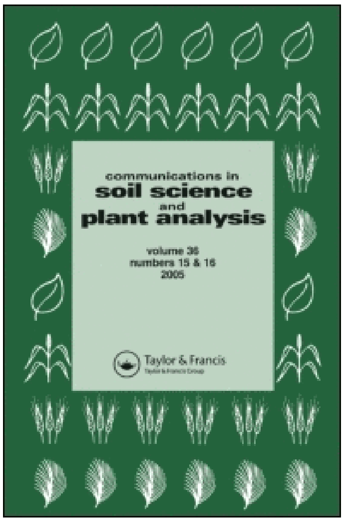

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PLENARY PAPER

PROFITABLE AND SUSTAINABLE SOIL TEST-BASED NUTRIENT MANAGEMENT

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ABSTRACT

Soil testing determines nutrient, lime, gypsum or S, leaching requirements for crops, and potential elemental toxicity to crops and/or their consumers. The majority of farmers do not use soil testing or use higher or lower than economic optimum nutrient rates. Shortcomings of the current soil testing methodology are inability to predict yields, large soil test spacial and temporal variability, inability to reflect dynamics of field parameters that affect nutrient availability, lack of accurate tests for nutrient mineralization, and lack of accurate nutrient response functions. In situ chlorophyll and quick sap tests; or remote sensing with variable rate technology (VRT) can overcome some of soil testing problems. Nutrient uptake efficiencies are low due to the lack of well-funded research efforts on breeding crops with better root systems and nutrient

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uptake efficiencies. Skogley's diffusion-dependent resin test, with a long equilibrium time, should be used as a standard to evaluate other soil tests, instead of the current resin test which requires shaking the soil and resin. The AB-DTPA test of Soltanpour and Schwab better reflected the effect of texture on P availability than Olsen $NaHCO_3$ or Mehlich 3 tests due to its narrower solution to soil ratio. We give new field calibration P levels for AB-DTPA. Mulvaney's test for soil organic N availability index shows promise and should be evaluated. We will discuss the available best nutrient management strategies and our projection of future needs. Future nutrient management systems should be developed by regional cooperation between environmental soil scientists, geneticists, and economists.

INTRODUCTION

Nutrient management refers to sustainable, site-specific and profitable use of lime, fertilizers, animal manure, green manure, composts, and sewage sludge, for a given cropping and tillage system in different soils and climates. Sustainability refers to minimizing environmental pollution, soil acidification, and soil erosion to a level that does not threaten economic survival of the farmers, human and animal health and habitat of the wildlife. Nutrient management is a function of soil test nutrient availability indices, soil and climate, soil available water and maximum yield level, tillage and water conservation techniques, selected variety, plant population and planting geometry, cropping sequence, weeds, diseases, insects, marketing, cost of nutrients and price of produce.[1] Proper irrigation management is an integral part of good nutrient management.[2] Due to complexity and diversity of the systems, and lack of complete knowledge, nutrient management is dependent on empirical field experiments and should be site specific.

Nitrogen and P are the most yield limiting nutrients world wide, although K, Ca, Mg, S, and micro-nutrient deficiencies might limit the yield significantly. Nitrogen, P or K recovery by the aboveground plant organs is the most common definition for nutrient use (uptake) efficiency (NUE).[3] Although losses of N due to leaching, denitrification, volatilization, and other mechanisms can not be avoided completely, they can be kept to a minimum with good management. Baligar et al.[4] reported a list of nutrient deficiencies and elemental toxicities associated with major global soil orders. Soil testing is the most common method for predicting nutrient deficiencies and toxicities, but many farmers do not use it and it should be promoted. Average nutrient use efficiencies are in general 50%

or less for N,[5] less than 10% for P and about 40% for K.[4,6,7] Baligar et al.[4] reported that fertilizer use was 78.7×10^6 tons for N; 13.5×10^6 tons for P; and 17.5×10^6 tons for K. At these low nutrient use efficiencies the economical losses are in tens of billions of dollars. For example, Raun and Johnson[8] reported that for worldwide cereal production the estimated global loss due to N losses was equivalent to 15.9 billion US dollars. Therefore, there is the need to increase nutrient use efficiencies by genetic engineering and plant breeding[9] and best management practices.[2]

Tissue testing, use of a portable chlorophyll meter, and remote sensing are used during the season at different stages of growth to determine the efficiency of fertilizer use and the need for N side-dressing or fertigation, and micro-nutrient sprays.[10–13]

In this review paper we will briefly discuss agronomic and environmental aspects of soil testing; tissue testing; chlorophyll meter use; fertilizer formulations, rates, timing and placement; remote sensing and VRT. We will also discuss the importance of root density and depth in increasing nutrient uptake efficiency and decreasing the nutrient requirements and potentially nutrient leaching and transport into waters. Use of nutrient uptake and some other relevant simulation models will be briefly discussed. Finally we will enumerate future research needs for improving nutrient uptake efficiency.

DETERMINING NUTRIENT NEEDS

Soil Testing

Soil testing refers to sampling, sample drying, grinding, extraction of available nutrients, analysis, interpretation of results and fertilizer recommendations.[14] Drying temperature, degree of grinding, vessel shape, and speed of shaker affect the level of extractable Zn, Fe, Mn, and Cu.[15,16] Increasing drying temperature from 40 to 105°C significantly increased NH_4 and organic N extracted with 0.01 M $CaCl_2$.[17] Soils should be air dried at room temperature within 12 hrs to reduce the probability of increasing NO_3-N significantly due to mineralization.[18] Alternatively, soils can be placed in plastic bags, frozen with dry ice or kept on ice, and extracted moist for NO_3-N determination, with soil water determined on a separate sample. Incubation of soils at field capacity and at room temperature for a week, and wet extraction reduced DTPA-extractable Fe, Mn. and Cu.[19] The correlation between original air dry values and wet-incubated values were o.54, 0.87, 0.91 and 0.13 for Fe, Zn, Cu, and Mn, respectively. Sample bags should be free of contamination.[20]

Sampling is one of the weakest links in soil testing. Sampling plan, intensity, depth, and tools to be used should be selected carefully.[21,22] Spacial and temporal variability exists for soil nutrients and other soil properties. The soil sampling error is usually much larger than analytical error.[23] Soil sampling error can be reduced by stratifying farm fields by soil type.[24]

Reuss, et al.[23] showed that average sampling error for a 90% confidence interval for NO_3-N was $\pm 26\%$ of the mean when 20 cores were taken per 8-ha fields. To reduce the average error to 15% required 82 cores, which is uneconomic. In addition, the NO_3-N changed significantly in perpendicular and parallel directions with respect to the rows in a non-predictive manner. Therefore, a systematic sampling plan should be used to get a representative mean. In the latter case, use of variable rate technology (VRT) for N recommendations was not feasible, unless remote sensing technology was used. Relative error of the same magnitude exists for other nutrients.[25,26] Since contiguous soil samples have a better chance of being similar than non-contiguous samples, semi-variograms and kriging will give a better picture of spatial variability (variance structure) and nutrient distribution than standard statistical methods,[22,25,27] but small sample sizes might give erroneous results.[28] Remote sensing yield maps can be used to devise better soil sampling plans.[29]

In sample extraction the solution to soil ratio, and time and force of shaking should be standardized. The solution to soil ratio determines the proportion of labile immobile nutrients that are extracted. For example, a 2:1 solution to soil ratio is used for NH_4HCO_3–DTPA (AB-DTPA) soil test of Soltanpour and Schwab,[30] as modified by Soltanpour and Workman[31] to extract labile NO_3, P, K, S, Na, Mg, Zn, Fe, Cu, Mn, Se, Cd, Pb, Ni, B, and Mo for determination of nutrient availability indices and elemental toxicity.[32] The $NaHCO_3$–P test of Olsen[33] uses a 20:1 solution to soil ratio. The ratios of extractable P are about 1:1, 1:2, and 1:3 between AB-DTPA–P and $NaHCO_3$–P in sandy, loamy and clay soils, respectively. It seems AB-DTPA test extracts a lower proportion of labile P in clay soils thus reflecting the higher buffering capacity and lower diffusion coefficient for P in clay soils. In Colorado Rodriguez et al.[34] obtained P critical levels of 6 mg kg^{-1} (AB-DTPA), 12 mg kg^{-1} ($NaHCO_3$), 20 mg kg^{-1} (Bray P-1) and 35 mg kg^{-1} (Mehlich P-1) for rainfed proso millet (*Panicum miliaceum* L.). Labhsetwar[35] obtained P critical levels of 7.7 mg kg^{-1} (AB-DTPA), 15.0 mg kg^{-1} ($NaHCO_3$), respectively, for rainfed wheat (*Triticum aestivum* L.). Rashid[36] obtained P critical levels of 8, 14, and 25 mg kg^{-1} for AB-DTPA, $NaHCO_3$, and Mehlich 3 tests for chickpeas (*Cicer arietinum. L.*) and 6, 31, and 65 mg kg^{-1}, respectively, for mungbeans (*Vigna mungo* L.) grown in Pakistan. The above tests showed that AB-DTPA critical P level varied from 6 to 8 mg kg^{-1} for different soils and crops, but $NaHCO_3$ critical P levels varies from 12 to 31 and Mehlich 3 from 14 to 65 mg kg^{-1}.

Rashid[37] recommended the AB-DTPA test for Pakistan because of its multi-element capability and field performance. Jones[38] recommended AB-DTPA test for neutral and alkaline soils and Mehlich 3[39] test for acid soils.

Soltanpour[32] calibrated AB-DTPA soil test with $NaHCO_3$ data. But now we have enough data to calibrate the AB-DTPA test on its own field performance. The interpretation for other elements remain unchanged.[32] The new AB-DTPA–P field calibration values are: 0–4.0, low; 4.0–8.0, medium; 8.0–12, high; and $> 12\ mg\ kg^{-1}$, very high, regardless of soil texture (for analysis of P in AB-DTPA see Ref. [40]). For example, if a sandy, a loamy and a clay soil test $4\ mg\ kg^{-1}$ in AB-DTPA–P; they would test 4, 8, and $12\ mg\ ha^{-1}$, respectively by $NaHCO_3$. Since we do not have separate calibration curves for different textures, and soil buffering capacity which is related to texture is usually not considered for P recommendations, use of $NaHCO_3$ will result in lower recommended P rates as clay increases. The AB-DTPA would call for the same P rate for all three soils which implies that the clay soil needs more P than lighter soils due to its higher P buffering capacity and lower P effective diffusion coefficient. P recommendation rates should be based on local field response functions. The above discussion shows that use of AB-DTPA creates less confusion as it uses the same critical P level for different textures, but due to its low solution to soil ratio it accounts for soil texture differences in P availability.

Usually, resins are mixed with a soil suspension and the P extracted by resin upon a period of shaking is used as a standard to evaluate other P tests.[41] Shaking eliminates the diffusion effect. Skogley[42] used anion–cation exchange resins in a saturated soil and allowed diffusion of nutrients to the resins. We believe Skogley's test is superior to the above resin test and should be used, with a long equilibrium time, as a standard for P and other nutrients. The problem with Skogley's test for routine soil testing is the long period required for equilibrium specially for micronutrients. We believe the AB-DTPA test for P is better correlated with Skogley's resin test than $NaHCO_3$ and Mehlich 3 tests with a wide solution to soil ratio which eliminates the soil texture (diffusion) effect.

Ryan et al.[43] discussed the problems faced by soil and plant testing laboratories in West Asia–North Africa region. Miller and Kotuby-Amacher[44] discussed North American proficiency testing to help soil, plant and water analysis laboratories identify and address quality control problems. Van Dijk[45] discussed the Wageningen worldwide proficiency testing program to help laboratories update their quality control protocols by sample exchange and development of reference material.

Nutrient Mineralization

Prediction of nutrient mineralization is a challenge for soil scientists. For more accurate N recommendations development of a rapid test to estimate N mineralization is needed. Mineralization of crop residue and soil organic matter depend on soil type; crop residue C/N ratio, lignin and hemicellulose concentrations, climate, and tillage method. Stanford and Smith[46] proposed incubating soils at optimum water, temperature, and incubation time and statistically determining N mineralization (N_s) from the following exponential function where N_0 stands for N mineralization potential, t for time and k for mineralization rate:

$$N_s = N_0[1 - e^{-kt}]$$

The k changes with C/N ratio, soil temperature, available water, and mineralogy. El Gharous et al.[47] used the above technique for Moroccan soils and showed that the lowest N_0 was usually associated with Palexerolls with a high lime content, a shallow depth and a petrocalcic horizon (low productivity). Vigil et al.[48] predicted N mineralization reasonably well by using Version 2.0 of CERES-Maize simulation model.[49] For a comprehensive discussion of N mineralization refer to Soil Testing: Prospects for Improving Nutrient Recommendations.[50] Mulvaney, et al.[51] developed a digestion and diffusion technique to measures hydrolizable NH_4 plus amino sugars and amino acids in soil hydrolisates. The amino sugars successfully separated N-responsive from non-responsive (manured) sites. Remote color photography and GIS was used to predict N mineralization potential of green and yellow sugarbeet tops which successfully separated N responsive from non-responsive crops that followed sugarbeets.[52]

Calibration of Soil Tests for Fertilizer Recommendations

Selection of appropriate soil extracting solution should be based on greenhouse and field experiments.[11,14] Dahnke and Olson[53] discussed the factors of soil test calibration. The soil test calibration experiments should be carried out for new varieties and new management techniques over a number of years and soil types, for calculating average economic returns from response functions. A standard old variety should be included in experiments to determine if fertilizer recommendations should be modified. For irrigated maize (*Zea mays* L.) cumulative growing degree days early in the growing season along with population and planting date are used to predict yield.[54,55] The predicted yield is then used to make a more accurate fertilizer recommendation rather than depending on average yields.

Westerman and Tucker[56] described Liebig and Mitscherlich models which are sometimes used to describe yield response to nutrients. Mobiela, et al.[57] used Mitscherlich, quadratic, and square root functions to describe response of potato (*Solanum tuberosum* L.) yield to soil test P and fertilizer P. First derivatives with respect to fertilizer P at a given soil P was set equal to cost/price ratio plus a marginal return. Predicted economic P rates were similar for three regressions. Linear-plateaux, and quadratic-plateaux models can also be used. The linear logarithmic form of Mitscherlich equation gives somewhat higher errors and a non-linear curve fitting is preferred.

We used a quadratic regression to describe rain-fed wheat response to soil NO_3-N plus fertilizer N. Preliminary analysis showed that the regression coefficients for soil and fertilizer N were almost identical. Actual grain yield (GY) and relative yield (RY) regression R^2's were 0.33 and 0.66, respectively.[58] The relative yield regression was selected for predicting fertilizer N requirements. The first derivative of RY was set equal to zero and maximum yield N requirement was calculated. Then, the calculated maximum-yield N rate was decreased incrementally and when the savings in N cost equaled the value of yield loss (at a given maximum GY), that rate was declared the most economic. Since yields can not be predicted accurately under rainfed conditions, we also calculated the N requirement for a 90% relative yield from the RY function. The average net return over the fertilizer cost for the 90% relative yield N recommendations was profitable at a cost/price ratio of 4.46, using 73 site-year experiments. Using actual yields to calculate the N requirements from the RY function, led to higher net returns. In above experiments soil organic matter had a narrow range and dropped out of regression. Soltanpour et al.[59] developed a N recommendation model based on critical soil NO_3-N, sample NO_3-N and the ratio of uptake efficiencies of soil NO_3-N and fertilizer N.

Field calibration of soil tests for making fertilizer recommendations should be done for important soil series in different regions[59] and over a period of time representing average climate. Portable weather stations should be used to define the climate of growing seasons when conducting field nutrient rate research, to be used for interpretation of results and simulation modeling.

Plant Tissue Testing

Bates[60] and Munson and Nelson[61] reviewed factors affecting critical nutrient concentrations in plants and their evaluation. Critical level is the nutrient level below which yields decline, or the level that gives an arbitrary RY level such as 90%. Critical level varies with varieties, other nutrients, growth stage, tissue type, and tissue age. Nutrient sufficiency range (NSR) approach is more realistic and instead of a critical level uses a sufficiency range at which nutrients are not deficient, excessive, or toxic. Soltanpour, et al.[13] used NSR successfully to diagnose nutrient sufficiency in corn, but DRIS indices[62] failed. The NSR should not be used for other elements when N is deficient. Kelling and Schulte,[63] indicated that DRIS should complement, but not substitute NSR. The problems with the standard DRIS are (i) very high level of one nutrient can cause false relative deficiency (imbalance) diagnosis of other nutrients, (ii) an optimal ratio between two nutrients produces maximum yields only when both are in their respective sufficiency ranges, and (iii) using the boundary analysis (yield vs. tissue nutrient concentration) to get optimal nutrient concentrations can lead to excessive application of N and P when yields are low and could cause pollution of waters with NO_3-N and P.[13] Baldock and Schulte[64] developed a plant analysis interpretation technique with standardized scores which combines DRIS with NSR. This approach should be field tested for future use. For information on nutrient sufficiency ranges for different crops, and different tissues at different stages of growth refer to Soil Testing and Plant Analysis.[65] Khiari et al.[66] developed a symmetrical chi square diagnostic model for leaf nutrient composition, referred to as compositional nutrient diagnosis (CND). The authors claimed that CND is perhaps superior to DRIS and NSR. The CND approach needs further validation.

Zhang et al.[67] tested the sap NO_3 content of sudangrass [*Sorghum sudanese* (Piper) Staph] and pearlmillet [*Pennisitum glaucum* (L.) R. Br.] with a Nitrate Meter in the field to detect toxic levels. This technique is useful for a quick diagnosis and prevention of animal NO_3 poisoning.

Use of portable chlorophyll meters can help in deciding if N should be side dressed.[12] Since variety, and growth stage affects the readings, a strip in the field should be well fertilized with N and other nutrients (luxury amounts of chlorophyll are not synthesized) and used as a standard.[68–70]

Remote Sensing and Variable Rate Technology

Remote sensing has been used to monitor crops for nutrient, water, disease, insect and weed stress, using a global positioning system (GPS) coupled with the geographic information system (GIS). This technique has the advantage of sampling large plant populations.[71–76] Techniques, such as N reflectance Index (NRI)[77] and the Normalized Difference Vegetation Index (NDVI)[78,79] were used to monitor N status. These indices can potentially be coupled with GIS techniques and used to develop maps that can be used for VRT in precision farming.

Variable-rate technology was used as a tool to compensate for soil type variability effect on yield and N requirements.[80] The use of latest concepts in VRT increased fertilizer N uptake only marginally.[81,82] Ortega, et al.[83] observed a wide range in grain yield and soil properties (soil organic matter, $CaCO_3$, inorganic N, $NaHCO_3$–P, pH, and elevation) across the landscape in eastern Colorado rainfed wheat fields. Using geostatistics techniques they found that most variables were autocorrelated, which allowed kriging to predict yield and soil variability accurately. Response to fertilizer P was not related to $NaHCO_3$–P alone and was related to other yield limiting factors. Therefore, these factors should be discovered and used in a multivariate regression for nutrient recommendations using VRT.

Khan and Soltanpour[84] found yellow beans at the bottom of hills in San Juan basin of Colorado. The cause was higher water levels which led to higher P diffusion coefficient and P-induced Zn deficiency in these soils of marginal Zn availability. Spraying Zn on yellow beans increased the yield. Potentially remote sensing can determine the area of Zn deficiency and economics of Zn spraying.

Moraghan, et al.[52] used aerial color photographs of sugarbeet fields late in the season and coupled it with GPS to determine response of succeeding wheat crop to N. Soil NO_3-N tests were low and a response to N was expected in 11 out of 12 sites. No response to N was found if antecedent sugarbeet fields were green, but yellow fields (low in tissue N) responded to N. They recommended use of late-season remote sensing coupled with GPS in sugarbeet fields and VRT application.

Strategies to Reduce NO_3 Leaching and P Transport

Soil testing is the first step in preventing excessive use of fertilizers. Ells et al.[85] showed that after fallow there was $>1400\,kg\,ha^{-1}$ of residual NO_3-N in the 2-m soil profile in the Arkansas Valley Research Center of Colorado, and $>160\,kg\,ha^{-1}$ was in top 33 cm which was enough for an onion yield of $>50\,Mg\,ha^{-1}$ with 112 cm of irrigation water. When twice the irrigation requirement was applied $>1000\,kg\,ha^{-1}$ of NO_3-N could not be accounted for, and probably mostly leached below 2 m. Placement of N in alternate furrows and irrigating other furrows reduced NO_3 leaching.[86]

The no till practice will reduce soil erosion[87,88] and minimize P and sediment transport into water bodies. In no till systems fertilizers should be banded into the soil which prevents carrying of P into waters and increases yields.[20,89,90, and 91] Furrow irrigation erosion was reduced with polyacrilamides (PAM) by as much as 99%.[92] Water and wind erosion can also be reduced by the use of winter cover crops.[93–98] Kristensen[99] showed that cover crops with a high root density and more importantly a longer root system explored the subsoil and reduced subsoil residual NO_3-N. Kristensen[99] recommended use of non-legume dicots as cover crops. Rotation is a traditional recommended best management practice (BMP) and it can be used to significantly increase nutrient uptake while conserving soil and water quality.[2,100–103] Delgado, et al.[101] showed that barley (*Hordium vulgare* L.), with deeper roots, after potatoes, with shallower roots, absorbed subsoil residual NO_3-N and reduced the probability of its leaching into ground water.

Banding of fertilizers was more efficient for N and P fertilization of potatoes[104] and P fertilization of wheat.[105] Rashid[36,37] showed that banding reduced P requirement of crops by 1/2 to 1/3 of the broadcast rates. Banding places nutrients away from the soil surface and reduces their chances of being transported into waters by erosion. Adcock, et al.[106] increased root growth of cotton (*Gossypium hirsutum* L.) by subsoiling plus deep lime placement in Georgia coastal plains with an acid subsoil and a hardpan.

Recommended BMPs by specific regions can contribute to increasing NUE and reduce environmental impacts.[2,100,102,103] BMP's such as split N recommendations into several applications, at planting, side-dressing and fertigation, increased NUE especially for sandy, coarser, low organic matter content soils.[100,101,107–112] Goose and Cruz[113] applied $(NH_4)_2SO_4$ to stimulate soil nitrifiers two weeks before applying urea and reduced NH_3 volatilization in two Mollisols and a sandy Oxisol, but without any effect in a clay Oxisol. Nitrification inhibitors and controlled release fertilizers can also increase NUE and reduce N losses into the environment.[114–122] Good irrigation management practices will reduce NO_3-N leaching.[85,101,123–128]

Excessive application of manure, usually to fields close to feed lots, has contaminated ground water with NO_3 and surface application can potentially pollute surface waters with NO_3 and P. Eghball and Power[129] concluded that P-based manure application should be used when P build up is a concern. Waskom and Davis[130] discussed BMP's for manure management. Use of sewage sludge is regulated by US EPA to control heavy metal levels in soils and crops.[131] Barbarick et al.[131] have calibrated AB-DTPA-extractable heavy metals from sewage-sludge treated soils to estimate wheat grain metal concentrations.

Gerloff and Gabelman[132] reported that the nutrient efficiency ratios could be used to differentiate genotypes into efficient and inefficient nutrient utilizers. Baligar et al.[4] reported P, K, Ca, and Mg nutrient efficiency ratios (shoot dry weight per unit weight of any nutrient in shoot) for efficient and inefficient genotypes of a series of major crops such as bean (*Phaceolus vulgarus* L.), maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], wheat, rice (*Oryza sativa* L.) and others. There is a large variability in the ability of crop varieties to have higher yields with significantly lower nutrient concentrations. Genetic engineers and plant breeders should incorporate nutrient uptake efficiency traits along with other desirable traits into new cultivars.

Use of potato varieties with larger root length density and surface areas will reduce N requirement and potential NO_3 available for leaching, substantially. Mortvedt, et al.[133] recommend 150 and 235 $kg\,N\,ha^{-1}$, respectively, for a yield goal of $>40\,Mg\,ha^{-1}$ of Russet Nugget and Russet Norkota. At the tuber initiation time the total root length of Russet Nugget and Russet Norkota per five hills were 490 and 240 m, respectively (A. Al-Sheikh, P.N. Soltanpour and G. Cardon, unpublished data). The Russet Nugget has a larger leaf area index, therefore the larger stolons and roots do not reduce yields. The residual NO_3-N under Russet Nugget was 45 and 48 $kg\,ha^{-1}$ lower in two consecutive years in Colorado (Ref. [134], Al-Sheikh, Soltanpour and Cardon, unpublished data). Davis and Quick,[135] Lynch,[9] and Baligar, et al.[4] recommend using nutrient efficient crops to increase nutrient and water uptake efficiencies.

We need to continue developing viable cropping systems, that can increase the nutrient use efficiencies, reduce nutrient losses while increasing soil and water conservation and productivity. It is important to use soil, plant, and water test results to develop nutrient management plans which reduce the potential transport of nutrients from the fields. When nutrients are transported off the fields by different mechanisms they can contribute to off-site impacts.[136–141] The removal of soil particles by water and wind reduce soil productivity and create off-site sedimentation and eutrophication.[142] It is important that we use innovative tools that reduce erosion, conserve soil and water quality, and increase nutrient use efficiency.[100]

Simulation Modeling for Nutrient Management

Simulation models allow us to consider many combinations of cropping systems and management scenarios for improving nutrient use efficiencies. Since it may be very difficult to conduct so many different studies to evaluate all kinds of possible combinations, computer simulation models are alternative technology transfer tools capable of assessing the impacts of agricultural practices on nutrient uptake across different agricultural systems. Models such as the Nitrate Leaching and Economic Analysis Package (NLEAP) enables a rapid evaluation for a series of best N and irrigation management practices for a farmer's field.[143–145] NLEAP has been used to predict NO_3-N dynamics and NUE for cropping systems with different rooting depths.[146–148] NLEAP has potential for evaluation of the effect of precision farming on NO_3-N dynamics and NUE.[143,149–151] NLEAP has also been used to study effects of different cropping systems, NO3-N dynamics, and crop rotations on NO_3 leaching and mining of NO_3 from underground waters.[100,101,152]

Other models such as Crop Estimation through Resource and Environment Synthesis (CERES,[153]), the Erosion /Productivity Impact Calculator (EPIC,[154]), the Nitrogen Tillage Residue Management (NTRM,[155]), LEACHM-N,[156], the Danish Nitrogen Simulation System (DAISY,[157]) and the Root Zone Water Quality model (RZWQM;[158]), the Barber–Cushman nutrient uptake model,[159] and the CENTURY model[160] can potentially be used to evaluate effects of management practices and physiological parameters on nutrient uptake efficiency and soil and water quality. Potentially, GIS and agronomic models can be linked to permit the simultaneous examination of spatial and temporal phenomena.[161] A comprehensive model, the Great Plains Framework for Agricultural Resource Management (GPFARM) is being developed for whole farm strategic planning[162] by scientists from United States Department of Agriculture-Agricultural Research Service and National Planning Unit (USDA-NRS-NPU).

Future Trends

Skogley[42] has proposed a theoretically superior soil test. It uses spherical anion–cation exchange resins in a saturated soil paste and allows diffusion rates of different nutrients along with their available quantities determine the available pools of labile nutrients. The common resin and chemical extraction tests require shaking the soil in suspensions, thus eliminating the diffusion effect. Potentially the buffering capacity can be determined by measuring the solution nutrient species in quasi-equilibrium with the species adsorbed on the resin. We recommend Skogley's test to be used as a standard to evaluate other tests, in addition to field calibration studies. The reason for lack of a widespread adoption of Skogley's test is the relatively long time required for diffusion, specially for micronutrients. Many farmers want very fast return times so that they will not lose the opportunity to plant and fertilize in time.

Jones[38] recommended use of AB-DTPA soil test[30,31] for determination of elemental availability and potential toxicity (to plants, and humans and animals who consume the plants or ingest the soils) for neutral and alkaline soils; and Mehlich 3 for acid soils. Rashid[37] recommended use of AB-DTPA soil test in Pakistan after extensive field calibration studies. Due to its narrow solution to soil ratio (2:1), the AB-DTPA extracts a lower proportion of labile immobile elements, such as P, in clay soils and more in sandy soils and thus roughly accounts for the smaller P diffusion coefficient in heavier soils. Therefore, it should correlate better with Skogley's test for P, and other immobile nutrients than soil tests with wider ratios such as Olsen and Mehlich 3 tests. We propose that AB-DTPA test be evaluated for acid soils.

Due to its high HCO_3-content it will neutralize the acidity and will give indices for different nutrients. Barbarick and Workman[163] used the AB-DTPA test successfully in a sewage sludge treated acid soil to predict chard leaf concentrations of Cd, Ni, Cu, and Zn. Colorado State University Soil Testing Laboratory has used the AB-DTPA test since 1977 and it has been calibrated by many scientists all over the world. In Western States of US, the AB-DTPA soil test is commonly used by environmental laboratories that are testing the mined lands for determination of soil fertility and potential toxicity of B, Mo, Ni, Pb, Cd, As, and Se for revegetation purposes. Use of AB-DTPA and simultaneous spectroscopy (ICP) enabled us to detect Pb, Cd, and Zn contamination in Aspen garden soils submitted for routine fertility tests.[164] The contamination was traced back to old silver mine spoils. Barbarick, et al.[131] have calibrated the AB-DTPA test for extraction of heavy metals from sewage-sludge treated soils to predict their accumulation in wheat grain. For organic soils we recommend the AB-DTPA test with a 4:1 solution to soil ratio. We believe in future the use of AB-DTPA for soil fertility and potential elemental toxicity evaluation will increase as more field calibration data become available.

To improve soil tests, we propose use of other parameters such as nutrient diffusion coefficient, mass flow, and variety root growth rate and nutrient uptake parameters and their dynamics for predicting nutrient availability and fertilizer needs. Obviously, this undertaking requires extensive field research. Use of soil maps, yield maps, climate data, crop root characteristic, nutrient response functions, economic parameters coupled with GPS, GIS and VRT will increase nutrient uptake efficiency and will reduce environmental pollution.

Tools such as chlorophyll meters, portable electrodes, remote sensors and others can help monitor N levels during the growing season and increase the NUE of split N applications.[100] Different authors correlated the field test strip techniques to determine sap NO_3-N concentration for vegetables[165–167] and small grains such as wheat and barley[168] with laboratory procedures. Similarly sap NO_3-N concentrations determined with a portable NO_3-N ion-selective instruments such as Cardy® meter or Hach meter® were correlated to laboratory procedures for potato,[169,170] cauliflower (*Brassica oleracea L.* Botrytis Group),[171] broccoli (*Brassica oleracea L.* Italica group),[172] winter cover crops[173] and other vegetables.[174] Potato petiole NO_3-N concentrations across the field have been found to be correlated with soil water holding capacity, sand, clay, and soil organic matter contents.[175] These innovative tools (chlorophyll and cardy meters) were used for determining N status in potato and barley.[101] Tuber quality and yield was also correlated to chlorophyll readings and in situ sap NO_3 measurements.[101] Use of mycorrhizae to increase P uptake efficiency should be explored.[176]

The potential to use remote sensing techniques and precision agriculture is promising for increasing nutrient use efficiencies across different regions of the world. In order to make these techniques economical, researchers have suggested the use of management zones for farmers.[177] These zones can be identified based on yield history, soil color from aerial photographs, topography and past management experiences. Delgado and Duke[178] reported that soil texture was an important factor in delineating areas for management zones. They reported that the areas with higher clay contents, had higher nutrient concentrations, residual soil NO_3-N, soil organic matter and potato tuber yields, than the sandier areas.

One of the most promising approaches to increasing nutrient uptake efficiency is use of varieties with better root and shoot phenotype and physiology. Al-Sheikh, Soltanpour and Cardon (unpublished data) showed that Russet Nugget had a root length double that of Russet Norkota. The N recommendation for Russet Nugget is 85 $kg\,ha^{-1}$ less than that for Russet Norkota, for an equivalent tuber yield.[133] Adoption of a new variety does not require additional labor and energy input as does adoption of other technologies such as side dressing of N, and therefore is potentially more effective.

Use of proficiency testing programs[44,45] should be promoted to improve precision and accuracy of laboratory analyses.

CONCLUSIONS

With continuing population growth and increasing demands for food, fiber, biomass energy, lumber and other agricultural products, there is the need to economically optimize yields per unit of nutrients, irrigation and/or precipitation, energy and other inputs with the simultaneous goal of reducing the negative environmental impacts to acceptable levels set by policy makers. The society should bear the cost of environmental protection if alternative practices cost more than the benefit to farmers. The society should support research and development with the goal of producing better varieties and better management practices to increase yields and to protect the environment. The increase in supply will lower food prices and benefit consumers.

There is the need to continue development of more efficient and better soil tests and quick sap tests and technologies for monitoring nutrient status of soils, and crops, in the laboratories and in situ. Mechanistic models that can be linked to agronomic models are needed to better understand the interactions between production factors. These models should account for soil acidification, nutrient recycling, residual soil N, mineralization of nutrients from crop residues and soil organic matter, C sequestration, denitrification, volatilization of NH_3, immobilization of N, NO_3 leaching, P and K fixation, and fate of other nutrients. For irrigated systems there is the need to test waters for potential availability of NO_3-N, SO_4-S, and B; and toxicity of B, and excessive levels of salts. In summary, we need to use soil, tissue, and water test results, yield goals, soil types, tillage method, and other site-specific and economic factors to plan the best nutrient, and soil and water conservation management practices. Use of nutrient efficient crops is the central component of this process. Cooperation between environmental soil scientists, crop scientists, geneticists, physiologists, modelers, economists and others is needed to develop crops that are high yielding, more efficient in nutrient and water uptake and have other desirable attributes.

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