasics.2016.0091

Precision Agriculture Basics. D.K. Shannon, D.E. Clay, and N.R. Kitchen, (eds.).

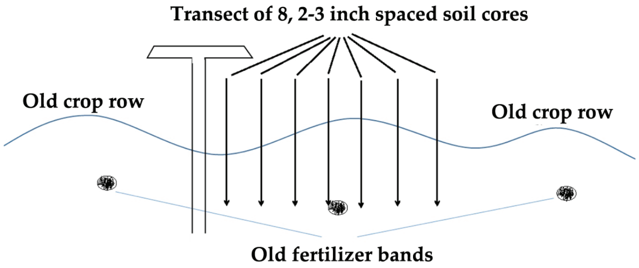


Fig. 6.1. Sampling strategy for soil P and K in a transect perpendicular to row direction spanning at least one complete row. Sample depth could be 6 to 8 inches depending on the sampling depth basis of regional, state, province or state P and K recommendations.

collected from a transect that is perpendicular to the row. In fields were banding is not practiced, or the band application is small, for example 5 to 10 pounds per acre P_2O_5 (5.6 to 11.2 kg ha^{-1}) in a seed band for corn, then 5–8 soil cores should be collected in a 10–30 foot radius around a central point (called cell sampling).

Original Soil Development

The five soil forming factors (Jenny, 1941) are parent material, vegetation, climate, topography and time. Differences within a field due to parent material are not immediately evident in many Corn Belt fields due to the mantle of loess that overlays the parent materials underneath. However, parent material differences are often the reason for crop productivity differences beneath the loess in the US Corn Belt states. Internal drainage differences are greatly affected by subsurface texture under loess, just as they are in soils with no loess cover. The depth to subsurface parent material is also a crop productivity factor. Loess depth next to the Mississippi River in eastern Iowa and western Illinois is up to 100 ft (30 m) thick, and is responsible for all relevant internal drainage properties of those soils (Leighton and Willman, 1950). As distance from the Mississippi increases, the depth of loess cover decreases, so in east central Illinois the depth is only 2 ft (60 cm) thick. In Indiana, loess depth is only 1 to 1.5 ft (30 to 45 cm) thick. As the surface loess thickness decreases, the properties of the glacial till, outwash and residuum become important in determining soil productivity. Glacial till variability is great at small spatial scales (Khakural et al., 1996; Franzen et al., 2002). As the glaciers melted, sands became present as a result of fast-moving meltwaters, loams became present in areas of slower moving meltwaters, and clays became present in areas where waters were slowly moving or still as at the bottom of glacial lakes.

Parent materials also include alluvium and residual materials. Residual materials originate from rocks that weather in place. In western North Dakota, for example, different soil textures within a field are present at different elevations due to layers of sandstone or siltstone (Fig. 6.2). A soil originating from sandstone has less available water when compared with a soil originating from a siltstone.

In the coastal plains of the eastern United States, the development of the present coastline has resulted in swirling patterns of sands of different silt and clay content (Duffera et al., 2007). Soils with less silt and clay are more susceptible to mid-season drought, while those with greater silt and clay content are more resistant to drought, due to their greater water-holding capacity. In central Missouri (Kitchen et al., 2005), the loess layer is relatively thin, and some soils have a very high clay content layer beneath the loess. Depth to the clay layer or 'clay pan' as it is called, determines the relative productivity. The shallower the depth to the clay pan, the lower the productivity, while greater depth to the clay pan results in higher productivity. Roots and water have difficulty penetrating the clay pan, resulting in greater mid-season drought susceptibility when the depth to clay pan is shallow, and more resistance to drought with greater depth to the clay pan. In some areas of the southeastern Corn Belt, a limiting layer known as a fragipan is present (Grossman et al., 1959). A fragipan is a pedogenic layer of soil cemented with silt-like material which is nearly impermeable to roots and water. Presence of a fragipan seldom affects entire fields, but results in poor rooting depth, poor drainage and poor drought resistance in the areas where it is found.

Salinity

In some soils, areas of high sodium, or sodic, soils are present. The sodium may originate from sodium-bearing rocks, such as sodium feldspars in the parental loess materials in south Illinois, or from shales in North Dakota and South Dakota (Wilding et al., 1963; Willard, 1902). In the area west of Grand Forks, ND, some sodium-affected soils are the result of salty artesian systems from deep underground ancient sea deposits, such as areas west of Grand Forks, North Dakota (Franzen et al., 2002). Excessive soil sodium results in a randomization of the soil clays that greatly reduce water percolation and crop rooting depth. In low-sodium, higher-calcium soils, clays tend to bind together in regularly structured micro- and macroaggregates. These aggregates have shear planes, which allow penetration of water and root growth. Sodium soils have few shear planes except at the edges of large structural columns, limiting productivity greatly compared with low-sodium companion soils.

Video 6.1. How can the knowledge of spatial variability facilitate decision making in fields? http://bit.ly/spatial-variability

Salinity is a worldwide problem. It has been estimated that by 2150, 50% of arable lands will have salt limitations for crop production (Jamil et al., 2011). From the eastern edge of the Great Plains to the Pacific Ocean, the presence of soil salts due to shallow, salty water tables is extensive. Soils mapped as productive during a relatively dry extent of time may become saline and unproductive following years of greater-than-normal rainfall and more shallow water tables. Excessive salinity reduces crop productivity due to its effect on water uptake and nutrient utilization. Large areas of salinity have prevented crop production in some regions; however, in other areas the saline or sodic areas may be relatively small. Sometimes, salinity develops along the edge of drainage ditches, whereas in other fields it occurs along the margins of wet areas, or from seeps. Still others develop at the edges of natural ponds or potholes. The spatial extent of these areas increase and decrease like tide water at the sea shore as a result of rainfall patterns. Techniques to mitigate these problems often include installing tile drainage, planting salt tolerant plants, planting cover crops, and returning these areas to perennial vegetation (Franzen, 2003).

Erosion

In areas to the east of the North American Great Plains, water erosion is a major factor impacting long-term sustainability. In shoulder areas and ridge tops, much if not all of the original top soil has been lost over time. In valley floors, depressions, and toe slopes, some of the A horizon has been deposited. Nutrients from the higher landscape positions accumulate in the lower landscape positions, which often results in higher soil nutrient availability in depositional areas than eroded zones. With the loss of topsoil, crops often have a greater reliance on fertilizers and tillage to maintain and increase production. Problems such as crusting and susceptibility to drought and adverse weather fluctuations have increased these problems.

In the North American Great Plains, billions of tons of soil were lost from the 1880s through today through wind erosion (Franzen, 2016). The 1930s were particularly catastrophic (Fig. 6.3). In North Dakota for example, an average of at least six inches of topsoil were lost from half of the cropland acres. Nine million acres of cropland, or about one-quarter of the total state cropland, was destroyed for future crop production and are now classified as 'range'. According to eye witness accounts, in some storms 'feet' of soil was lost from some fields. Although climatic conditions have improved since the 1930s, and although large areas have been no-till or modified no-till farmed since the 1970s, the combined impacts of wind and water erosion continues to influence agricultural production (Fig. 6.3; Sharratt et al., 2017). Based on soil characterization at a site

Fig. 6.2. Landscape in western North Dakota near Hettinger. Soils within a field could be the result of weathering more than one sedimentary parent material.

northwest of Grand Forks, ND in the early 1960s compared to 2014, a total of 19 in of topsoil was lost. The total soil phosphate lost in North Dakota from the 1930 until 2015 is equivalent to 70 yr of P fertilizer application at today's present historically high rates. As a result, patterns of P and K are strongly related to landscape position, despite years of fertilization.

Fig. 6.3. A wagon in South Dakota, 1934, nearly covered with eroded topsoil (Source: USDA). Aftermath of topsoil erosion due to wind, northern Red River Valley, North Dakota early 1990s. A. C. Cattanach, American Crystal Sugar, retired, image used with permission.

Fig. 6.4. Manure misapplication northwest of Fargo, ND.

Reports from newly cultivated lands in the 1880s in North Dakota indicate wheat yields using questionable varieties and ancient seeding practices were as great as 70 bushels per acre (4.7 Mg/ha). After subsequent soil loss, yields were no more than half of the original average yields for the state until the use of fertilizer beginning in the 1960s. Productivity of hilltops and slopes is low compared to depressions, mostly due to the lack of topsoil, which results in increased crusting, lower water holding capacity, and surface layer presence of high lime, which was originally capped with high organic matter soils at the surface, but are now gone and more susceptible to conditions such as iron deficiency chlorosis and water stress (Chaves et al., 2002). The adoption of reduced tillage systems and cover crops can be used to improve soil health and reduce soil nutrient losses (Dozier et al., 2017).

Systematic Variability

Application of fertilizers and manures can result in systematic variability (Fig. 6.4). Systematic variability is non-natural soil variability due to the activities of human. Examples of systematic variability are application of fertilizer and/or manure either too close, resulting in increased nutrient content in strips in the direction of travel, and application of fertilizer and/or manure too far between passes, leaving untreated strips of soil between wider strips of applied nutrients. Other less common examples of systematic variability are hydraulic oil pressure problems on the fertilizer and/or manure applicator that reduces the ability of the fertilizer applicator to fling fertilizer and/or manure the usual distance from the center of the applicator, concentrating most nutrients toward the center of the application pattern; with spinner fertilizer applicators, application of fertilizers higher in dust or with varying sizes of fertilizer granules result in uneven application patterns; the integration of smaller fields of different cropping and fertilization histories into larger fields can also be considered systematic variability. Nutrient factors particularly affected long-term by systematic variability are P, K and soil pH. Systematic variability is a greater problem long-term in fields fertilized with high fertilizer rates during nutrient buildup applications. Additional examples of man-induced variability are provided in Chapter 2 (Kitchen and Clay, 2018).

Soil Sampling Strategies for Site-Specific Nutrient Management

Grid Sampling

Soil sampling strategies for site-specific nutrient management are based on grid sampling or zone sampling. The grid sampling philosophy is based on the assumption that nutrient levels are random, unrelated to anything in nature, and should be sampled without any sampler bias toward where to place the sample locations. Zone sampling philosophy assumes that nutrient levels and the patterns in which they appear in a field are the result of some logical reason. Examples demonstrating how to determine management zone boundaries are provided in Clay et al. (2017).

Grid sampling is used and preferred in regions where past fertilization or manure application has been high. Native fertility levels that tend to be zone-based have been masked and overwhelmed through past fertilizer and manure applications. Grid sampling is used when there is no apparent logical method of dividing a field into relatively homogeneous areas. A grid sampling strategy uses a sufficiently dense grid of samples to reveal fertility patterns within a field. Not all fields have patterns of nutrient availability, but this is only revealed through sufficiently dense sampling (Franzen and Peck., 1995).

There are several grid sampling strategies that have been used in the past and at present. These include random (Fig. 6.5), random cluster (Fig. 6.6), systematic (Fig. 6.7), staggered start (Fig. 6.8), and systematic unaligned (Fig. 6.9) (Wollenhaupt, 1996). Random sampling might be appropriate in a field with no recent history of fertilization or manure, such as a government set-aside program break-out field or an old pasture to be converted to cropland. Regular systematic was a common grid sampling approach in the era before GPS (global positioning system) receivers. This approach allowed a sampler to use a vehicle tachometer or even "step off" distances to achieve the desired pattern. A staggered start systematic recognized that systematic errors in one direction are possible, and the start and end of each sampling rank was offset to try to compensate for these errors in one direction. The clustered approach is a type of random sample that might help compensate for small-scale variability and larger-scale variability by grouping

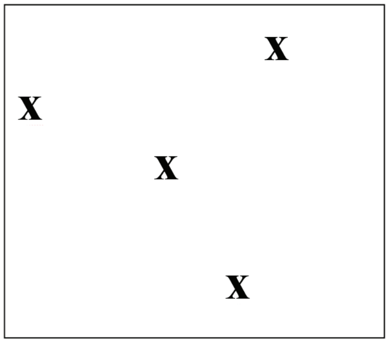


Fig. 6.5. Random sampling example.

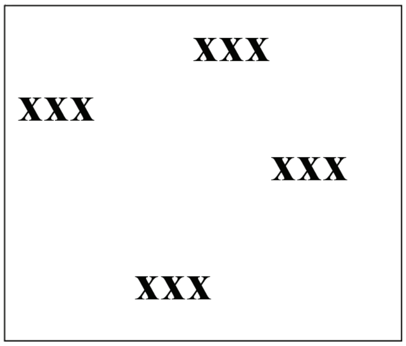


Fig. 6.6. Random cluster sampling example.

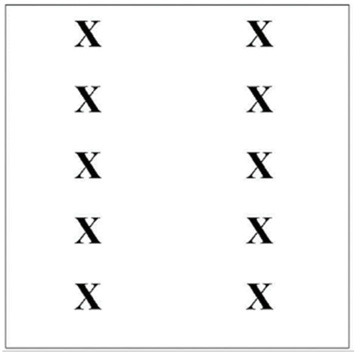


Fig. 6.7. Regular systematic grid sampling example.

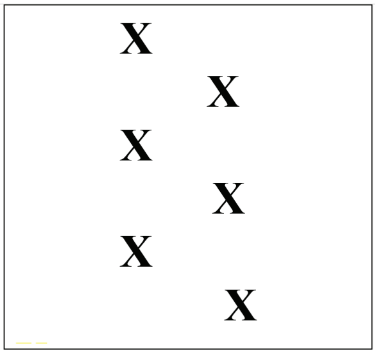


Fig. 6.8. Staggered start (or triangular, or diamond) grid sampling example.

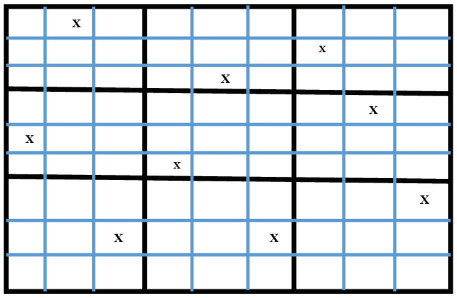


Fig. 6.9. Systematic unaligned grid sampling example.

two to three sample core composites around random points. The systematic unaligned grid was made practical through a combination of GPS and field software that would allow random grid locations within a systematic grid. This approach minimizes the effects of systematic errors in two directions. It is also the method that most supports kriging: the statistical interpolation method that relates distance to value estimation between sampling points. The systematic unaligned grid is probably the method most used by commercial grid samplers today. Additional information on kriging and spatial statistics is available in Hatfield (2017).

Selecting the systematic unaligned grid minimizes the effect from streaks of under- and overfertilized areas of a field as a result of fertilizer and/or manure application traffic. Fields have also been consolidated over the years; therefore, assuming that the present planting direction has always existed is unreasonable. The direction of fertilizer application may have been turned 90 degrees from the original direction by the new operators (Kitchen and Clay, 2018).

Sampling in fields with banded P and K fertilizer applications is an additional challenge due to small-scale variability. Banding more than small amounts of nonmobile fertilizer nutrients leaves a residual level of elevated soil test P and/or K levels in the immediate region of the band. If the bands are oriented in the direction of present rows, it is relatively simple for a sampler to avoid the enriched band under the stubble after the first year. However, after the second year, the sampling strategy is more difficult. Sampling in a transect composite across rows for each sample would help to minimize the errors of sampling a fertilizer band preferentially. This strategy would lend itself to grid-point sampling, rather than grid-cell sampling.

Once a grid strategy is chosen, it is necessary to consider how to collect the composite sample. Single cores should not be used to represent a grid. Recommendations for the number of individual samples that should be composited into a sample range from 5 to 8. From three to five soil cores have been recommended when sampling at depths greater than 10 in (25 cm). When first sampling a field, erring on the high side of sample core number for each composite sample is advised (Rehm et al., 2001).

Grid-point sampling uses the grid-point identified by the sampler as the center of a small area, usually not more than 10-ft (3-m) radius, to obtain the additional two to eight soil cores that will represent the grid-point composite. The basis for using a grid-point is that it addresses small-scale variability better than grid-cell sampling and collecting the sample is relatively quick. In grid-cell sampling, the additional two to eight sample cores are obtained randomly throughout the cell, although some guidelines limit the area to an 80-ft (25 m) radius around the grid-point location. Grid cells usually produce better data than grid point.

To adequately represent field nutrient levels in fields where the range of variability is great enough that different recommendation rates of nutrients are represented, about a sample per acre grid is required (Franzen and Peck, 1995; Franzen et al., 1998). The expense and time required for such intensive sampling has led many growers to use a sampling density less than this, usually one sample per 2.5 acres (1 ha). In regions where soil test P or K levels are high, a lower sample density would provide similar recommendations to the grower. However, in fields where lower nutrient levels are present, the lower density might result in significant under- or overfertilization, since patterns of relative fertility are poorly represented by a 2.5 acre grid. The differences in

Video 6.2. Why is soil testing better with precision agriculture? http://bit.ly/soil-testing-better

the depiction of soil nutrients using different soil sampling density from one sample per acre to one sample per five acres is shown in a series of figures in Franzen and Peck (1995).

Zone Sampling

Zone sampling strategies were developed in North Dakota and other states where a more conservative approach to fertilization has historically been used due to the high frequency of crop failure due to drought, and to a lesser extent, floods. In these areas, patterns of fertility, particularly for residual soil nitrate but also for P, K, soil pH and other nutrients, are stable over time. The levels for particular nutrients may increase or decrease over time, but the patterns they form in the fields are remarkably stable. A number of tools are available to delineate nutrient management zones: topography, satellite imagery, aerial imagery, soil electrical conductivity (EC) sensors, soil electromagnetic sensors (EM), and multiyear yield maps (Franzen, 2008). The use of NRCS–published soil survey boundaries is highly discouraged, because most only depict polygons over 2.5 acres (1 ha) size, and soils change over time. Unfortunately, this is often the first 'tool' that some use to define zones because they are easy to access; however, they should not be used unless the polygons in the soil survey match well with boundaries defined by some of the tools mentioned previously (Franzen et al., 2002).

Topography

Within fields, topography influences crop productivity and nutrient availability to crops. The obvious affect is the thickness of A-horizon (the organic rich layer at the soil surface). In depressions, moisture for previous plants prior to agriculture and to present crops in agriculture is maximized. The water table is generally closer to the surface, since water running downhill from ridges, hilltops and slopes accumulates in depressions. In addition, depressions receive not only rain water and snow melt from the atmosphere, but runoff from neighboring landscape positions. As a result, plant growth is a maximum in most years, and decomposition is minimized due to more reduced oxidizing environment compared with other landscape positions. Excessive rainfall at ridge tops, hilltops and slopes does not have time to percolate into the soil except in the sandiest-textured soils, and lose some of annual precipitation to runoff, resulting in less plant and/or crop growth and less chance for organic matter accumulation. The upper landscape positions are also subject to stronger oxidizing conditions compared to those in depressions.

In addition to influencing A-horizon organic matter levels, internal water flow in landscapes affects nutrient accumulation, transformation, and availability. In areas with climate similar and drier to those in North Dakota and South Dakota, lime tends to accumulate in certain landscape positions due to historic internal water movement. In the Red River Valley of North Dakota and Minnesota, the topography appears flat at first glance. However, slight differences in elevation, perhaps only six inches in altitude variation, result in lime accumulation in the landscape "bumps" due to summer evaporation that is greater than

Video 6.3. Zone sampling vs. grid sampling.
http://bit.ly/zone-sampling-vs-grid-sampling

Fig. 6.10. "Level" elevation in Red River Valley of North Dakota. Severe iron deficiency chlorosis is located on "bumps" in the landscape, where centuries of summer upward water movement has resulted in accumulated lime and soluble salts. Greener areas are leached of lime and salts.

precipitation over centuries. It is common for these bumps to have calcium carbonate levels of greater than 20% by weight and pH of 7.5 to 7.8, while 50 yards away, a more depressional soil may have a pH of about 6 (Fig. 6.10).

Some soils in depressions within the glacial till plains of North Dakota may have high or low pH depending on the direction of water flow in and out of these areas. In what is classified as a recharge depression, where water is flowing through the depression into the soil and outward to somewhere else, pH is often below 6. In a discharge depression, where water flows into the depression subsoil from somewhere else, the water table is shallow and soil pH is > 7. The presence or absence of lime in response to landscape and internal water movement affect soil pH and iron availability. Recharge depressions may develop a need to agricultural limestone applications, whereas areas of high lime do not. Soils with high free lime also develop iron deficiency chlorosis in soybean and other sensitive crops. Areas of high lime occur in both large and small spatial scales. Methods have been developed to determine the boundaries of these high lime areas, particularly those affected by iron deficiency chlorosis.

Nitrogen management is greatly affected by topography and the texture of parent material. Nitrogen in the form of nitrate is affected by two important processes: leaching and denitrification. Soils with a high leaching potential tend to be loamy texture or sandier, on higher landscape positions. Soils with high denitrification potential tend to have a greater clay content in lower landscape positions. In sandier soils, higher landscape positions tend to have less available N than lower landscape positions due to nitrate leaching and deep water tables. In soils with higher clay content, wet seasons may result in N deficiency in depressions due to N loss from denitrification.

Topography influences nutrient levels because water moves through a landscape constantly due to gravity and inherent soil flow-through directions (Ruhe, 1960). Soil-mobile nutrients, such as nitrate, sulfate and chloride are influenced by water moving through the soil. In environments that are subject to leaching, hilltops may have low nitrate following a wet year compared with depressions. However, in environments that support high activity of denitrification, depressions may also be low in nitrate following a wet year. In North Dakota, depressions in the eastern edge of the state are usually very low in nitrate following a wet season, whereas depressions in the western half of the state tend to be high in nitrate after a wet season, probably because denitrification processes are not very active in that environment.

Soil nonmobile nutrients are also affected by topography (Franzen et al., 2006). In a landscape, natural development of available P and K and other nutrients are greatest where there is more moisture: toe-slopes and depressions. Hilltops, ridge tops and slopes generally contain less moisture due to leaching depth at higher landscape positions and runoff during periods of more intense rainfall. Therefore, plants growing at higher landscape positions do not accumulate as much P and K as do crops growing in more favorable moisture conditions and lower amounts of nutrients back into the soil in a more plant-available form after senescence. After these soils are cropped, these same processes influence residual P and K after grain or hay removal, releasing less P and K back into the soil. In addition, erosion history plays an important role in determining the residual P and K and other nonmobile nutrients available in the soil. In North Dakota, nearly all nonmobile nutrients are less available on hilltops and slopes compared with depressions.

The topography relationship may also be important in regions where buildup and maintenance approaches to P and K nutrition have been used in soils with varying productivity. For example, within the Kankakee Outwash Plain of Illinois and Indiana, ridges of sandy materials are arranged between more loamy, higher organic matter soils (Gross and Berg, 1981). Soil P in the higher organic matter soils is relatively low, while the soil P in the sandy ridges is often very high due to lower crop productivity combined with decades of high, uniform P applications. A zone approach would involve separating the field into landscape positions.

Topography is difficult to define within a GIS program. Use of watershed definition tools can be used as a proxy. Use of elevation divided into categories of altitude should be discouraged, because it is not altitude that influences nutrients, but landscape shape (topography). Relative elevation may be acquired with a high-resolution GPS receiver, although altitude contains three times the amount of error as latitude and longitude in these instruments. Some regions have access to LIDAR data, which is highly useful in zone development using topography.

Satellite Imagery

Satellite imagery quality and pixel size have improved during the past twenty years. Where LandSat satellites once provided pixels about 100 ft^2 (30 m), newer satellites in an affordable context provide 10 to 15 ft^2 (3 to 5 m). Additional satellites provide even greater resolution; however, these have not provided additional nutrient boundary definition and result in more confusion of patterns than firm definition. Satellite imagery has the advantage of obtaining large tracts in a single image. However, satellite imagery always has the disadvantage of cloud interference (Bu et al., 2017). As a nutrient management zone delineation tool, an archived image may be acceptable. The image should come from a vegetative season of crop development; in wheat this would be before heading, in corn before tassel, sugar beet and potato it could be anytime, except where disease is affecting the canopy. Images are often digitized into numbers from 0 to 255. Categories can be defined by the person working with the image to correspond with what can be 'seen' in the image.

Aerial Imagery

Aerial imagery from aircraft has been used for many years to identify problems in fields. For use in zone delineation, aerial imagery that data can be collected on cloudy days. However, this is also a disadvantage in that image contains cloud shadows. The extent of the image depends on the altitude of the aircraft. At an altitude of 5000 ft (1500 m), about 160 acres (65 ha) of land can be photographed. There are sophisticated programs available to compensate for cloud shadows, but these are not regularly available for use by practitioners. Unmanned aerial vehicles (UAV's) may eventually be very useful in providing timelier and cheaper images; however, scientists are currently determining strengths and weaknesses of UAV image acquisition. UAV's, unless allowed to operate at the height of aircraft, are forced to take a series of images that are 'stitched' together. The images may be obtained several minutes of time apart, and different sun angles may confound the final imagery. The technology of UAV's is rapidly developing and it is possible that the use of imagery from these devices will become easier to manage in the near future. Additional information on remote sensing is available to Chapter 8 (Ferguson and Runquist, 2018).

Electrical Conductivity

Soil clay content, moisture content, nutrient levels and soluble salts contribute to different electrical conductivity (EC) readings. A popular EC detector is manufactured by Veris Technologies (Salinas, KS). It uses a series of coulters, with electrodes at one of the edge coulters and one internal to send an electrical signal through the soil, which arcs through the soil and is detected in another coulter electrode, providing a 'shallow' EC reading and 'deep' EC reading in a single pass through the field (Fig. 6.11). The coulters are in contact with the soil during readings, and the soil needs sufficient moisture to allow the

Fig. 6.11. Veris Technologies soil EC sensor. Courtesy of Veris Technologies, Salinas, KS.

Fig. 6.12. EM-38 sensor, and electromagnetic sensor, courtesy of Geonics, Ltd., Mississauga, ON.

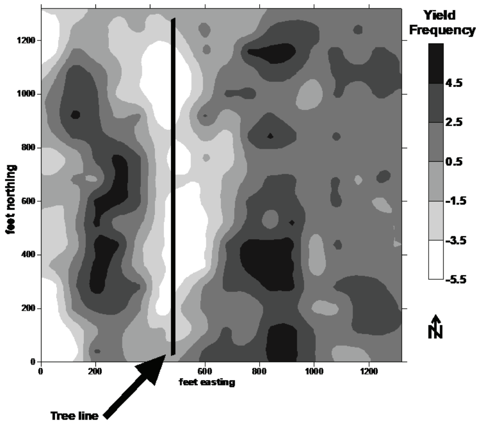


Fig. 6.13. A multiyear yield map of corn and soybean rotations in a 40-acre field near Thomasboro, IL, over 4 yr. Yield frequency is relative yield from the mean (0) value. Positive values are increasing yield over mean yields, while negative values are decreasing yield from the mean. From Franzen, 2006.

electrical signal to travel from one coulter to another. In some regions, the EC readings are directly related to a single soil trait. In regions of low soluble salt content, the instrument can be used to estimate soil clay content, which is useful in predicting crop productivity potential (Sudduth et al., 2005). In other regions, including North Dakota, soil clay, moisture, and soluble salts are present independently of each other. Therefore, the EC detector is a zone pattern detector and may not be related to any particular soil property. The Veris EC detector use is also limited by the frequency of rocks at the soil surface.

Electromagnetic Sensors

Electromagnetic (EM) sensors measure the capacity to measure changes in the soils ability to conduct and accumulate electrical charge (Chapter 9; Adamchuk et al., 2018). In physics, electricity and magnetism are mathematically related, thus enabling the use of either one for a similar purpose. Electomagnetic sensors have been used to map the depth of a clay limiting layer in Missouri. It is also a zone delineation tool, producing zone maps similar to those developed using the EC sensor. The EM sensors can also be used in fields with rocks without harm to the sensor (Fig. 6.12).

Multiyear Yield Maps

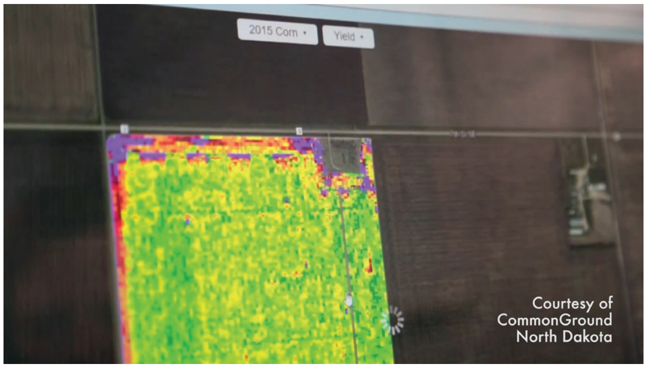
To be most useful, several years of yield maps should be integrated into a multiyear yield map (Franzen et al., 2008; Chapter 5, Fulton et al., 2018). Whether a field has had a history of a single crop or a diverse crop rotation, the same general procedure should be followed to create the multiyear yield map. A field that has been in continuous wheat might average 80 bushels per acre (5 Mg ha^{-1}) one year and 20 bushels per acre (1.2 Mg ha^{-1}) another year. The actual bushels for the field therefore cannot be used when the data sets are combined. If the field was corn one year, soybeans the next, wheat the next, and sunflowers the year after, their yield cannot be added to each other spatially with any meaning. The range of yields in any year therefore must be standardized.

Standardization is a simple mathematical exercise that converts bushels per acre into relative yield. In the example year of high wheat yield with highest yield of 80 bushels per acre (5 Mg ha^{-1}), divide each yield by 80. The range of yield is then 0 to 1. If the next year is canola, and the highest canola yield was 3500 pounds per acre, divide each yield by 3500. The range of yield is from 0 to 1.

When developing a yield map, it is important to clean the data. First, impose a grid on the cleaned combine yield data (cleaning out unreasonable low and high yields due to combine traffic patterns, stops and starts). A second step is to separate the field into grids that correspond with soil samples collected from the field. A field should have at least 40 grids to produce a meaningful map.

To produce the grids and the average yield within a grid, use a software program such as Surfer (Golden Software Co., Golden, CO) or ArcGIS (ESRI GIS Software Co., Redlands, CA) that can import spatial data and then convert them to estimated values. Additional information for geographic information software (GIS) is available in Chpater 4 (Brase, 2018). This estimation feature usually is used for taking less dense data and estimating values at small distances; however, it can also be used to take densely sampled data, such as the thousands of points of yield data or EC data, and average them within a less dense grid of user-choice. In Surfer, the resulting grid file can be saved in an ASCI text file and then uploaded into a spreadsheet.

Within the spreadsheet, the grid is given a +1, -1, or 0 value, depending on whether the average of the grid is greater than the field average, less than the field average or within 0.5 bushel per acre (32 kg ha^{-1}) of the field average. Transforming yields into +1, -1, or 0 is a normalization procedure. Then



Courtesy of CommonGround North Dakota

Video 6.4. How can yield maps aid with soil sampling? http://bit.ly/yield-maps-soil

these normalized grid values can be exported into a spreadsheet and summed by grid with other years' data that have been treated in the same manner. In this way, multi-years can be combined to produce a more meaningful yield map.

The multiyear yield map has been used as a zone delineation tool in North Dakota and using Illinois data. The maps can be used to reveal areas that require additional management, such as a change in N management, or a change in drainage. It can also reveal yield drag due to saline areas, compaction and areas with harmful levels of sodium.

Use of a multiyear yield map helped explain much of the reasons why soil P and K levels alone throughout a 40-acre field in Illinois was not related to yield, but within a multiyear yield zone, they were related (Fig. 6.13).

Combinations of Zone Mapping Tools

Management zone soil nutrient maps are often based on elevation, soil nutrient levels, crop reflectance, EC, and yield maps (Franzen et al., 2011). These maps can be produced by first producing individual zone maps of each tool database for the field. A layering program then is used to superimpose the value and location of each zone map pixel geographically over the corresponding pixel of the other zone map(s). A clustering program then is used to analyze the patterns from each zone map to produce the final multi-zone map. An example of this approach is available in Clay et al. (2017).

The choice of zone number is largely left to the consultant or grower. Usually three to five zones for fields from 40 acres (16.1 ha) to 640 acres (259 ha) are selected. Up to 10 zones have been used to manage fields in extreme cases. There is no absolutely correct number without knowing the underlying spatial character of the field. The developer and end user need to understand that zones are useful to improve management of the field from the present state of uniform management, but that small-scale variability may need to be addressed using additional methods if agronomics and economics of the procedures and tools to achieve them are practical and compatible.

Selecting a Soil Sampling Strategy

Grid sampling has been most useful for farms that have received large amounts of fertilizer or manure in the past, which overwhelms any relic of natural soil nutrient variation. Examples of this are many areas in Iowa, Illinois and Indiana, where the fertilizer "buildup and maintenance" approach have resulted in high soil test levels. There is variability in these fields, but the variability is all in the 'high' range, so the recommendation would be the same. Because of the uniformity of recommendation, a 2.5-acre grid (1 ha) is acceptable in these fields. If there is high variabililty in the recommendation, then a high sampling density may be required to create an accurate map (Franzen and Peck, 1995; Mallarino and Wittry, 2004).

Zone sampling is most useful for soil nitrate where the fertilizer recommendation is based on the residual soil nitrate (Morris et al., 2018). Residual soil nitrate is related to water movement and crop productivity, which is most often related to topography and natural variation. In areas where farmers fertilize using a more conservative 'sufficiency' approach, even soil phosphorus and potassium levels are best delineated using a zone approach. In the sufficiency approach, the farmer fertilizes each crop, and although rate is linked to soil test level, the goal is to apply the most profitable fertilizer application in a given year, not to build a soil test level to a higher fertility status. In Iowa, Mallarino and Wittry (2014) reported that the grid approach was best for soil phosphorus, while the management zone approach was better for potassium and soil pH (Mallarino and Wittry, 2004).

How would one choose a sampling strategy? In a field that has never been sampled for site-specific nutrient application for non-mobile nutrients such as P and K, a screening sampling of a 2.5-acre grid (1-ha) would provide some level of understanding. If the field was well-fertilized in the past using a buildup–maintenance approach, it is likely that nearly all the sample analyses will be in the 'high' range. If this happens, then continued use of the 2.5-acre grid (1-ha) would make sense.

If the sampling came back with a range of values in the low to high range, then it would be best to sample the field initially in a one-sample-per-acre grid to reveal patterns. Once the patterns of P and K were identified, future grid sampling density could be reduced. In the northern Great Plains, if the farmer used the sufficiency approach, then a zone sampling should reveal the same patterns as a one-sample-per-acre grid at greatly reduced cost. If the charge for each grid point from a sampler, and laboratory analysis is $15 per point, the sampling using a 2.5-acre grid (1 ha) would cost $6 per acre ($15 per ha). If the field was in a region where residual nitrate sampling is important the zone approach would nearly always be appropriate.

Chapter Questions

1. How might field topography influence soil nutrient variability?
2. Name four factors other than topography that might influence natural soil nutrient variability.
3. Name two factors that might contribute to systematic variability of soil nutrients.
4. Fields where high rates of phosphate and potash fertilizer were applied in a soil test buildup

program would benefit from which site-specific soil sampling strategy for P and K: grid or zone?

5. Name four possible tools that might be utilized to help delineate soil nutrient zones.
6. What soil sampling strategy is used most often to avoid systemic soil sampling errors and why is it more effective than other strategies?

ACKNOWLEDGMENTS

Support for this document was provided by North Dakota State University, the Precision Farming Systems community in the American Society of Agronomy, the International Society of Precision Agriculture, and the USDA-AFRI Higher Education Grant (2014-04572).

REFERENCES

Adamchuk, V., W. Ji, R. Viscarra Rossel, R. Gebbers, and N. Tremblay. 2018. Proximal soil and crop sensing. Chapter 9. In: D.K. Shannon, D.E. Clay, and N.R. Kitchen, editors, Precision agriculture basics, ASA, CSSA, SSSA, Madison, WI.

Brase, T. 2018. Basics of geographic information systems. Chapter 4. In: D.K. Shannon, D.E. Clay, and N.R. Kitchen, editors, Precision agriculture basics. ASA, CSSA, SSSA, Madison, WI.

Bu, H., L.K. Sharma, A. Denton, and D.W. Franzen. 2017. Comparison of satellite imagery and ground-based active optical sensors as yield predictors in sugar beet, spring wheat, corn and sunflower. Agron. J. 109:299–308. doi:10.2134/agronj2016.03.0150

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P. Ricardo, M.L. Osorio, I. Carvalho, T. Faria, and C. Pinheiro. 2002. How plants cope with water stress in the field? Photosynthesis and growth. Ann. Bot. (Lond.) 89:907–916. doi:10.1093/aob/mcf105

Clay, D.E., N.R. Kitchen, E. Byamukama, and S.A. Bruggeman. 2017. Calculations supporting management zones. Chapter 7. In: D.E. Clay, S.A. Clay, and S.A. Bruggeman, editors, Practical mathematics for precision farming. ASA, CSSA, SSSA, Madison, WI.

Dairy One. 2017. Soil testing. Cornell Soil Analysis Laboratory, Ithaca, NY. http://dairyone.com/analytical-services/agronomy-services/soil-testing/ (verified 15 September 2017).

Dozier, I.A., G.D. Behnke, A.S. Davis, E.D. Nafziger, and M.B. Vilamil. 2017. Tillage and cover crops effect on soil properties and crop production in Illinois. Agron. J. 109:1261–1270.

Duffera, M., J.G. White, and R. Weisz. 2007. Spatial variability of southeastern U.S. coastal plain soil physical properties: Implications for site-specific management. Geoderma 137:327–339. doi:10.1016/j.geoderma.2006.08.018

Ferguson, R., and D. Runquist. 2018. Remote sensing for site-specific crop management. Chapter 8. In: D.K. Shannon, D.E. Clay, and N.R. Kitchen, editors, Precision agriculture basics. ASA, CSSA, SSSA, Madison, WI.

Franzen, D. 2008. Developing zone soil sampling maps. North Dakota State University Extension Circular SF-1176-2 (revised), Fargo, ND. https://www.ndsu.edu/fileadmin/soils/pdfs/SF-1176-2.pdf (verified 15 Sept. 2017).

Franzen, D.W. 2003. Managing saline soils in North Dakota. North Dakota State University Extension circular SF-1087, Fargo, ND. https://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf1087.pdf (verified 15 September 2017).

Franzen, D.W. 2006. Summary of grid sampling project on two Illinois fields. North Dakota State University Special Publication, North Dakota State University, Fargo, ND. https://www.ndsu.edu/fileadmin/soils/pdfs/Summary_of_Grid_Sampling_07.pdf.

Franzen, D.W. 2011. Collecting and analyzing soil spatial information using kriging and inverse distance. In: D. Clay and J. F. Shanahan, editors, GIS applications in agriculture. Volume Two. Nutrient Management for Energy Efficiency. CRC Press, Taylor & Francis Group. Boca Raton, FL. p. 61-80.

Franzen, D.W. 2016. A history of phosphate export from North Dakota. In: 2016 Proceedings of the Great Plains Soil Fertility Conference, Denver, CO, 1-2 March 2016. IPNI, Brookings, SD.

Franzen, D.W., and L.J. Cihacek. 1998. Soil sampling as a basis for fertilizer application. North Dakota State University Extension Circular SF-990. North Dakota State University, Fargo, ND. https://www.ndsu.edu/fileadmin/soils/pdfs/SF-990_Soil_Sampling.pdf (verified 15 Sept. 2017).

Franzen, D.W., and T.R. Peck. 1995. Field sampling for variable rate fertilization. J. Prod. Agric. 8:568–574. doi:10.2134/jpa1995.0568

Franzen, D.W., T. Nanna, and W.A. Norvell. 2006. A survey of soil attributes in North Dakota by landscape position. Agron. J. 98:1015–1022. doi:10.2134/agronj2005.0283

Franzen, D.W., F. Casey, and N. Derby. 2008. Yield mapping and use of yield map data. North Dakota State University Extension Circular SF-1176-3 (revised), North Dakota State University, Fargo, ND. https://www.ndsu.edu/fileadmin/soils/pdfs/SF-1176-3.pdf (verified 15 September 2017).

Franzen, D.W., L.J. Cihacek, V.L. Hofman, and L.J. Swenson. 1998. Topography-based sampling compared with grid sampling in the northern Great Plains. J. Prod. Agric. 11:364–370. doi:10.2134/jpa1998.0364

Franzen, D.W., D.H. Hopkins, M.D. Sweeney, M.K. Ulmer, and A.D. Halvorson. 2002. Evaluation of soil survey scale for zone development of site-specific nitrogen management. Agron. J. 94:381–389. doi:10.2134/agronj2002.0381

Franzen, D.W., D. Long, A. Sims, J. Lamb, F. Casey, J. Staricka, M. Halvorson, and V. Hofman. 2011. Evaluation of methods to determine residual soil nitrate zones across the northern Great Plains of the USA. Precis. Agric. 12:594–606. doi:10.1007/s11119-010-9207-0

Fulton, J., E. Hawkins, R. Taylor, and A. Franzen. 2018. Yield monitoring and mapping. Chapter 5. In: D.K. Shannon, D.E. Clay, and N.R. Kitchen, editors, Precision agriculture basics. ASA, CSSA, SSSA, Madison, WI.

Gross, D.L., and R.C. Berg. 1981. Geology of the Kankakee River system in Kankakee County, Illinois. Env. Geol. Notes, Vol. 92. Illinois State Geological Survey, Champaign, IL. https://archive.org/details/geologyofkankake92gros (Verified 15 Sept. 2017).

Grossman, R.B., J.B. Fehrenbacher, and A.H. Beavers. 1959. Fragipan soils of Illinois: I. General characterization and field relationships of Hosmer silt loam. Soil Sci. Soc. Am. J. 23:65-70.

Hatfield, G. 2017. Spatial statistics. In: D.E. Clay, S.A. Clay, and S.A. Bruggeman, editors, Practical mathematics for precision farming. ASA, CSSA, SSSA. Madison, WI.

Jamil, A., S. Riaz, M. Ashraf, and M.R. Foolad. 2011. Gene expression profiling of plants under salt stress. Crit. Rev. Plant Sci. 30:435–458. doi:10.1080/07352689.2011.605739

Jenny, H. 1941. Factors of soil formation: A system of quantitative pedology. McGraw-Hill, New York.

Khakural, B.R., P.C. Robert, and D.J. Mulla. 1996. Relating corn/soybean yield to variability in soil and landscape characteristics. In: P.C. Robert and W.E. Larson, editors, Precision agriculture. ASA, CSSA, SSSA, Madison, WI. p. 117-128.

Kitchen, N.R., D.G. Westfall, and J.L. Havlin. 1990. Soil sampling under no-till banded phosphorus. Soil Sci. Soc. Am. J. 54:1661–1665. doi:10.2136/sssaj1990.03615995005400060026x

Kitchen, N.R., K.A. Sudduth, D.B. Myers, S.T. Drummond, and S.Y. Hong. 2005. Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Comput. Electron. Agric. 46:285–308. doi:10.1016/j.compag.2004.11.012

Kitchen, N.R., and S.A. Clay. 2018. Understanding and identifying variability. Chapter 2. In: D.K. Shannon, D.E. Clay, and N.R. Kitchen, editors, Precision agriculture basics. ASA, CSSA, SSSA, Madison, WI.

Leighton, M.M., and H.B. Willman. 1950. Loess formations of the Mississippi Valley. Report of Investigations No. 149. State Geological Survey, Urbana, IL. https://www.ideals.illinois.edu/bitstream/handle/2142/42761/loessformationso149leig.pdf?sequence=2. doi:10.1086/625772

Mahler, R.L. 1990. Soil sampling fields that have received banded fertilizer application. Commun. Soil Sci. Plant Anal. 21:1793–1802.

doi:10.1080/00103629009368340

Mallarino, A.P., and D.J. Wittry. 2004. Efficacy of grid and zone soil sampling approaches for site-specific assessment of phosphorus, potassium, pH and organic matter. Precis. Agric. 5:131–144. doi:10.1023/B:PRAG.0000022358.24102.1b

Morris, T., T.S. Murrell, D.B. Beegle, J.J. Camberato, R.B. Ferguson, J. Grove, Q. Ketterings, P.M. Kyveryga, C.A.M. Laboski, J.M. McGrath, J.J. Meisinger, J. Melkonian, B.N. Moebius-Clune, E.D. Nafziger, D. Osmond, J.E. Sawyer, P.C. Scharf, W. Smith, J.T. Spargo, H.M. Van Es, and H. Yang. 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. Agron J. 110:1–37.

Pierce, F.J., and P. Nowak. 1999. Aspects of Precision Agriculture. Adv. Agron. 67:1–85 ASA, CSSA, SSSA, Madison, WI. doi:10.1016/S0065-2113(08)60513-1

Rehm, G.W., A. Mallarino, K. Reid, D. Franzen, and J. Lamb. 2001. Soil sampling for variable rate fertilizer and lime application. North Central Multistate Report 348. University of Minnesota Experiment Station, St. Paul, MN. https://www.extension.umn.edu/agriculture/nutrient-management/docs/608-2001-1.pdf (verified 15 September 2017).

Reisenauer, H.M. 1978. Soil and plant-tissue testing in California. Bulletin 1879. Division of Agricultural Sciences, University of California, Berkley, CA.

Ruhe, R.V. 1960. Elements of the soil landscape. p. 165-170 In Transactions of the 7th International Congress of Soil Science. Vol. 4. International Society of Soil Science, Madison, WI.

Sharratt, B., F. Young, and G. Feng. 2017. Wind erosion and PM10 emissions from no-tillage cropping systems in the Pacific Northwest. Agron. J. 109: 1303–1311.

Sikora, F.J., and K.P. Moore. 2014. Soil test methods from the southeastern United States. Southern Cooperative Series Bulletin No. 419. Southern Extension and Research Activity Information Exchange Group, University of Georgia, Athens, GA. http://aesl.ces.uga.edu/sera6/MethodsManual-FinalSERA6.pdf (verified 15 Sept 2017).

Sudduth, K.A., N.R. Kitchen, W.J. Wiebold, W.D. Batchelor, G.A. Bollero, D.G. Bullock, D.E. Clay, H.L. Palm, F.J. Pierce, R.T. Schuler, and K.D. Thelen. 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. Comput. Electron. Agric. 46:263–283. doi:10.1016/j.compag.2004.11.010

Tewolde, H., T.R. Way, D.H. Pote, A. Adeli, J.P. Brooks, and M.W. Shankle. 2013. Method of soil sampling following subsurface banding of solid manures. Agron. J. 105:519–526. doi:10.2134/agronj2012.0400n

Van Meirvenne, M., K. Maes, and G. Hofman. 2003. Three-dimensional variability of soil nitrates in an agricultural field. Biol. Fertil. Soils 37:147–153.

Wilding, L.P., R.T. Odell, J.B. Fehrenbacher, and A.H. Beaver. 1963. Source and distribution of sodium in solonetzic soils in Illinois. 1963. Soil Sci. Soc. Am. Proc. 27:432–438. doi:10.2136/sssaj1963.03615995002700040021x

Willard, D.E. 1902. The Story of the Prairies. The landscape geology of North Dakota. Third ed. Rand, McNally & Co., NY.

Wollenhaupt, N.C. 1996. Sampling and testing for variable rate fertilization. p. 33-34. In: Proceedings of the 1996 Information Agriculture Conference. Vol. 1. Urbana, IL, 30 July–1 Aug. 1996. Potash & Phosphate Institute, Norcross, GA.