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DETERMINATION OF SOIL NITROGEN CONTENT IN-SITU: A LITERATURE REVIEW

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SUMMARY:

"Site - Specific Crop Management (SSCM)" is increasingly becoming popular among agricultural scientists and engineers because of its potential to reduce production cost, increase productivity and protect the environment. This innovative and futuristic concept of SSCM is often referred by several other *buzz words* such as *"Farming by Soil", "Prescription Farming", "Farming by the Foot", "Farming Soils, not Fields", and "Environmentally-Friendly Production"*. Recent advances in computer technology which made it possible to process tremendous amount of information in a short period of time, has made the concept of "Site-Specific Farming" almost a reality. A Geographic Information System (GIS) or a Field Information System (FIS) can be used to map the variability within a field. This map along with a Global Positioning System (GPS) can be used to apply an appropriate amount of chemical or some other input in real-time. Most of this technology is already available. A differential GPS system with a precision of about an inch is currently available for about $9000.00. This kind of accuracy is more than adequate for most site-specific applications. The technology in this field is advancing very rapidly and cost is expected to go down even further. Sensors to sense soil organic matter on-the-go have been successfully developed. Grain meters to map the yield have also been developed. The main bottle-necks are the lack of reliable sensors to determine various inputs such as soil fertility level - particularly soil nitrogen, soil texture, and the form of empirical yield function for different crops in different soils. This report presents a comprehensive review we conducted which deals with soil nitrogen and its implications on crop production, health and environment, SSCM, spatial variability and GIS, position detection and GPS, sensing soil nutrients such as soil organic matter and nitrogen, sensing soil texture, grain flow meters and yield mapping, remote sensing, and techniques for determining soil mineral nitrogen.

DETERMINATION OF SOIL NITROGEN CONTENT IN-SITU: A LITERATURE REVIEW

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NITROGEN AND AGRICULTURAL PRODUCTION

Four decades of remarkable progress in Agriculture has doubled agriculture production while reducing labor input by threefold (Addiscott et al., 1991; Upadhyaya, 1992). Although hybrid seeds played an important role in increasing production, this impressive production would have been impossible without the use of chemical fertilizers. This has resulted in a plentiful supply of very high quality and inexpensive food. Adequate food and clean water are thought of as basic human rights. (Addiscott et al., 1991). In recent years, some concerns have been raised about the sustainability of this type of agriculture. One major factor at the root of this concern is the *nitrate problem*.

Nitrate is essential to life. Most crops respond readily to nitrogen fertilizer input. Thus nitrogen fertilizer provides an inexpensive means of producing large amounts of food. Addiscott et al.(1991) state that if you take away nitrogen fertilizer, food price will skyrocket. However, nitrate can be a hazard when found in a wrong place at a wrong time. It is readily soluble in water and highly mobile (CDFA, 1989). If it is not taken up by the plant, it can leach down to the ground water and contaminate it. During the last four decades nitrate concentration has been steadily increasing in ground water which coincides with the increase in fertilizer use on the farm. Incidentally, during the same period urban population as well as animal agriculture has also been increasing, both of which contribute to nitrate in ground water. California ranks first in egg production, second in dairy, second in sheep and lamb, seventh in beef, and eight in poultry. Associated with this animal agriculture is a large supply of manure which presents a problem. Peters and Reddell (1976) report a serious concern with beef manure because of its potential for ground water pollution. Other potential sources of nitrogen in ground water are the cultivation practices, precipitation, irrigation and geological origin of the soil parent material (Power and Shapers, 1989). Increasing levels of nitrate has been detected in California's vast ground water resource in recent decades (FREP 1990-92). On a national level also, nitrate concentration in the ground water is a serious concern since almost 50% of drinking water comes from wells (Kanwar et al., 1985). In rural America, ground water accounts for 90% of the water supply (Power and Shepers, 1989).

NITRATE PROBLEM:FACT AND PERCEPTION

The "*nitrate*" is a nuisance when found in a wrong place whereas "*nitrite*" is a potential health hazard. However, "nitrate" can very readily be converted into "nitrite" by microbes requiring oxygen. "Blue-baby" syndrome and stomach cancer are two health problems often blamed on nitrite. Theoretically increased nitrite concentration should lead to increased incidence in stomach cancer. Clough (1983) found a correlation between gastric cancer mortality and increasing nitrate level in Kent, Southwest England. He cautioned that this result should be interpreted along with other socio-economic factors. However, careful studies have not been able to relate stomach cancer with nitrate concentration in drinking water (Forman et al., 1985; Addiscott et al., 1991). Workers in fertilizer plants often have higher NO_3^- concentration in their salvia, but do not show higher incidence of stomach cancer. Ironically, during the past 30 years although nitrate concentration in the water has gone up, the incidence of stomach cancer has actually gone down.

Another problem is the increased plant growth in rivers and lakes due to increased nitrate concentration. Algal bloom is of particular concern. When the algae dies, the bacteria which consume algae require oxygen which in turn takes away oxygen from other form of aquatic life thus upsetting the ecological balance (Addiscott et al., 1991). Increased calf abortion rate and loss of quality of fruit and other crops are also blamed on the nitrate problem (FREP 1990-92). CDFA (1989) reported that birth defects may also be associated with the nitrate problem.

Yet another problem associated with fertilizer use is the evolution of nitrous oxide. N_2O may evolve during de-nitrification and nitrification, although de-nitrification accounts for majority of N_2O evolution (Addiscott et al., 1991; Millier and Williams, 1991a,b,c; Ryden and Lund, 1980; Stewart, 1986). De-nitrification was found to increase with applied fertilizer and soil wetness (Addiscott and Powlson, 1992). They found that de-nitrification accounted for 0 to 35% loss of nitrogen in a winter wheat crop over a three year period. N_2O fluxes from irrigated land planted to vegetable was found to be in the range of 0.0038 to 1.06 kg/ha/day (Ryden and Lund, 1980). N_2O contributes to the greenhouse effect and depletion of the ozone layer. The current estimate is that the fertilizer contribution to N_2O release is small on a worldwide basis (Jenkinson, 1986).

Although, health and environmental implications of reasonably high nitrate levels (more than 100 ppm) in water is confusing and inconclusive (UK Dept. of Environment, 1986), the perception of the nitrate problem by the society is clearly negative. This perception has led to a serious concern regarding nitrate concentration in drinking water. Restrictions have been placed on the amount of NO_3^- in drinking water by various regulatory agencies. The current public health standard for drinking water in California is 44.3 ppm of NO_3^- (FREP, 1990-92). The European community has recently imposed a limit of 50 ppm on NO_3^- in drinking water (UK Dept. of the Environment, 1986; Addiscott et al., 1991)· The world health organization (WHO) recommends a limit of 100 ppm of nitrate in drinking water.

In Germany nearly 36% of the Phosphorus and 42% of the nitrogen in the ground water are attributed to agricultural practices (Auernhammer et al., 1991). Nitrate concentration of less than 1 to 133 ppm with a mean of 20 ppm have been observed in shallow ground waters of Georgia (Hubbard et al., 1986). In the sandy soils of lower Delaware, intensive poultry farming has led to serious ground water pollution. Much of the ground water in this region has been deemed unfit for drinking. Hundreds of wells in various regions of California contain nitrate concentrations in excess of the State limit. The problem is particularly serious in the tree-fruit producing region of the east side of the central valley and the major vegetable producing areas of the central coast valleys . Fruits and vegetables account for about 28% of cropped area, but account for 41% of agricultural fertilizer use (FREP 1990-92). Correcting this problem is very expensive. Moreover, excess nitrate in ground water leads to restriction in land use, denial of loans, lack of suitable water supply and reduction in tax base (FREP 1990-92). One of the major objective of the CDFA's nitrate management program through FREP is to develop nitrate-reducing farming practices.

FERTILIZER AND CROP PRODUCTION

Since one of the most widely accepted causes of increased levels of nitrate in ground water is fertilizer use in agriculture, questions arise about its continued use. Alternate farming practices which use very little or no chemical fertilizers have sprung up all over the country. Organic farming and Low Input Sustainable Agriculture (LISA) are becoming popular (Upadhyaya, 1992). However, proponents of fertilizer use argue that the nitrate problem has been greatly exaggerated and very little scientific evidence exists that links the ground water nitrate level with the health and environmental effects listed. They also point out that even the most optimistic outlook predicts the world population to increase over the 10 billion mark during the next 40 to 50 years. Food production needs to double without an appreciable increase in cropped area. With limited land, the possibility of use of this land to produce organic manure and legumes to supply N may become limited. Although, biotechnology and genetic engineering can help in improving yield, chemical fertilizers will remain as the main hope for providing high quality food at a reasonable price. Therefore any Sustainable Agriculture system should include strategies to optimize crop uptake of nitrogen while minimizing nitrate leaching to ground water (Cassaman, 1990). In California, the native level of organic matter is low and nitrogen fertilizer will continue to play an important role in insuring crop production.

Since increasing nitrate concentration is a potential concern, it is wise to use techniques to avoid improper use of fertilizer. The Nitrate working group recommended the development of maps that identify areas sensitive to ground water pollution, and management techniques that reduce the pollution potential(CDFA, 1989). One of the most innovative and intriguing possibility is to apply just the right amount of fertilizer based on crop requirements taking into account the soil type, topography, soil fertility level, soil organic matter content, and soil moisture content. This approach is gaining support among agricultural scientists and engineers. This method of prescribing chemical to each and every location in the field, rather than subjecting the whole field to uniform application of chemicals is known as Site Specific Crop Management (SSCM). Prescription farming can increase productivity and reduce environmental pollution (Gaultney, 1989). This technique relies on the use of geostatistics, Geographical Information System (GIS), Global Positioning System (GPS), nutrient sensing, and real-time control.

SITE SPECIFIC CROP MANAGEMENT (SSCM)

Successful application of SSCM in real-time requires a knowledge of soil type, topography, climate, soil fertility - particularly soil nitrate level, soil organic matter content, soil moisture and the potential yield function. A geographical information system (GIS) is very useful in mapping the variability of soil by location using geostatistics and storing the data in a retrievable data base. Yield mapping is often used to get an integrated effect of variability in the field. Soil organic matter and nitrate level needs to be determined either in real-time or determined and mapped ahead of time. Development of these sensors are the main bottle-neck in real-time sensing of soil properties (Gaultney, 1989). Once the inputs are determined, a potential yield function can be used to estimate the amount of chemical fertilizer requirement at each location within the field. Han and Goering (1993) developed a user friendly prototype Field Information System [FIS] which will acquire field data [field registration], soil data [geographic information] including any relevant sensor information and create application rate map. To make real-time application possible, a geographic positioning system (GPS) is needed to identify the exact location of the chemical applicator in the field (Schueller, 1991). Some of these components are discussed in more detail in the following sections:

CROP RESPONSE TO FERTILIZER INPUT:

Nitrogen is essential for plant growth. Although, other macro- and micro-nutrients play an important role in crop growth, nitrogen is the key to increasing crop production in many crops. Nitrogen increases leaf area, crop development, and improves crop quality (increased protein). At low fertility levels, crop response to nitrogen is almost linear. Under such circumstances a dollar invested in N-fertilizer fetches about six dollars in increased crop yield. However, at higher fertility levels or application rates, most crops exhibit the law of diminishing returns. Above a certain amount, the residual NO_3^- in the soil after harvest increases. This point can be considered as the point of satisfaction. Unused NO_3^- leaches down to the ground water (Addiscott et al., 1991).

Several researchers have attempted to relate crop yield to applied chemical (Boyd et al., 1976; Cooke, 1975; Hills et al., 1983; Johnson, 1991; Lanzer et al., 1981; Sparrow, 1979). Crop response to fertilizer depends on the crop type. For example, sugar beet takes more soil-N than tomato which requires more soil-N than corn (Hills et al., 1983). The form of crop response to fertilizer is usually assumed to be a polynomial or an asymptotic function. The following are some of the common response curves obtained by various investigators (Cooke, 1975):

1. Mitscherlich curve:

$$y = y_0 + y_m(1 - e^{-kx})$$

where

y = crop yield
y_0 = crop yield without fertilizer input
y_m= limiting response to fertilizer
k = crop dependent constant
x = input fertilizer

2. Quadratic curve:

$$y = a + b x + c x^2$$

where a,b,c are crop dependent constants

3. Square root curve:

$$y = a + b\sqrt{x} + cx$$

4. Inverse curve:

$$\frac{1}{y} = a + \frac{b}{x + c}$$

Boyd et al. (1976) found intersecting straight lines to be a better model to represent cereal response to nutrient input. Sparrow (1979) found that inverse quadratic, Greenwood's modification of the linear, and two intersecting straight lines represented Spring barley response to fertilizer well. These three models differed from each other very little. Lanzer et al. (1981) and Johnson (1991) developed a joint response function for crop response to fertilizer input. In one experiment maize showed quadratic response to soil nitrate-N at low levels of K, but a saturation curve at high levels of K. This result shows that interaction between various macro-nutrients may be important (Cooke, 1975).

EFFECT OF SOIL VARIABILITY (SV) ON CROP PRODUCTION:

Neither the amount nor the position of Mineral N is constant in any given field (Addiscott and Darby, 1991). Moreover, mineral N shows temporal variation due to mineralization, de-nitrification, immobilization, nitrogen fixation, leaching and plant uptake. Mineralization refers to the conversion of organic matter into ammonia and subsequent nitrification of ammonia to NO_3^- by soil microbes. When there is a large amount of carbon compared to nitrogen in the soil (C/N > 25) microbes grow and divide by utilizing the energy in the organic matter. They derive the protein for their growth from mineral N (ammonia and nitrate) in the soil. This process ties up the mineral N and makes it temporarily unavailable for plant growth. This process is called immobilization. De-nitrification refers to the process of breaking down of nitrate and ammonia by microbes to nitrous oxide and releasing it to the atmosphere. Wet soils and high temperatures encourage de-nitrification. Negatively charged NO_3^- ions are repelled by the clay particles and leach down. Nitrogen fixation by micro-organisms such as blue-green algae and nitrogen fixing bacteria convert the nitrogen directly from air and make it available to plants

(Addiscott et al., 1991). These processes make soil nitrogen one of the most variable quantity both spatially and temporally.

Reed and Rigney (1947) found great variability in P, K, organic matter, and pH in a field. Jensen and Pesek (1962a, b, c) studied the effect of soil nutrient variability on yield loss. They concluded that significant yield reduction occurred due to the spatial variability in nutrient level in the field. Tits et al.(1989) compared the yield variability with topography, drainage, soil analysis, and fertilizer application rate. They used a grain flow meter to map the yield. Position in the field was determined by instantaneous combine speed and with the use of beacons. Grain yield was found to vary in the range of 3 to 9 t/ha with a mean of 5.7 t/ha. Grain yield correlated with percent soil carbon and soil-N. Biggar (1978) reported a coefficient of variation for native-N to be in the range of 15 to 60%. Ramanarayan et al. (1993) found variability in nitrate-N in all the fields tested in the Tipton wetland protection area. Lutz(1975) found that non-uniform application of fertilizer by spreaders leads to a reduction in corn, barley, soybean and wheat yield. Cassman (1990) reported that an ability to apply site-specific amount of nutrients may affect nutritional utilization efficiency. Cassman and Plant (1990) found that applying site-specific amount of nutrient to match the plant requirement in a non-uniform field can increase yield. They ran simulation studies for wheat, rice and cotton. Response of wheat to total plant nitrogen was assumed to be a saturation curve whereas, response of rice was assumed to be quadratic. The response of cotton to solution phase K was also assumed to be a saturation curve. They found that increased variance in native nutrient distribution leads to increased fertilizer application under uniform field treatment. However, effect of skewness was to reduce the effect of variance if it was positive. On the other hand if skewness was negative, the effect of variance was increased. Our simulations indicate that a coefficient of variation(CV) of 30% leads to an yield loss of 2 bushels/acre; whereas, a CV of 50% leads to yield loss of 13 bushels/acre for corn. These simulations were based on a normal distribution in native nitrate level of soil. Biggar(1978) points out that large variations in soil fertility level usually implies a large skewness in the distribution. Chancellor and Goronea (1993) studied the variability of soil mineral nitrogen, weed infestation and moisture content. They found large kurtosis in the distribution of native -N level. For low to medium rate of application of chemicals, their simulations revealed that spatially modulated application can result in 12% advantage for N and 40% advantage for herbicide. They recommended a sampling and response interval of 1m or less. If the sampling interval is more than 1 m, there will be a reduction in the benefits. Furthermore, benefits tended to decrease if the application rates are high compared to the native N-level.

Adjusting fertilizer application based on soil fertility level can lead to considerable savings (AURI, 1992). Carr et al.(1991) claimed a savings of $22 to $ 24 /acre when fertilizer application was tuned to soil unit rather than the whole field unit. They found that yield was more uniform when fertilizer was adjusted to the soil condition rather than applying a constant rate to the whole field. On the average, they found an yield increase of about 10 bu/acre. Luelln (1985) reported a net savings of $ 5 to $ 15 /acre when fertilizer application is fine tuned to soil fertility variations. Reichenberger and Russnogle (1989) found that savings for managing soils *not* fields is in the range of $ 10 to $ 15/acre. Robert et al. (1991) reported a maximum of $ 17/acre benefit for soil specific management compared to conventional management.

SOIL NUTRIENT SENSING:

Development of two sensors in the recent past marked a major step in SSCM technology. These are (i) soil organic matter (SOM) sensor, and (ii) grain yield meter. The soil organic mater sensor works on the principle of soil reflectance and the grain yield meter works on the basis of capacitance change or the principle of a nucleonic device. The idea behind the grain yield meter is that yield is a single measure which integrates various inputs to the crop. Site-specific applicators have been developed which use these types of sensors. Tyler industries has developed a variable rate, on-the-go, site specific pesticide applicator which utilizes soil organic mater content information. Soiltek has developed a fertilizer applicator which utilizes yield maps developed by grain yield meter and GIS along with GPS.

SOIL ORGANIC MATTER SENSING:

It is well known that the darker the soil the more is the organic matter. This suggests the possible use of spectral reflectance in the visible or near infrared (NIR) range to sense soil organic matter. McKeague et al. (1971) found that the color value of soil correlated with soil organic matter (SOM). Page (1974) reported that SOM correlated well with the readings from a color difference meter. Schreier (1977) studied the spectral reflectance of soil derived from five different parent materials from the air, on the ground and in the laboratory with a multi-channel spectro-photometer. A comparison with the chemical analyses revealed that the spectral reflectance correlated well with % C, % Fe, and exchangeable Mg and perhaps K. Steinhardt and Fransmier (1979) established a semi-quantitative relationship between SOM and soil color (Munsell soil color chart) for cultivated silt loam soils of Indiana. This relationship was found to be accurate in predicting SOM 90% of the time. Krishnan et al. (1980) investigated the spectral reflectance of soils in the visible and near-infrared (NIR) region. No absorption peak was found in the visible or NIR region due to SOM. However, visible region provided more information about SOM than NIR. The first derivative of the spectral reflectance curve had broader peaks that correlated better with the SOM than the second derivative. Krishnan et al. (1981) developed a device which utilized the spectral reflectance of visible light by soil to determine SOM. This device worked quite well, although it had difficulty differentiating between sandy soils with low SOM and silt-loam soils with high SOM. Griffis(1985) tested two different light sources (incandescent light versus light emitting diode) and found that both sources worked fine although the incandescent source was slightly better. Pitts et al. (1986) used red, green and an unfiltered light as a source of light in detecting SOM. They found that the amount of reflected green increased with SOM whereas amount of reflected unfiltered light decreased with SOM. Ratio of reflected Red/Green varied significantly with SOM. The reflected Green, Green/White and Red/Green each had difficulty predicting SOM in some part of the 1 to 5% SOM range.

Fernandez et al. (1988) found that soil color and organic matter correlated very closely within a landscape in Indiana both for dry and moist soil. Over a wide geographical region the correlation was not very good. Therefore, a SOM sensor should be calibrated on a field by field basis. Gaultney et al.(1989) developed a real-time SOM sensor based on reflectance of visible light. It uses a photo-diode to measure reflected light. A red LED was found to be the best source for field application. This sensor was found to be accurate in less than 1% to 6% SOM range. If soil had more than 6% SOM it was difficult to estimate it from sensor readings. Other soil parameters such as soil texture, moisture content, surface roughness, and iron dioxide content influenced the sensor reading. Gunsaulis et al. (1991) also found that the red range reflection of soil depended on SOM and aggregate size. Therefore, this sensor needs to be calibrated for each landscape. This sensor was successfully employed to measure SOM in several locations in Indiana, Illinois and Texas (Shonk and Gaultney, 1989). Shonk et al. (1991) developed a prototype real-time SOM sensor. This sensor was retrofitted to an herbicide applicator to accomplish site-specific application of herbicide. The greater the organic matter the greater is the requirement for herbicide. SOM has also been correlated with water holding capacity and yield potential.

Leedahl and Strand used a commercial version of the SOM sensor developed by Gaultney et al. (1989). They retrofitted it onto a dry granular fertilizer applicator which coated fertilizer granules with liquid herbicide (Ligon, 1993a, b). Alsip and Ellingson (1991) tested the SOM sensor developed by Shonk and Gaultney (1989) by integrating it with a Tyler M250 applicator. A Trimble Navtrack GPS system was used to position the device. Error in position was less than 5 m. Atmospheric conditions, satellite switching and satellite geometry can lead to an errors up to 50 m. The SOM sensor was calibrated using known organic matter levels. Field tests were conducted at 18 km/h at the rate of 2 seconds/ sample. Limited tests gave very promising results. Yang et al.(1993) used an on-the-go SOM sensor and two inclinometers to map the field. Both the sensors worked well, although SOM sensor output was influenced by soil moisture content. The inclinometers provided the slope information. They used standard GPS with post-processed differential corrections to locate position in the field with about 5 m accuracy.

Kocher and Griffis(1989) used infrared rays to determine soil carbon content. In their system soil was lifted from 1 to 3 cm depth and presented to the sensor. This sensor was more accurate compared to the sensor developed by Shonk and Gaultney (1989). However, they suggested that where accuracy is not a major concern, it may be better to use the simple and inexpensive system developed by Shonk and Gaultney (1989).

Sudduth et al. (1991) developed a prototype NIR reflectance sensor to measure SOM in the surface layer of soil. They used stepwise regression, principal component analysis, and partial least square regression of NIR spectra as well as visible spectra and found better correlation of SOM with NIR spectra than with the visible spectra (Sudduth and Hummel, 1989, 1991; Sudduth et al., 1991). However, this device was unable to provide the required accuracy in the field. Sudduth and Hummel (1991) correlated NIR data in 1720 to 2380 nm range to SOM. Data were smoothed over the 60 nm range. This multiple wavelength NIR reflectance sensor worked well. Nitsch et al. (1991) used spectral reflection in the range of 400 to 900 nm to analyze soil reflectivity data. They found that normalized reflectivity data in 800 to 850 nm range was useful in differentiating living plant material from crop residue.

SOIL TEXTURE SENSING:

Liu et al. (1993) reported that both soil organic matter sensor and soil moisture sensors are sensitive to soil texture. Moreover, soil texture influences the ability of soil to retain nutrients. In a coarse textured soil nutrients may leach out easily and add to soil water contamination. On the other hand, adding additional nitrogen may increase yield in a heavy textured soil without increasing ground water pollution, if the native nitrogen level is low. Thus texture information is critical in making decision on spatially modulated chemical application rate. A Geographical Information System (GIS) which utilizes SCS soil survey map can be helpful in determining soil texture. However, spatial resolution of this approach is low and an in-situ texture sensor is desirable. Hellebrand (1993) suggested the use of a horizontally moving cone penetrometer to measure soil texture. Liu et al. (1993) used acoustic signals produced by cutting tools moving through soil to determine its texture. Their preliminary results are encouraging. Glancey et al. (1989) developed an instrumented chisel for the study of soil-tillage dynamics. They used this device to predict various tillage implement draft requirements in different soil type and conditions (Glancey et al., 1991). Their results indicated that the draft requirements of this device depends on soil type and conditions when it is operated at a constant depth and forward speed. This device has the potential for use in soil texture determination.

GRAIN FLOW METER AND YIELD MAPPING:

Stafford et al. (1991) suggested that grain yield monitoring is a good method of monitoring several spatial variables since crop yield integrates the effect of these spatial variables. A yield map can be developed with this data which can be used to control devices such as fertilizer applicators to achieve site specific farming. Grain flow meters on a combine may provide a simple means of obtaining yield data(Luelln, 1985). Searcy et al. (1989) used a grain flow meter and a location detector to map the yield in the field. The total yield determined by the grain flow meter was 7.1% less than the yield obtained by manual sampling even after correcting for combining losses. He suggested the use of this yield map for future management since this yield map accounted for spatial variability in soil type, fertility level, weeds, and pests. Stafford et al. (1991) used a nucleonic grain flow device (γ-ray) and a capacitance type flow sensor. They found that the calibration of the nucleonic device was not sensitive to grain type whereas capacitance type device should be calibrated for different grains. However, since capacitance flow meters are free of radioactivity, they are a better choice for field application. Auernhammer et al. (1991) found that a specific pressure sensor on self-loading trailer can be quite accurate (<1%) in determining yield in grass land. They also tested a X-ray flow sensor on a combine in a wheat field. They obtained an error of less than 2% and found that this interfaces with GPS system well. Peiffer et al. (1993) developed a yield sensor which employed a beam of light projected across the clean grain elevator to sense the height of grain on individual flights. Multifle diodes located on the opposite side detected the grain height over the flights. When properly calibrated, this device had an accuracy 3%.

Soil-Teq, Inc. [60% owned by Ag-Chem Equipment Co. and 40% owned by Cenex/LOL] has developed a map-controlled variable rate application equipment. At the heart of this device is a Soilection system, a patented process owned by Soil Teq Inc [letter dated June 23, 1993 by the CEO of Soil Teq, Inc.]. An on-the-go grain monitor developed by Dawn Equipment Co., a sister company of AgriCAD provides yield variability in the field. AgriCAD has developed an interface between AgMAPP and the Soilection system. AgMAPP is a database which contains such information as field perimeter, soil types, soil test information, and fertilizer recommendations. Soil-Teq is planning to move over to GPS rather than dead-reckoning to determine position location in the field. This system was successfully used to blend NPK for sugar beet and PK for corn and soybean (Glaeser, 1993). Soil-Teq, Inc. is expecting to use this device for controlling fertilizer applicators, planters, and direct injection sprayers.

Fisher et al. (1993) developed a spatially variable liquid fertilizer applicator for wheat. They used soil data obtained by manual sampling for nitrogen level, soil organic matter content, soil moisture capacity, wheat yield data obtained by a yield sensor and topography data obtained from maps and inclinometers mounted on field equipment, and produced a fertilizer application rate map based on an expert system developed by He et al. (1993). A Differential Global Positioning System (DGPS) was used to determine the location of the fertilizer applicator in the filed. A chisel plow was modified to vary the fertilizer application rate in the range of 0 to 120 kg/ha based on the application rate map. This system reduced the total fertilizer application by 25%. More tests are currently under way at the University of Idaho.

REMOTE SENSING:

Remote sensing provides an alternate means of detecting soil properties relevant to crop production. Aerial photography and satellite based scans can provide valuable information. Vinogradow (1982) investigated the possibility of using remote sensing to determine soil characteristics. He found that 400 nm to 1200 nm visible to NIR reflectance corresponds well with the humus content of soil. The far red band (680 to 780 nm) was particularly sensitive. The best time to use remote sensing to acquire field data was found to be after harvesting and late fall plowing up to the third leaf stage and tillering of small grain crops.

Zheng and Schreier (1988) explored the use of direct spectral reflectance of soils and multi-emulsion analysis of aerial photographs for soil and fertility management in agricultural fields. They found percent organic carbon, soil water content, and color values were the most sensitive variables that related to the remote sensing data. They felt that this information in conjunction with the information from conventional soil analysis can be used to determine fertilizer requirements at various location in the field. Stecker and Brown (1993) used aerial photography of no-till corn fields obtained from a height of 600 to 900 m to detect the weed species and weed distribution within the field. Information from RGB channels produced by scanning both conventional and color-infrared films provided information to detect all weed species with at least 75% accuracy. They claimed that this information can be imported into a GIS system and used to create spatially variable herbicide application map.

New remote sensing devices are being developed which can provide a large amount of data on soil. The Landsat multispectral scanner has a low spatial resolution of 80 m and a spectral resolution of 100 nm. Introduction of Thermatic Mapper (TM) in 1982 increased the spatial resolution significantly (down to 30 m). The new generation High Resolution Imaging Spectrometer (HIRIS) which will be released sometimes during the nineties will have a spectral resolution of 10 nm. The spatial resolution will be 30 m (Henderson et al.,1989). Bhatti et al. (1991) measured soil organic carbon, P and wheat yields along a 655 m transect in complex eroded hills of the Eastern region of the Washington State. They used Thermatic Mapper Images to estimate soil organic matter content. Data were analyzed using statistics and Geostatistics. Classical statistics showed moderate variability in soil properties (25 to 50%). Semi-variograms of soil properties and wheat yields showed a spatial dependence in the range of 70 to 145 m. Semi-variograms of Landsat SOM was almost identical to the ones obtained for the land based measurements. They concluded that remote sensing of SOM along with limited ground sampling offers a great promise in assessing spatial pattern in grain yield and soil P over large regions. Remote sensing can also be useful in sensing soil humus, crop chlorophyll, crop growth state and crop weeds (Curran et al., 1990).

SPATIAL VARIABILITY, GEOSTATISTICS AND GEOGRAPHICAL INFORMATION SYSTEM (GIS):

In agriculture and biology spatial variability has been more a rule than an exception. Up until recently, agriculturists have chosen to ignore this variability as a mere nuisance

(Biggar, 1978). However, increased environmental concern is forcing agriculture to leave the paradigm of uniformity and address the small spaced variability through SSCM (Auernhammer et al., 1991). Classical statistics is unable to deal with variability. Geostatistics provides a powerful tool to deal with spatial variability (McBratney, 1985; Miller et al., 1988). The semivariogram is a measure of dissimilarity as against correlation which is a measure of similarity. Semivariograms are useful to identify factors related to soil properties of interest. Kriging can be used to interpolate between measured values in an unbiased manner (McCammon, 1975; Clark, 1986; Lopez-Bakovic, 1988; Isaak and Srivastava, 1989) .

The Geographical Information system (GIS) is useful in mapping spatially variable geographic data (Zhang et al., 1990). It contains hardware and software for data input, storage, processing and display of computerized maps. GIS consists of computer mapping, spatial database management, spatial statistics and cartographic modeling. The mapping and database capabilities are the backbone of the GIS systems (Berry, 1986). Tan and Shih (1990) used GIS to study possible changes in the land use and location of artesian wells. Srinivasan and Engel (1991a, b) used GIS to estimate slope steepness for estimating soil and chemical loss. They used GRASS (Geographic Raster Analysis Support System) and a knowledge based approach to extract 22 grid based input data for AGNPS model. This model is used to estimate concentration of sediments, nutrients (N,P), and chemical oxygen demand in runoff waters in agricultural watersheds. Rosenthal et al. (1991) developed a GIS package for estimating potential runoff from a certain region in South Dakota. Heatwole and Shanholtz(1991) added livestock production data to the Virginia GIS system for seven counties to calculate an animal waste pollution index for various locations in these counties. O' Callaghan et al. (1991) developed a GIS based irrigation demand simulator. Lal et al. (1991) used a GIS system to produce yield maps for best planting dates in Puerto Rico by linking yield potential of soil and weather data.

Reichenberger and Russnogle (1989) suggested the following steps in developing field fertility management maps:

1) Develop a soil map from SCS survey data . Add additional details by remote sensing.
2) Produce a soil management map.
3) Take soil samples and obtain fertilizer recommendations for various areas on the soil management map.

They suggested a grid size of 2 acres for potatoes, 5 to 10 acres for corn, and 10 acres for wheat.

Mulla (1991) and Mulla et al. (1992) used GIS techniques to produce spatial maps for fertility management. They sampled and mapped P and K fertility levels in the field. The field was divided into three management zones based on soil and fertility data (26 ha of high fertility, 26 ha of moderate fertility and 4 ha of low fertility region). They found that wheat yield did not decrease due to SSCM although there was a significant reduction in fertilizer input. The University of Missouri, Columbia; the Soil Conservation Service (SCS); and the Missouri Department of Natural Resources started a project to map the field to see if SSCM is warranted. A GIS system capable of using infrared photography, aerial photo maps, and SCS soil survey maps were used to determine soil type, texture and water holding capacity of soil (Holmes, 1993). They plan to extend the area and incorporate GPS in the next step. Han and Goering (1992) generated a field information map based on soil type, slope, and soil erosion map. A yield goal map was included. He et al. (1992) linked a GIS database to an expert system to develop a cell by cell fertilizer rate map. The GIS database included potential yield, soil and water condition, crop parameters, topographic and environmental conditions for each individual blocks in the field (He and Peterson, 1991). This system reduced fertilizer application rate significantly, especially on slopes. They obtained a savings of about $ 7/acre with SSCM. Nowels (1993) developed a spatial variability map for PH, P,K and SOM to produce a fertilizer variability map. There are plans to use this map with a GPS system to accomplish SSCM.

GLOBAL POSITIONING SYSTEM (GPS):

For a GIS based fertility management system a Global Position System [GPS] is a necessity to locate management sites in the field. Palmer (1990) built and tested a radar based positioning system. This system had an accuracy within 8 in. and a repeatability of less than 4 in. Hellebrand (1993) used a combination of fluxgate compass and radar to update position during GPS drop out [periods of selective availability (SA), explained below]. Although radars, dead-reckoning, lasers, or terra-based systems could be used for position location, GPS is emerging as the most convenient and holds the best potential for agricultural application (Auernhammer and Muhr, 1991; Stafford and Ambler, 1991). GPS is a satellite based radio navigation system that provides 3-D position and speed (Luepke, 1991). A group of 24 satellite constellation was expected to be in place by mid 1993 for 24 hr worldwide coverage . At present all 24 satellites are in their respective orbits and are available for global position detection [Shropshire et al., 1993]. Jasumback (1989) evaluated a GPS receiver for forestry application. He found that position accuracy degenerated when operating under tree canopy. He indicated that a differential GPS system may be superior. Luepke (1991) estimated an average error of 4% with a maximum error of 9.6% in position location during timber harvesting. Shropshire et al. (1993) discussed the details of GPS technology and its application to spatially modulated farming in the Palouse region of the eastern Washington and northwestern Idaho for wheat production. They found the inherent accuracy of GPS to be about 20 m. However, because of "selective availability (SA)", which is random degradation of the GPS signal by military intentionally, the position accuracy can be as poor as 300 m. This problem can be overcome with the use of differential GPS [DGPS]. DGPS utilizes a stationary base station located at a known position. The base station provides a check to correct GPS signal. For agricultural purposes, the base station can be located hundreds of km away. A position accuracy of 5 m is attainable with DGPS. Yang et al. (1993) used soil organic matter sensor, two inclinometers and DGPS in a post-processed mode to produce field management maps. For real-time application a radio link should be established between the rover and the base station. GPS hardware and software can be purchased for less than $1000.00 today (Brown 1993). GPS is still in its infancy. It can become a marvelous tool which may make a profound difference in the field SSCM tomorrow. It is developing very rapidly. A differential GPS system which has a position accuracy down to less than an inch can be purchased for about $9000.00!

DETERMINATION OF SOIL MINERAL NITROGEN:

Most of the SSCM systems discussed so far do not obtain soil mineral nitrogen data directly . Although yield maps provide some information on field variability in turns of soil fertility level, mineral nitrogen is highly variable both spatially and temporally. A modeling approach which takes into account crop growth, applied fertilizer, soil native fertility, soil texture, potential leaching, mineralization, immobilization, irrigation, drainage, and rainfall is very complex and subject to large errors due to uncertainty in the input parameters. A direct approach to determine soil mineral nitrogen is preferable. The Kjeldahl method is a standard laboratory method of determining soil nitrogen (Page et al., 1982). This is a very slow process. Carlson (1978) developed an instrument to measure ammonia rapidly and continuously. He further improved his system to measure soil nitrate by incorporating a reduction stage in which granular zinc pretreated with Cu was used to reduce nitrate to ammonia. Carlson et al. (1990) built a dual channel diffusionconductivity meter to measure nitrate and ammonia in the soil and plant samples very rapidly. However, this is also a laboratory device which is not suited to field application.

Ammonia Sensing Electrodes: Ammonia gas sensing electrodes are available to measure water quality. However, these are not very stable (Princz and Literathy, 1977). Pungor and Buzas (1977) reported that an ammonia probe can be used to measure nitrate after homogeneous reduction. Ammonia probes are preferable to nitrate selective electrodes since these are more stable (Coomas et al. (1977). Babbitt (1991) discussed the development of an ammonia sensor that can detect ammonia gas down to a concentration of 10 ppb. This device works on a interferometric principle. Yatazawa et al. (1984) designed and fabricated a portable gas chromatograph using a gas sensor which they used for measuring nitrogen fixing activity of soil. Bocksnick (1977) claimed that the ratio of light reflected by soil to incident energy can be determined by photo-voltaic cells. This ratio was found to be proportional to the amount of nitrogen in the soil.

Nitrate Selective Electrodes: In order to measure soil nitrate level in the field rapidly, a nitrate sensor would be very useful. Nitrate ion selective electrodes work on the principle of electro-chemical energy conversion. An emf is produced which is a function of ionic activity of the solution. Newer liquid membrane electrodes are very efficient. Interference due to chloride, bicarbonate, bromide and other ions is a major problem. Calibration drift is also a problem (Milham et al., 1970; Pungor and Buzas, 1977; Wright and Bailey, 1977; Vesely et al., 1978; Liteanu et al., 1981). Adsett and Zoerb (1991) developed an on-the-go nitrate sensor using an Orion 93-07 nitrate electrode. Laboratory tests indicated that this device worked well. They designed a field unit which incorporated a soil sampler, a nitrate extractor, a flow cell, and an electronic control unit. A slot cutter made from a chain saw was used to dig the soil to a depth of 15 cm. This device operated at 3 km/h and sampled at the rate of 24 s/ sample. De-ionized water was used for nitrate extraction. The sensor was fast and accurate, but the calibration was tedious and time consuming. The nitrate extraction unit needed further refinement.

Ion Sensitive Field Effect Transistor (ISEFT): This is a more recent development which consists of a membrane which responds to nitrate ions. This sensor has less problems with the calibration drift (Smith, 1991; Goering, 1992). HORIBA Inc. has developed a nitrate meter to measure nitrate ion concentration rapidly. Frequent changes of reference solution is the main problem for field application.

Electrical Slurry Resitivity: Colburn (1986) investigated the possibility of heating soil using exhaust gas to determine the amount of NO released. He assumed that the amount of NO released would correspond to the amount of nitrate in the soil. This method turned out to be neither simple nor economical. Instead they found that an impressed overpotential using copper electrodes in aqueous solutions lead to changes in liquid resistivity called slurry resistivity which correlated well with soil nitrate level and nitric oxide gas liberated. They built a prototype device and conducted limited tests to prove the feasibility of the concept. This device was named the "Smart" injector. A commercial unit called "Soil Doctor" was developed by the Crop Technology, Inc using this principle. No data are available on the field performance of this unit. When contacted by the authors, the company refused to give any information on this device stating that this device is not suitable for California conditions.

Leaf Color: Leaf reflectance in the visible range can indicate moisture and nitrogen stress (Ahmed and Reid, 1991). Corn plants deficient in nitrogen tend to become pale, yellowish green. Plant leaf color can provide information on plant N requirement. Interaction with plant water status may make it difficult to estimate nitrogen requirement accurately. Moreover, the color indicates the presence of stress, detectable states of which may occur too late for any timely response.

Search for a suitable mineral nitrogen sensor, particularly a nitrate sensor continues. Since mineral N is the key to crop growth, a soil mineral N sensor is almost a necessity to make the SSCM concept a successful management scheme. In the following section we will discuss the possible use of γ-rays, NMR, NIR and changes in dielectric constant as a possible means of determining soil nitrogen content.

Gamma Rays: γ-rays have been used to measure the in-situ density of soil (Soane, 1968). Use of γ-rays for determining soil nitrogen content arises from the atomic structure of ^{14}N. When the ^{14}N nucleus is bombarded with low energy neutrons(so called thermal neutrons), some of these ^{14}N nucleus get excited to the ^{15}N state. When the source of excitation is removed, these ^{15}N nuclei fall back to ^{14}N state, releasing γ-rays of characteristic energy. A 10.8 mev γ-rays is an easily detectable, unique signature of the nitrogen atom (Knoll,1989 ; Waldrop, 1989). This principle has been successfully employed in airports to detect plastic explosives in suitcases and to detect land mines during the Desert Storm Operation. γ-rays lead to no residual radioactivity making them relatively safe. Our preliminary studies using the UC Davis Cyclotron showed that although peaks due to ^{15}N dropping back to ^{14}N are visible under neutron activation, the chance of using a relatively "*clean*" and inexpensive source is very remote. Very low energy thermal activation is necessary. Such a system tends to be bulky and unacceptable for field application.

Nuclear Magnetic Resonance (NMR): Like γ-rays NMR is also a nuclear phenomenon. An element with an odd mass number such as H, C, N, O, P has a spin quantum number(I)which is non zero (I=1/2, 1, 3/2 etc.). When these nuclei are placed in a magnetic filed, they attain a thermal equilibrium with the applied magnetic field. The nuclei tend to align with the applied magnetic field. But because of their magnetic moment they start to precess about the axis representing the direction of the applied magnetic field. When a radio frequency (RF) is applied to the nuclei in a magnetic field at right angles to the static magnetic field, some of the nuclei get excited to a higher quantized spin state if the applied RF is equal to the precessional frequency. This condition is called Nuclear Magnetic Resonance and the frequency at which it occurs is called Larmor frequency. When the RF is turned off this energy is released. This resonance frequency depends on the chemical structure of a molecule. This makes it possible to use NMR in identifying structure of the molecules (Paudler, 1987; Wilson, 1987). NMR is non-invasive, does not utilize ionizing radiation, and does not cause damage to biological tissues (Siegel, 1983). These characteristics make it particularly suitable for agricultural application.

NMR has been used to study the moisture content and its distribution in several agricultural commodities such as wheat, corn, peanut, food gel, starch, flour etc. (Rollwitz, 1983; Rollwitz et al., 1985; Brusewitz and Stone, 1986; Song and Litchfield, 1990; Tollner and Verma, 1989; Tollner et al., 1989; Scharder and Litchfield, 1991). McCarthy et al. (1989) correlated NMR signals with the dry weight of avocados. Chen et al. (1989) used NMR to determine ripeness of fruits by measuring their sugar content. Li et al. (1992) employed NMR to study the soluble solids in whole cherries, samples cut from apples, nectarines and pears. He suggested the possible use of NMR to sort fruits into two or three categories.

The ^{14}N has a quadruple moment (I=1) and produces a very wide NMR spectra. The width is about 1000 Hz. ^{15}N has a spin quantum number of 1/2 and responds to NMR techniques readily. Unfortunately it is only 0.36% abundant in nature. Expensive high resolution field equipment is necessary to observe ^{15}N spectra (Wilson, 1987; Almendros et al., 1991). Our attempts to use NMR technique to determine soil nitrogen indicated that it is infeasible at this time.

Near Infrared Rays (NIR): NIR refers to spectral band in the range of 750 to 2600 nm. Norris (1962) indicated that NIR can be very useful in determining the quality of agricultural and biological materials. Massie and Norris (1965) claimed that spectral reflectance of corn, wheat, oats, soybean, rice, alfalfa seeds, and milled rice in the NIR range can be useful in drying experiments in determining moisture content with time. Sewell et al. (1971) used NIR sensing techniques to determine soil moisture content. Finney and Norris (1978) found that NIR transmittance in the 700 to 1100 range correlated well with corn moisture content. Hooper et al. (1979) conducted diffuse reflectance studies in the 1100 to 2100 nm range and found that silage moisture related to NIR diffuse reflectance. Lamb and Hurburgh Jr. (1991) employed NIR techniques to measure soybean kernel moisture. Bull (1991) suggested the use of NIR reflectance at the 970 nm band rather than the 1450 nm band in developing a moisture meter based on this principle. This is because the penetration is higher at 970 nm than 1450 nm, although, the absorption band at 970 nm is weaker compared to the one at 1450 nm. Thomasson and Shearer (1992) were able to relate NIR reflectance data of cotton fiber to its maturity and firmness.

Isaak and Johnson (1984) found that NIR reflectance of many plant tissue (corn, peanuts, soybean, wheat, pecan, bermuda grass, and bent grass) related to its protein content as measured by Kjeldahl technique. NIR reflectance data of cocoa, meat, milk and dairy products correlated well with their protein content (Osborne and Fearn, 1986). NIR spectroscopy was also found to be useful in determining fat in biological materials (Oil- Osborne and Fearn, 1986; live hog - Klueter et al., 1989).

Williams and Norris (1987) discussed the possible use of NIR spectroscopy in the determination of internal structure of the substance. Dalal and Henry (1986) studied the spectral reflectance of soil in the 1100 to 2500 nm range. They found that NIR in the range of 1000 to 2500 nm range is useful in determining soil moisture, organic carbon and nitrogen. Wavelengths corresponding to 1702, 1870 and 2052 nm are useful in determining soil nitrogen. They felt that the negative results obtained by Kishanan et al. (1980, 1981) were due to soil particle size distribution. Derivative techniques are available to overcome some of these difficulties.

Preliminary experiments conducted by us indicate that a soil with varying amounts of inorganic N responds differently in the 1800 to 2400 nm range. First and second derivative techniques showed very high correlation between percent inorganic nitrogen and NIR reflectance. A Fourier transform technique is currently being investigated to explore these signals further. We expect to conduct many more tests to confirm these results.

Dielectric Method: Arulandan (1991) developed a dielectric dispersion technique to measure soil structure and cation exchange capacity. Our preliminary tests indicate that soils with different amount of nitrogen show different degrees of dielectric dispersion. This is a very encouraging result and more tests are currently being planned.

CONCLUSIONS AND RECOMMENDATIONS

From the foregoing review it is clear that agriculture in the future will have to take into account spatial variability in prescribing fertility management. This Site Specific Crop Management (SSCM) has the potential to reduce cost, increase yield and profit, and reduce environmental pollution. Rapid advances in such technologies as GIS and GPS have given a real boost to SSCM. The development of soil organic matter (SOM) sensors and grain flow meters have further helped in making the dream of SSCM almost become a reality. GIS can be interfaced with an SOM sensor to obtain real-time control of herbicide in the field. Grain flow meters can be used to map the yield. GIS provides such information as soil texture, topography, climate, etc. which can be integrated with the yield map to develop a fertility management map. Native soil nutrient level, particularly soil nitrogen, is necessary to come up with fertilizer recommendation on a site-specific basis. Because of the fact that soil nitrogen is both spatially and temporally variable, the determination of soil nitrogen on-the-go is a necessary prerequisite to a successful SSCM. Once all the necessary information is available, spatially variable fertility management can be achieved in real-time. A GPS device will assist a fertilizer application equipment to identify its location in the field. It appears that there are three important developments that are required to make the SSCM concept come true. One of these is the development of *yield potential function for various crops*. The second one is the *development of soil nutrient sensor, particularly soil nitrogen*. The third important development is the soil texture sensor. In fact, the development of soil-nutrient and soil texture sensors, along with sensors already on the market such as moisture sensor and yield monitor , will make it possible for an agricultural implement equipped with these sensors to obtain yield, soil fertility, texture and other relevant information to develop a prediction equation between yield and other inputs, i.e. a potential yield function. A curve fitting procedure or a neural network technique can be useful in developing these yield potential functions. In other words, these "smart" equipment can "teach" themselves the yield potential function. Thus development of sensors for soil nutrient level and soil texture are critical to the successful application of SSCM.

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