OPTICAL SENSING FOR NITROGEN MANAGEMENT

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ABSTRACT

Although nitrogen (N) nutrition is as or more important than other nutrients, it has been largely ignored by those applying variable rate fertilizer (VRF) due to its loss potential for VRF applications that occur many weeks prior to crop need. Applications of N are best applied as close to crop uptake as possible in order to avoid leaching, denitrification, and other losses. Spatial variability for crop N need is often considerable due to differences in yield potential and, to a lesser degree, soil N contribution. Optical sensing can be used in part to determine N rates for unique management zones. Bare soil imagery is a good optical sensing technology that can be used to define initial management zones based on spatially unique soil productivity and N contribution. Spatial differences in soil color often reveal areas of significant variation in soil texture, organic matter, and mineralogy. Through imagery and other layers of information, highly productive soils, which require relatively high N, can be managed separately from other zones requiring less N. Further delineation of N management zones can be fined tuned with in-season imagery and/or yield mapping, especially when maps from several years are combined to determine areas of consistent canopy health patterns. In addition, optical sensing of the current season crop, from either aerial or ground based sensors, can be used to more accurately determine and meet current season plant N needs on a micro-scale, particularly when near infrared (NIR) wavelengths are used in the optical sensing instruments.

SPATIAL NITROGEN NEED

Nutrition is crucial in determining crop yield and quality. Nutrition not only provides essential building blocks for plant growth, but also influences the plant's ability to withstand environmental pressures due to pests, water, temperature, and other stresses. Nitrogen (N) deficiency or excess has more impact on yield components than all of the other nutrients.

From an N demand standpoint, more N is needed in areas of the field with the best soil, water, microclimate, and topography. <u>These "good" areas of a field usually produce relatively higher yielding and better quality crops and require more N as yield potential increases. Conversely, less N is needed in areas with low yield potential.</u>

Residual soil nitrate (NO_3^-) also creates variability in the field and may be higher in areas of low productivity and lower in higher yielding areas due to differences in crop removal (Kitchen et al., 1994). Topography, drainage, soil texture, organic matter, and previous crop residues may cause spatial differences in the amount of N contributed by the soil. However, yield potential seems to have a much greater impact on spatial N needs than the soil contribution (Hopkins et al., 2006).

Recent innovations allow for fertilizer to be applied precisely where it is needed in a field using global positioning systems (GPS) and variable rate fertilizer (VRF) controllers (Hopkins et al., 2006, Bowen et al., 2005, Cook et al., 2005, Raun et al., 2002). Using this technology to improve N use efficiency may increase crop yields and quality. Variable rate N application methods have also shown an environmental benefit by reducing over application of N fertilizer in areas where it is not needed by the crop. This equates to less residual N in the soil, thus, potentially reducing NO_3^- runoff to surface waters and leaching to ground water.

NITROGEN RECOMMENDATIONS

Nitrogen fertilizer recommendations are traditionally made by applying a yield goal and a soil test nitrate-nitrogen (NO_3^-–N) value to a research derived table or equation, such as that for potatoes as reported by Stark et al. (2004). The N rate is increased to account for immobilization when carbon rich materials, such as straw, are incorporated into the soil without sufficient time for decomposition. The N rate is reduced to account for that found in irrigation water and/or manure/biosolids or if a legume was the previous crop. Spatial rate adjustments can be made as any of these parameters change across a field. However, the primary impact on spatial N need is related to yield potential and, in some cases, expected N contribution from the soil.

The N contribution from the soil is related to residual NO_3^- concentrations, as well as differences in soil and organic matter. These parameters are determined by soil analysis and, in the case of VRF, intensive grid or zonal sampling is used to determine spatial differences. Blind grid sampling is a common method employed for VRF. The accuracy of a grid map is directly related to the grid size. Grids larger than 1-2 acres have generally shown to be insufficient to accurately capture spatial variability of soil test values. In contrast, zonal sampling does not ignore prevalent soil characteristics and, therefore, sampling intensity can often be reduced without loss of accuracy.

Although the soil contribution is an important consideration, the most important consideration in determining the N rate is yield goal. The field or regional yield average (plus 5-10%) is a good starting point for a field wide yield goal. Ideally, adjustments for spatially unique yield goals are made based on yield mapping histories that most accurately identify soil productivity potential in each management zone. Unfortunately, most growers do not have accurate yield maps from previous crops (requires several years combined into one map for an average relative yield). In these cases, an educated guess can be made by factoring in various properties including, but not limited to: soil borne pests/pathogens, topography, depth, compaction, organic matter, pH, nutrient concentrations, water/nutrient holding capacity, salts, sodium, and mineralogy [such as the presence of free excess lime (calcium/magnesium carbonates)] (Cook et al., 2005, Fleming et al., 2004, Kitchen et al., 1994, Stark et al., 2004, Stephens, 2006). Many of these properties can be identified with optical sensing technologies.

BARE SOIL IMAGERY

One method of determining spatially unique field properties, for which variable rate N decisions can be made, is aerial imagery of the bare soil (Fig. 1). Research has shown that differences in soil properties often exhibit themselves as soil color variations (Fleming et. al, 2004). Soil properties play a major role in crop growth and development variations across the field. Many (not all) of these differences are visible from the surface. Differences can be detected for organic matter, water/nutrient holding capacity, and mineralogy. The bare soil image can also be used to help identify differences with many other soil properties, such as topography or compaction, as they are often related to properties that exhibit color differences.

As soil color properties don’t change much over time (unless soil is eroded or physically moved), a high quality bare soil image can be used repeatedly for many years. However, multiple bare soil images can be very helpful. For example, wet soil is often darker than dry soil and, in some cases, having two images of the soil when it is uniformly dry and wet can help refine management zones not apparent with either image alone. Furthermore, a series of bare soil images after a significant precipitation/irrigation event can show areas of moisture accumulation and their drying patterns, revealing drainage and/or water holding capacity problems.

As with all methods of zonal delineation, bare soil imagery needs "ground truthing" (on-site assessment of each zone to confirm soil color differences and expected impacts on crop growth and development). Management zones are then identified based on the bare soil imagery, soil analysis, and site characterization. Variable N recommendations can then be made for each zone based on unique yield goals and expected soil N contribution.

A recently completed three year (fifteen fields) study in southeastern Idaho on *Russet Burbank* potatoes showed that bare soil imagery can be used effectively to delineate management zones that benefit from variable application of N (Hopkins et al., 2006). Yield potential for soils in southeastern Idaho is mostly impacted by calcareousness, with eroded hill tops/slopes having shallow soil high in excess lime (Fig. 1). These soils have a much lower yield potential than soils in other field zones with deeper A horizon (topsoil), higher organic matter levels, and lower excess lime content. Applying higher rates of N to the "good" soil and less to the "poor" soil resulted in significant yield increases for the variably applied N over a uniform application (Fig 2).

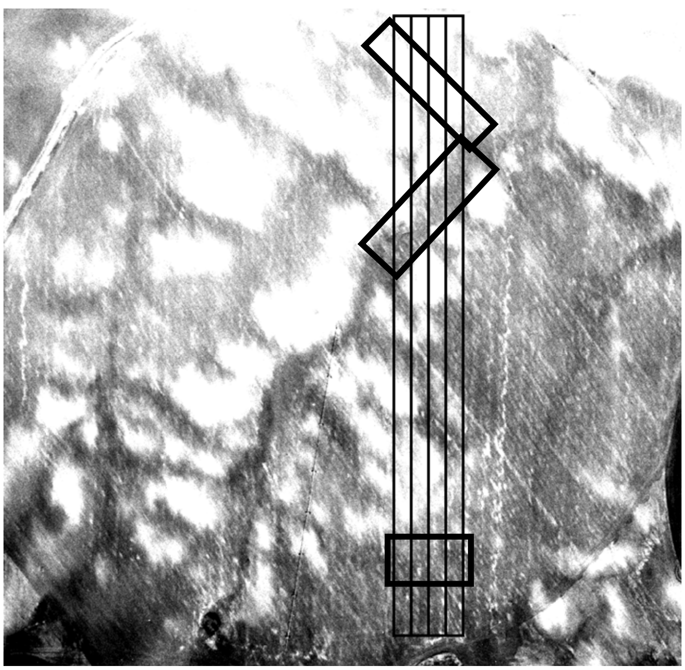


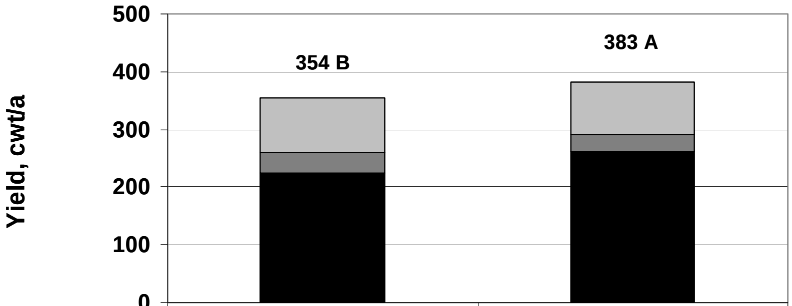
Fig. 1. Bare soil image of an Idaho field used in a variable rate nitrogen study with the fertilizer strips and sampling areas of the three unique color based zones.

In this study, the variable rate N was based on zonal delineation based on bare soil imagery followed by zonal characterization through on-site characterization and intensive soil sampling and analysis. The average increase for all 15 fields was 36 cwt/a for US No. 1 and 29 cwt/a for total yield, with many of the most highly variable fields showing larger response. Tuber size was also increased, with an increase of 3% in premium size US No. 1 tubers over 6 ounces. After subtracting costs of the variable rate technology, the average difference in net profit was significant at $214/a.

IN-SEASON IMAGERY

Aerial images of the crop canopy from previous years can serve in the same way as bare soil imagery and yield mapping to help define or refine N management zones. Ideally, these maps are used as multiple layers of information to guide decisions, but any of them can be used independently as a starting point for zone delineation. With regard to in-season imagery, the question of timing is an issue. If cost was not a limiting factor, weekly images would be preferable. However, most growers feel limited by cost to 1-3 images per cropping season.

Early-season images often show differences in canopy development. Areas that do not develop as quickly often exhibit variation in soil, topography, irrigation system, or have other spatially unique features. These areas tend to perform poorly with regard to yield and crop quality. In the case of potatoes, areas of slow canopy closure are more prone to produce tubers with internal and external defects caused by high soil temperatures and temperature/moisture fluctuations. This is in addition to yield potential that is lost because of inefficiency in capturing sunlight by the canopy.



	uniform fertilization	variable rate nitrogen
cull	95	92
US No. 2	34	30
US No. 1	225 b	261 a

Fig. 2. Combined potato yield results for 15 fields for a variable rate nitrogen study in Idaho 2003-2005. Total yield (shown on top of bar stack) and US No. 1 yield were significantly different when comparing the variable rate method with the traditional uniform N application. (*P*=0.10)

Unlike early-season images, those taken mid-season often do not show clear contrasts unless problems are severe. However, imagery taken late-season shows areas of premature canopy senescence due to a variety of pest, pathogen, soil, etc. In-season imagery is most often used for scouting purposes in the current season, but is also helpful in making decisions for future crops. Late-season and, to a lesser degree, early-season images correlate well with yield maps and can be used as a less accurate substitute for determining spatial yield goals in their absence.

Spatially unique problems in crop growth from different areas of a field that are identified with in-season imagery or yield maps can be classified as random or non-random variability. Random crop damage is due to any event that is not tied to a specific location, such as hail damage. Non-random crop damage tends to be found in the same areas year after year. There are many of these spatially unique issues that can affect crop growth and development, including, but not limited to: soil fertility, pH, compaction, salinity, sodicity, mineralogy, water holding capacity, slope, aspect, proximity to field borders, irrigation equipment limitations, and soil borne pests and pathogen infestations.

There are two primary keys to using in-season imagery and yield mapping in helping to guide management to subsequent crops. The first is to use the imagery in a timely fashion for site specific investigation regarding the cause of the crop damage. The second is to combine the imagery from two or more seasons to separate the non-random from random variability. Patterns will emerge from one crop to the next for spatially unique issues, whereas the random events will be averaged out of the picture. In this way, true zonal characteristics will be made manifest. It generally takes three or more years of data before the history is truly reliable.

Combining images is a simple matter of data manipulation. The light reflectance captured by the photo detector being used for optical sensing is a numeric value. As such, these values can be combined and averaged across images from different years. It is important that the images are accurately geo-referenced in order to insure that the averaging that takes place is from precisely the same areas. It is beneficial to average across years for all crops, as well as for individual crops. For example, six years of imagery from a field having a potato-grain rotation would have three historical images (in addition to each individual year), namely: 1) potato, 2) grain, and 3) combined. Many spatially unique problems will affect both crops, such as shallow, eroded soils. However, many other problems will affect one crop, but not the other. For example, certain soil borne pathogens will negatively impact potato and not grain and visa-versa.

These in-season imagery histories can be added to other layers of information to fine tune the separation of fields into management zones. Management zones should be evaluated separately for the various spatially unique properties previously mentioned for their own unique yield goal and estimate of N contribution from the soil.

SEEING THE UNSEEN

Although imagery based on visible light reflectance is highly useful, optical sensing technology allows the user to "see the unseen". Unhealthy plants often look different than healthy plants. For example, plants that have a deficiency of N become yellow (chlorotic). These plants look yellow because they have less chlorophyll, thus absorbing less light and reflecting more in the yellow than in the green.

The electromagnetic spectrum contains many more wavelengths of light than the very narrow band that is visible (380-760 nm). The wavelength immediately past the visible range is the near infrared (NIR). Plants also reflect these longer wavelengths of "invisible" light. In fact, the amount of reflectance is much higher for the NIR than the visible range. Similar to the differences in green light reflectance, stressed plants reflect less NIR light than healthy plants. However, the magnitude of the difference in reflectance from healthy vs. stressed plants is much larger for NIR as compared to the visible. Furthermore, this difference in percent reflectance occurs much earlier for NIR than with the visible light. In other words, a NIR image can sense water, nutrient, or other stress much sooner (~1-3 weeks) than can be detected with the naked eye or with a visible image.

There are many ways of expressing this plant stress as determined by the various wavelengths of light, but the most common is the Normalized Difference Vegetative Index (NDVI). The NDVI is calculated by subtracting the red light reflectance (671±6 nm) from the NIR reflectance (780±6 nm) and then dividing by the sum of both. This gives a value from 0 to 1, with healthy plants reading closer to 1 than unhealthy plants. The NDVI is being used in a variety of applications to assess canopy health and manage the current and future crops.

NDVI is often used as a plant health indicator for scouting purposes. The earlier detection with NIR is a clear advantage over imagery from the visible range alone. However, the visible imagery is often less costly and late season visible imagery correlates well with yield mapping and, therefore, can be used effectively to define or refine N management zones.

FERTILIZING EACH PLANT?

One of the emerging applications of NDVI is for in-season N adjustments (Bowen et al., 2005, Raun et al., 2002). This is accomplished by applying a very conservative rate of N across the entire field near planting. At the same time, an N-rich strip is applied across the field, which is typically double the rate applied to the rest of the field. Early in the cropping season, an average NDVI is taken for the N-rich strip and used to determine the N application rate for the rest of the field. Areas of the field not needing N will likely have an NDVI reading similar to the N-rich strip, whereas deficient areas will have a lower value. The NDVI values and associated N rates have to be determined from replicated research for each crop and region (Fig. 3). A possible drawback to this method is that the assumption is made that any plant stress is related to N and, therefore, error may be introduces if other factors, such as other nutrient deficiencies, water stress, or pest pressure are present.

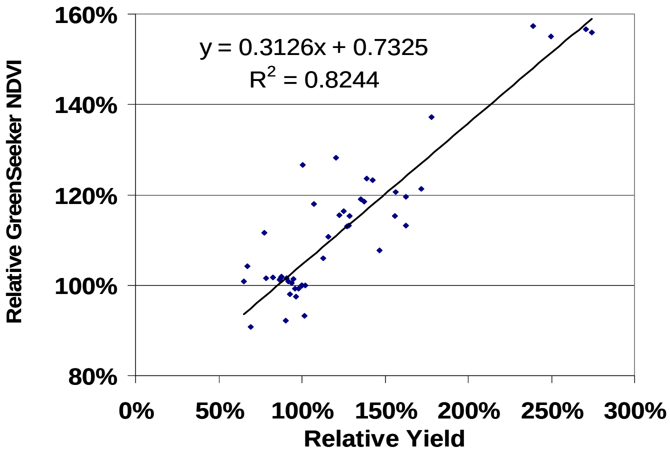


Fig. 3. Correlation of barley yield and ground sensor (GreenSeeker) based NDVI at 54 Idaho locations in 2003 and 2004.

The timing for this in-season variable rate N application occurs after modest plant growth (typically Feekes 6 stage for small grains and immediately prior to row closure for potato). If the NDVI is taken too early, the soil reflectance will mask any plant stress differences. If the image is taken too late, N deficiency may have irreversibly impacted yield potential.

The application is made by a fertilizer sprayer equipped with optical sensing (GreenSeeker, N-Tech Industries, Ukiah, CA) and variable rate application control for each spray nozzle. Currently available controllers are able to adjust the N rate every two or three feet and, if the sensing equipment is mounted over each row, the plants receive a very unique amount of fertilizer to nearly meet individual need. Prior to this technology, variable rate fertilization was limited by the width of the fertilizer application equipment (~60-90 feet width), but precision fertilization increases in accuracy an order of magnitude when using this approach.

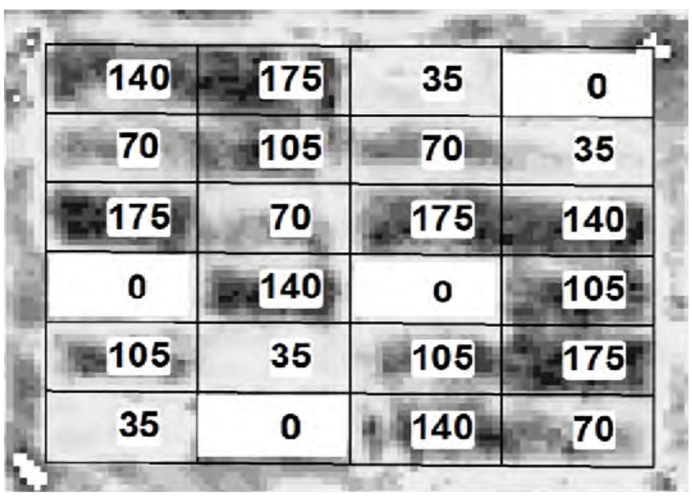


Fig. 4. Aerial imagery (NDVI) of barley with six rates of nitrogen (0-175 lb-N/a). High NDVI values are dark and represent healthy plants and low NDVI values are light and represent N stressed plants.

Another advantage of this technology is that timing and prediction issues associated with pre-plant N applications are reduced. In-season N application based on NDVI is “real-time”. Variably applying N can occur pre-season, but the odds of getting a positive response are correlated inversely with the amount of time between application and plant uptake. Fertilizer retailers and applicators have time constraint issues in the spring immediately before planting. For these reasons, variable rate in-season applications of N are very good alternative to pre-plant timing.

NDVI imagery from airplane or satellite platforms can also be used instead of the ground based sensors (Fig. 4); however, availability issues can be a hindrance. For example, satellite images can’t be taken on cloudy days and, a series of many such days may prevent timely application of the N.

PROBLEMS WITH VRF PHOSPHORUS APPLICATION

A potentially serious problem with variable rate N applications is that the rate can be confounded when P is also variably applied. Most all P fertilizers are ammoniated and, therefore, N is variably applied in proportion to the P with VRF. Unfortunately, most of the P that is variably applied occurs weeks to months ahead of planting and all or part of the associated N may be lost to leaching, denitrification, or volatilization or moved to low lying areas in the field through surface runoff or lateral flow through the soil.

Nearly all of the applied N can be lost in cases of warm temperatures and high precipitation. In other cases where precipitation is low, all of the N may be retained. Most cases lie somewhere in between and predicting the N loss/movement is nearly impossible. Furthermore, measuring residual N through soil testing is also less than perfect as much of the N that is applied enters the organic phase of the N cycle and release rates are difficult to predict. Therefore, accounting for the variably applied N associated P fertilizers applied weeks ahead of planting is complicated at best. This issue is a frequent cause of nil or negative VRF results and should not be ignored.

It is best if fertilizers that contain N be applied as close to plant uptake as possible. Another alternative is to use slow release coated fertilizers or materials that slow the loss of N (urease or nitrification inhibitors) or P fertilizers that do not contain N.

SUMMARY

Nitrogen nutrition is vital to optimal plant growth and development. Variably applying N fertilizer can result in tremendous crop yield and quality increases, as well as reducing environmental impacts. Variable rate applications (including P fertilizers that contain N) should occur near or after planting to avoid N losses. Determining N management zones for pre-emergence applications of variable rate N can be determined through bare soil and/or historical in-season imagery. These optical sensing technologies should be combined with other layers of information, such as yield map histories, in order to fine tune management zones. Variable rate in-season N applications can be used to enhance or instead of pre-plant applications through use of either aerial or ground based sensors that detect differences in NIR (preferable) and/or visible light reflectance.

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