Potential of precision agriculture to protect water bodies from negative impacts of agriculture

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Abstract

Precision agriculture is sometimes promoted as the solution to controlling non-point contamination of surface and ground water. The potential is high for improved nutrient management practices to protect water quality and promote agricultural sustainability, but these efforts must be undertaken with due consideration of the uncertainties associated with weather and crop growth patterns. Synchronizing nutrient availability with crop nutrient needs is an important key to making progress. Site-specific management tools, including remote sensing, enable producers and consultants to improve many aspects of crop management.

Keywords: Crop Sensors, Economic Incentives, Nutrients, Nitrogen, Remote Sensing, Water Quality

Zusammenfassung

Möglichkeiten der Präzisionslandwirtschaft zum Schutz von Gewässern vor negativen Einflüssen der Landwirtschaft

Präzisionslandwirtschaft hat ein großes Potenzial um diffuse Nährstoffeinträge aus der Landwirtschaft in Gewässer zu reduzieren. Diese wird jedoch in hohem Masse von Unsicherheiten bei der Vorhersage von Witterungsverläufen und Wachstumsentwicklung von Pflanzenbeständen beeinträchtigt. Besonderes Augenmerk ist hier auf die Synchronisierung von Nährstoffanlieferung aus dem Boden und dem Bedarf der Pflanzen zu legen.

Schlüsselwörter: Pflanzenbau, Bodennutzung, Düngung, Nährstoffe, Ökonomie, Sensorik, Stickstoff, Wasserqualität

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Approaches to protect water quality typically fall into two general categories: reactive or proactive. These categories are not mutually exclusive because the practice of growing crops and the need for environmental stewardship are intimately related by extremely complex interactions. The search for new tools that integrate across the many considerations involved in crop and livestock production brings us to the topic of precision agriculture.

Spatial and temporal variability in nature are significant contributing factors behind many of world's environmental problems. These realities become accentuated as mankind imposes uniform, and often inappropriate, management practices onto the landscape. The unpredictable nature of weather adds to the problem because it tempts and even encourages farmers to anticipate what might happen weather-wise for several months into the future. Farmers do a great job of anticipating "worst-case" scenarios and making management decision accordingly. Over the years, producers have accumulated a rich background of experiences and likely even acquired some "hand-me-down" tidbits from past generations. These traditions, beliefs, and habits are hard to combat unless economic pressures or governmental regulations dictate the need for change. In any case, the truism stating that "A picture is worth a thousand words" is noteworthy because it offers a clue to human behavior and the decision making process. Pictures and images instantly integrate ever so many factors that are expressed as spatial variables in color, shapes, texture, tones, shadows, distance, etc.. It would literally take thousands of words to describe everything that a picture or image displays. The interesting part about looking at a picture is that each individual will have a different impression depending on their training, experiences in life, and interests.

A common perception is that precision agriculture involves a transition from uniform treatments to variable-rate treatments in an attempt to compensate for the effects of spatial and temporal variability in fields. This can be summarized by indicating that producers would attempt to do the ***right things***, in the ***right places***, at the ***right times***. Making the decision to impose some kind of variable-rate treatment or spatial treatment on the landscape requires spatial information. Sources of this information may come from sampling the soil for chemical constituents, yield maps showing patterns of spatial variability, soil survey maps, aerial photographs of crop vigor, etc. (Table 1). Acquiring spatial information is frequently the most expensive and time consuming part of making variable rate applications. At the end of the day, one of the most difficult tasks is to quantify the environmental attributes when considering which precision agriculture tools to consider. Deciding what treatments to impose and where to impose them is the first task.

Table 1:

Sample of precision agriculture measurements, methods of determination, and application of information

Measurement	Method	Application
soil samples	manual	nutrient management decisions delineation of management zones
field scouting	manual	problem identification
tissue testing	manual	nutrient status
pH	Veris	lime applications
apparent electrical conductivity	Veris or EM-38	rooting depth, drainage, salinity, clay content, cation exchange capacity
soil color	imagery, near infrared sensors	organic matter content
elevation and aspect	Imagery, global positioning system	drainage, topography
biomass, leaf area index, chlorophyll content, water status, yield estimation	imagery or sensors	nutrient management, irrigation decisions, in-season crop assessment
yield, grain moisture content, protein content	harvest machines	post mortem evaluations

An alternative way to think about precision agriculture is as an organized scheme to remove or compensate for the effects of natural processes from a management program, to the extent possible, and recognize and engage those processes that need to be a part of a management plan. Laws of physics like ***gravity*** dictate that water is going to naturally flow down-gradient and percolate through soil. Laws of chemistry, like the fact that ***nitrates are soluble in water***, are here to stay so wherever the water goes, so goes the nitrate. Therefore, the task set before producers, agricultural consultants, and scientists is to design and develop management systems that work around and with the above laws of nature to accomplish the desired goals. For example, precipitation can be both a blessing and a curse so producers must learn to accommodate this uncertainty (temporal and spatial) in their management strategies. Likewise, there usually isn't a lot that producers can do to modify soil textural properties and landscape features (topography) to make them more desirable in terms of minimizing the impact of natural processes other than to reduce the opportunity for unfavorable consequences. For example, installing terraces with an under-ground tile outlet system is one way to channel the flow of excess precipitation from a field while minimizing soil erosion and related nutrient losses. In other situations, installing subsurface drainage systems in fields with poor internal drainage is a way to work around the slow permeability properties of fine-textured soils. A different situation exists with flood (gravity) irrigation of soils with variable soil texture within the root zone. It follows that water infiltration and nitrate leaching are likely to vary considerably because of spatial variability in soil properties, so sprinkler irrigation provides an opportunity to apply the water more uniformly across the landscape. These examples do not necessarily involve spatially variable cultural practices but demonstrate the realization that landscapes, soil properties, and weather are factors that have a bearing on the environmental implications of management practices.

Several practical examples are available where local and regional government agencies have created incentives to entice producers to lessen the environmental implications of their nutrient and water management practices. For nearly a decade the Central Platte Natural Resources District in Central Nebraska has provided cost sharing incentives to producers who convert from furrow irrigation to center-pivot sprinkler irrigation. In this case, the local agency that is supported by tax revenues paid for much of the under-ground pipe to deliver the irrigation water to the center of the field. This decision was based on research showing that center-pivot irrigation reduced water application rates by at least 50 % compared to furrow irrigation and that fertilizer N application rates for corn could be reduced by ~30 % (Schepers et al., 1995). Concurrently, they also cost share on a flow control and manifold system to improve the uniformity of fertilizer rates across the applicator. They also cost share on flow meters for irrigation wells to help producers monitor their water application rates. These incentives were intended to improve whole-field water and nutrient management practices, but other agencies are now offering incentives to improve within-field nutrient management practices. In the State of Missouri, producers can receive a one-time payment of \$150/ha for adopting a reactive N management strategy based on either SPAD meter data or crop sensor technologies. Producers must enroll for three years to qualify, but receive the entire incentive payment the first year. This program is funded by the Natural Resources Conservation Service (USDA-NRCS) through the Environmental Quality Incentives Program (EQIP). The commercial availability of active crop canopy sensor technologies has allowed real-time nutrient management (reactive approach) to become a reality.

Early approaches to precision agriculture were based on the premise that grid soil sampling would provide the information needed to make spatially variable nutrient applications. This concept was driven by a segment of the agricultural industry that had developed and patented equipment to apply multiple nutrients at variable rates. One hectare grid maps were quite common, but positioning the sampling points was sometimes problematic when the grid pattern was established via a computer without visualizing various landscape features (i.e., topography, old field boundaries, previous crops and cultural practices, etc.) (Schepers et al., 2000). As such, sampling points were likely to be designated in transition zones between soil types, within small areas of the field that were not representative, near areas protected by trees, and in areas known to have received significant quantities of manure in the past. Supporters of the concept were disappointed to learn that their efforts did not remove the spatial variability in crop growth and yields. Adjusting the position of the soil sampling points to accommodate field conditions helped, but many times producers were only equipped to make variable rate applications of one nutrient. Grid sampling has gradually migrated to management zone sampling to reduce costs and improve the reliability of the nutrient and soil property maps.

The feasibility of monitoring crop yields via combines and generating yield maps was realized in the early 1990s. Tremendous advancements in user friendliness and accuracy have been made since then. Seeing the spatial depiction of yield variability within a field is a powerful tool for analyzing relative profitability and creating awareness of spatial attributes in general. Today, yield monitoring devices have been designed and installed on various kinds of harvesting equipment. Grain moisture content sensors were developed concurrently, but now other attributes like grain protein content can also be mapped during harvest. The limitation of yield maps is that they can only illustrate spatial patterns, while producers would also like to know when during the growing season the differences began appearing. One simple and effective approach for determining the cause(s) of differential plant growth is to apply a strip of manure across a spatially variable field. Some plants within this transect are likely to respond and others are not. Making side-by-side comparisons (with and without manure) of the nutrient content in the leaf tissue can be an effective way to determine which nutrient(s) is likely to be deficient (Masek et al., 2000). This approach uses the crop as a bio-indicator of nutrient balance rather than relying of chemical extraction procedures to quantify the relative proportion of plant available nutrients in the soil. Multiple sampling times in several locations along the manure-applied transect may be required to identify the cause and location of differential crop responses. In any case, once the problem(s) are identified, producers are in a position to make better informed management decisions.

Capitalizing on the power of imagery is a new and exciting possibility for society, and especially agriculture. This is because of new technologies that enable the rapid and inexpensive collection and storage of high resolution imagery. Digital cameras from a decade ago offered a few hundred pixels but now cameras with 10 or more megapixels are quite common. In 2007, commercial cameras mounted in small aircraft are able to provide 7.5-cm spatial resolution of 17-ha fields with a 39 mega-pixel camera. What this means is that farmers, consultants, environmentalists, community planners, and policy makers have many options for integrating spatial and temporal information using remote sensing tools. Along with this opportunity comes the need for personnel who have the technical expertise to manage and analyze huge quantities of digital data and the practical experiences to add value to the imagery by offering interpretations that can lead to improved management options.

Lessons learned

Failure of several recent commercial efforts to introduce remote sensing into agriculture has left some very compelling road markers for future efforts. A brief description and analysis will serve to define several key criteria that need to be met for success. One effort (Resource21) began in the early 1990s as a consortium of large diverse companies that each hoped to play a major role in the delivery of field maps based on satellite imagery to farmers. The concept was that one partner would build the needed satellites, another would capture and interpret the data, and a third would deliver the final product to producers through an existing network of retail outlets and service centers. Several other notable agricultural seed and fertilizer suppliers partnered in this venture with specialized interests related to their business. Over nearly a decade the consortium collaborated with a dozen or so University and USDA-Agricultural Research Service groups to assist with the calibration between near-satellite imagery and ground-based observations. Along the way, both low and high altitude aircraft were used to explore spatial and temporal resolution issues along with other complicating problems encountered with imagery.

The various goals of the project and related field activities revealed many useful findings about the potential for characterizing different types of vegetation (weeds versus crops) from imagery, differentiating between nitrogen and phosphorus deficiencies and water stress in key crops (corn, wheat, soybean, and cotton), and estimating yield potential during the growing season. A team worked from the beginning to develop products that they anticipated would be valuable to producers, agricultural consultants, and suppliers. Procedures and mechanisms were in place and tested to electronically deliver field maps to producers within 24 hours of a scheduled high altitude flight (proxy for an image that would be provided by a satellite). Field maps were delivered to producers utilizing a satellite-based information system that was already in place for delivering weather and market reports to subscribing producers. The color reports received by producers were quite revealing in terms of spatial patterns in fields and changes that had occurred since the previous image a week earlier. At the end of the growing season, producers could compare their sequence of images for each field with yield maps generated by their harvesters. Producers were generally impressed with the degree of similarity in patterns and could even offer explanations for many of the notable areas. The major comment was that even though the reports were delivered promptly the consortium did not provide an agronomic interpretation and recommendation in terms of field management options. The next year, subsidized field maps were hand-delivered to the participating producers via consultants employed by the local agricultural cooperative. The dominate situation at the end of the year was that most producers questioned how they could recover the cost of the imagery and consultant services. A broader observation is that producers were not prepared to make management decisions and implement changes that would add value to the field maps and related reports. No effort was made to assign environmental implications to map interpretations or consultant recommendations other than those that amounted to intuitive impressions. While the Resource21 effort was; never commercialized, the concurrent research helped to better understand the difficulties in differentiating between different types of plants stresses using imagery (Osborne et al., 2004a, 2004b; Schlemmer et al., 2005).

For years, the U.S. National Atmospheric and Space Agency (NASA) has worked to market LandSat imagery to producers for making routine management decisions. An interest group called Ag 20/20 comprised of commodity groups representing corn, cotton, wheat, and soybeans noted that LandSat imagery lacked the needed spatial resolution and the turn around time for the imagery was unacceptable. This group prioritized the types of information producers hoped to acquire using remote sensing tools. Top emphasis was given to nutrient management, followed by water stress detection, characterization of weed pressures, and early detection of crop diseases and insect infestations. All of these management considerations have environmental implications, but the quest for additional information to enhance profitability was the dominant factor influencing producer responses.

An interesting commercial remote sensing effort organized by John Deere was recently terminated after three years. This program was based on data that was acquired by a multi-band digital camera that was attached to the landing gear of a fleet of small aircraft (e.g., Cesena 172). Initially, the program was marketed to cotton producers for variable rate application of growth regulators early in the growing season and for application of defoliants to facilitate harvesting. A subsequent use of the imagery was for making variable-rate N applications to cotton during the growing season. This program expanded into corn production areas of the U.S. for making variable-rate N applications but was not readily adopted. Again, producer feedback indicated that they were not prepared to make management decisions that would add obvious profitability to their operation. Even higher prices of N fertilizer were not enough to entice producers to place a greater emphasis on in-season N management. Lack of commercial high-clearance equipment for making in-season N applications to corn was not a limitation. Rather, the risk of encountering an N deficiency and fear of a subsequent yield reduction were strong deterrents for making management decisions that could substantially reduce profitability. For example, corn producers can economically justify applying 16 g N fertilizer if it results in an extra kg of grain (i.e., ~10 lbs N @ $0.35/lb N for each bushel @ $3.50/bushel). The environmental concern is that the incremental recovery for the last unit of N fertilizer applied (i.e., nitrogen use efficiency, NUE) near the point of maximum economic yield is <10 %.

The attitude of most corn producers in the U.S. is that spatial N management for corn production is not worth the cost and effort, but this is because the yield, quality, and market value of the grain do not decline with modest amounts of excess N fertilizer. This is in contrast to crops like sugar beet and malting barley where excess N availability can result in market penalties. Other crops like certain types of wheat garner a bonus if the grain exceeds a protein content threshold of 14 %. In this case, producers strive to only apply enough N fertilizer to minimally exceed the protein content threshold that triggers the bonus price because excess N fertilizer is likely to induce lodging. These examples, with the exception of corn, offer some obvious and very tangible opportunities for using the crop as a bio-indicator of N status. Assuming the remote sensing tools and analytical techniques are available to reliably monitor the crop (accurate, inexpensive, and timely), then it should be possible to implement spatial and temporal N management strategies that enhance profitability and help protect the environment.

Nitrogen management in crop production systems is incredibly complex because this nutrient is used in such large quantities by plants and, as an essential nutrient, is dynamic to the point of being evasive to crops in some situations. Nitrogen, as an element or simple compound, has a wide range of oxidation states and can exist as a gas, liquid, or solid depending on conditions of temperature and pressure. In the nitrate form (NO_3^-) it is totally soluble in water and thus subject to leaching. To complicate matters, soil microorganisms tend to transform all forms of N to NO_3 when conditions are favorable for plant growth (ideal water and temperature). Under conditions with excess water, N can be lost to the atmosphere through denitrification. Because N can be so transitory, it is unwise to attempt to store it in the soil for any length of time other than in the organic form. Within the plant, N is the most abundant element and comprises 50 to 70 % of the chlorophyll molecules that capture energy from the sun in the photosynthesis process. As such, N availability is critical in the production of plant biomass, which translates into forage and grain production. Plant chlorophyll levels continue to increase until one of the other essential elements used in metabolism becomes limiting. The difficulty for producers and managers is that most crops are known to take up excess N when it is available (luxury consumption). The limitation when using remote sensing techniques to assess crop vigor is in knowing if the element of environmental interest (e.g., P, NO_3, etc.) is limiting crop growth or if it is present in excess amounts. Only destructive laboratory tests will provide these answers at this time.

It is no wonder that producers who support their livelihood through the production of grain and forage products are keen on nutrient management and especially N. The green color that humans see in plants is an indication of chlorophyll level, which is a function of N status in the tissue and thereby soil N availability. So how can producers and consultants use remote sensing to tighten their N management practices and thereby protect the environment? Stated differently, how can remote sensing be used to achieve the desired level of environmental stewardship and what kinds of incentives and subsidies will be required to entice the desired actions to achieve these goals?

Promising approaches

One of the more intuitive outcomes of the Resource21 effort was documentation showing that relative corn yield for a field could be predicted with considerable accuracy (>80 %) during the growing season (Shanahan et al., 2001). The statistical significance of this relationship increased as the season progressed because there was progressively less time for weather to impose stresses that might reduce yields. This relationship helps support the premise that the crop can be used as a bio-indicator of crop vigor for making in-season N management decisions. Other supporting evidence is that chlorophyll meter data (Minolta SPAD) for corn typically shows a strong positive relationship between relative yield and relative SPAD readings. Minolta SPAD readings are highly correlated with leaf chlorophyll concentrations, which is why the device is commonly considered the chlorophyll standard for field measurements. As such, remote sensing approaches for assessing crop N status frequently attempt to emulate

SPAD meter results. In the case of the John Deere remote sensing program (called Opti-Gro), they used SPAD meter data to calibrate their "crop vigor index" that was generated from the images and used to make in-season fertilizer N recommendations.

A company called Mosaic (partnership between Cargill and IMC) picked up on the above late-season relationship between vegetation indexes and corn yield generated from imagery (Shanahan et al., 2001) to generate a proxy yield map. This approach generated a relative vegetation index value for each pixel based on the field average. Each relative pixel value was then used to redistribute the total amount of grain harvested from the field after producers provided realistic upper and lower yield values for the field. The resulting proxy yield map was used as the "yield goal" factor when making variable-rate fertilizer N recommendations for the following crop year. One shortcoming of this approach is that it generates proactive fertilizer N recommendations based on the results of the previous growing season as influenced by weather, nutrient management, and cultural practices. Another weakness that has environmental implications is that temporal differences in weather patterns from year to year can have a strong and frequently contrasting influence on crop yields (Schepers et al., 2004). The result is that imagery can be grossly problematic for parts of a field and thereby represent a significant environmental challenge in some areas and an economic loss in others.

The intended outcome of variable-rate nutrient applications is to redistribute the fertilizer to more closely match crop needs. Intuitively, this approach should reduce applications in fertile areas and possibly increase the applications in less-fertile areas. If done correctly, variable-rate nutrient applications should be environmentally friendly and at least break-even economically. A possible caution is that if increased application rates in less fertile areas are not accompanied by increased plant uptake, then an environmental risk can result. In-season nutrient management based on real-time imagery offers a way for producers to respond to the way weather affects spatial landscape features.

Corn producers in the U.S. are usually not inclined to make more than one variable-rate N application because of the cost and time requirement. Timing of this application limits the use of real-time imagery because the crop needs to exhibit differential signs of N deficiency for the approach to be effective. Imagery from early in the growing season is less likely to display spatial patterns related to nutrient availability. The risk of delayed image collection is that more strongly nutrient deficient areas may have already encountered yield-limiting physiological processes. Strategies that involve multiple images are better suited for in-season management decisions (i.e., reactive) but still run of risk of having to deal with low-quality images because of cloud cover and shadows. For these reasons it may be advisable for producers who plan to make proactive management decisions based on imagery to be selective about when the data are collected (i.e., urgency should not override the importance of quality). Reactive management decisions are probably best made using real-time sensors if the appropriate devices are available. The ideal scenario would be to have access to a series of inexpensive aircraft or satellite images collected during the growing season that offer enough spatial resolution to display meaningful patterns if they exist (i.e., coarse tuning) so that field scouting and perhaps higher resolution imagery could be justified (i.e., verification and fine tuning). These high resolution images or ground-based sensor data could then be used to guide real-time applications.

Reactive strategies

Access to current and reliable information at the appropriate spatial resolution is essential when considering reactive management decisions. Information with these characteristics has the greatest potential to have a positive environmental impact. However, documenting the impact of management practices on the environment (i.e., water quality, NO_3 leaching, greenhouse gas emissions, and runoff losses) is usually difficult to quantify because the studies need to be conducted under natural field conditions (i.e., realistic conditions for crops growing in undisturbed soils). Efforts to document these losses are frequently confounded by a variety of spatial and temporal factors. For example, measurement of NO_3- N leaching losses with suction lysimeters placed at the bottom of the root zone under furrow irrigation of a silt loam soil showed 2 to 5-fold differences in water infiltration rates between rows depending on the traffic pattern of the planting and tillage equipment (personal communication, Dr. Darrell Watts). This large difference in water percolation rate totally overshadowed any modest differences in NO_3 leaching that might have ensued due to spatial N fertilizer treatment differences. Measuring greenhouse gas emissions is fraught with equally serious problems because losses depend on the placement of the collection chambers relative to areas of compaction, incorporation of crop residues or manure, soil water content differences, and proximity to plant roots that release exudates that stimulate microbial activity. Finally, nutrient loss events related to weather are frequently not captured by periodic sampling protocols (e.g., weekly or monthly) unless samples are collected continuously and analyzed frequently (i.e., not composited). For these reasons, documentation of the environmental benefits of spatial and temporal management decisions based on remote sensing technologies is frequently intuitive or indirect (i.e., reduced application rates, yield differences, lower amounts of carry-over nutrient into the next growing season, etc.).

A new generation of active sensors is able to generate real-time maps of field attributes like soil color and crop vigor when coupled with GPS (global positioning system) technologies. The idea for using modulated light to evaluate crop vigor goes back ~70 years (Holland et al., 2004). Sophisticated electronics and modern optic designs make it possible for users to select the desired wavebands to characterize a given set of plant parameters (e.g., chlorophyll status, amount of living biomass, water status, leaf area index, etc.). Because these devices generate their own light, they can be used any time of the day or night (see www.hollandscientific.com for examples of applications). Comparisons between passive and active sensors are limited, but indications are that the data collected are comparable, with certain limitations (Stamatiadis et al., 2005 and 2006).

Proactive applications

Imagery can be a powerful environmental tool because it documents the current situation and can serve to illustrate change over time. Sometimes imagery identifies simple but unknown problems that have practical solutions. Examples of remote sensing applications with environmental implications are quite diverse. The environmental implications may be both direct and indirect as follows:

Document invasive species (weeds and trees) – Information on the occurrence and spread of invasive weeds (e.g., leafy spurge) and trees (e.g., Western Red Cedar) in grazing lands is used to initiate chemical spraying and burning programs. Imagery after treatment documents the successes. In other instances, imagery showing habitat changes in and near rivers is used to make management decisions.

Land use (crops and irrigation) – Natural Resources Districts in Nebraska use annual imagery to document the types of crops grown and the type of irrigation used on each field. This information is merged with groundwater nitrate-N concentrations from irrigation wells, fertilizer records, and yields to identify crops and cultural practices that result in significant risks to groundwater quality. Historic records (since 1988) in one region have identified seed corn, popcorn, and potato production (all high-value crops) as problem systems. Fields receiving manure had higher nitrate-N concentrations in the groundwater while fields under center-pivot irrigation had lower concentrations.

Hail damage – Imagery is sometimes used to document the spatial extent of crop damage to establish fair insurance payments. Producers use the information to develop weed and disease management strategies.

Wind damage – Forestry companies used high resolution aircraft imagery after hurricane Katrina to identify areas within forests that were severely damaged. Selective harvesting was initiated to inhibit the spread of disease and reduce the risk of future fires.

Fire losses on the landscape – Imagery is used to assess the aerial extent of damage caused by fires and to plan conservation measures. These applications include forests, grazing lands, areas along railroad right-of-ways where accidental fires were started, and accidental fires in crop fields started by catalytic converters and sparks from field implements.

Irrigation uniformity – Producers use aircraft and satellite imagery to evaluate the uniformity of water distribution within fields. Problems related to topography have strong environmental (leaching and denitrification) and economic implications. Mechanical problems with sprinkler irrigation systems identified in imagery can have both economic and environmental implications.

Accidental herbicide damage – The economic shortcomings of herbicide spray drift are of intense interest to producers and insurance companies. Environmental implications follow because reduced crop uptake of mobile nutrients means that they will be subject to runoff and leaching losses. Similar concerns exist when the wrong herbicides are inadvertently used and a crop is destroyed.

Wetlands – Changes in wetland size, density, and the species present are signs that management options should be re-evaluated. Massive wetland areas in Nebraska are imaged annually (30-cm spatial resolution) to document changes.

Buried pipeline leaks – High pressure gas pipelines (natural gas and anhydrous ammonia) are imaged routinely to detect vandalism and leaks. A lack of vegetation over the pipeline generally signals a leak and related environmental concern.

Taxation – Cities, counties, and governmental agencies use imagery to detect destruction of wetlands, unapproved construction practices (ponds and drainage ways), and existence of real estate in general to support local government operations.

Elevation and drainage – Imagery is a powerful tool to identify plugged and ineffective tile drainage systems in fields. Remedies may involve simple repairs or be more complex if additional tile drainage lines are required. The environmental implication frequently amounts to a trade-off between denitrification on the landscape or delivering the high NO_3 water to a stream for others to deal with (i.e., treatment by municipalities before domestic consumption and contribution to the hypoxic zone in the Gulf of Mexico). The vertical resolution of imagery is usually about twice the horizontal resolution so many government entities use 7.5 or 15-cm spatial resolution imagery to estimate elevation for purposes of calculating runoff and designing roads, bridges, and drainage ways.

Security assessment – Surveillance issues related to security can potentially conflict with environmental concerns (trees and scrubs to prevent erosion and control runoff versus line-of-sight detection of human activity). Remote sensing is used by military personnel to design environmentally friendly landscapes that provide the needed security.

Establish commodity contract Prices – Large corporations use remote sensing to estimate the amount of land planted to certain crops and to estimate production. They use the area information and estimated yields to establish contract prices for crops like potato. Large scale (low spatial resolution) imagery is used to estimate production levels so they can plan for storage, transportation, and processing. All of these operations have direct and indirect environmental implications at some level within the food chain.

Opportunities for Remote Sensing

The tools and technologies involved in remote sensing will forever be improving and becoming more sophisticated. When it comes to integrating remote sensing into production agriculture and concurrently into environmental stewardship efforts, several disciplines are involved. No tool is able to integrate all of the factors and considerations that have a bearing on the food chain and environment as can be accomplished with remote sensing. Adoption of these technologies is hindered because it is difficult to quantify environmental attributes. In contrast, the economy of the world operates on monetary values. Another difficulty that needs to be overcome is that the remote sensing community does not know what agricultural producers want or could use. Conversely, producers and consultants are not usually aware of the remote sensing technologies that they could have with little or no modification. In between these groups is the need for individuals who are able to apply scientific principles to link what remote sensing tools have to offer to profitable and environmentally sound agronomic applications. The latter group is in short supply at present and probably holds the key to integrating various disciplines. It is quite clear that one discipline or interest group alone will not be successful. The Resource21 and John Deere efforts showed that the end user needs to be involved from the beginning because they are the ones who must ultimately add value to the products that they produce and profitability to their operation. Alternatively, government entities may choose to develop incentive programs (subsidies and cost sharing) or regulate producer management activities. Efforts to legislate things like water quality and environmental stewardship have never worked very well so more participatory approaches are appropriate. This is going to require some level of technology transfer to producers to help them gain confidence in what precision agriculture and remote sensing has to offer. Unless the financial incentives are quite high or the "regulatory stick" is debilitating it is going to take some serious "hand holding" on the part of scientists to promote adoption of remote sensing technologies. Identifying the "low hanging fruit" is recommended (i.e., high value crops, situations with obvious environmental problems that are candidate for regulation, and technologies that are minimally intimidating to users) as a starting place. Promotion of remote sensing technologies should be on the basis of profitability. Policy makers are advised to be content that environmental friendliness will follow if producers adopt a sound program that integrates the temporal and spatial aspects of appropriately combined proactive and reactive management strategies.

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