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Crop Nitrogen Requirement and Fertilization

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The topic of "crop nitrogen requirement and fertilization" involves the summary of the major N-cycle processes, described throughout this monograph, into practical "tools" for managing N efficiently, profitably, and with low environmental impact. The foundation to achieve these tasks is a practical understanding of the major soil N-cycle processes within the N management zone, followed by the development of fertilizer N management strategies to achieve high N use efficiency and profitability. The main factor affecting N use efficiency is the rate of applied N, as shown by many studies that have found that N losses increase rapidly when N inputs exceed the crop assimilation capacity (e.g., Broadbent and Carlton, 1978; Legg and Meisinger, 1982; Vanotti and Bundy, 1994a; Schlegel et al., 1996; Dobermann et al., 2006). The effects of N timing, N source, and N placement are also important but usually produce smaller improvements in N use efficiency compared to optimizing the N rate (Power and Schepers, 1989). Efficient N management is essential for profitable production because N is required in large amounts by cereals and N is the major limiting nutrient in most agricultural soils. Efficient N management will also minimize excess N and environmental effects, such as nitrate losses to water resources, nitrous oxide effects on global warming, and ammonia deposition to neighboring ecosystems.

The objectives of this chapter are to describe the fundamental principles for N management, with emphasis on estimating the rate of N to apply; to review and analyze current preplant N recommendation systems; and to discuss opportunities for improving N recommendations through application of within-season technologies. Readers seeking a discussion of the other factors affecting N use efficiency should consult Chapter 17, by Raun and Johnson (2008).

Nitrogen in Agricultural Systems, Agronomy Monograph 49.

Historical Perspective

Estimating crop N requirements and N fertilizer needs has been a challenge to agricultural scientists for over 150 yr, when the classic experiments of Lawes et al. (1882) revealed that N was the major limiting nutrient for continuous wheat. Over the decades since 1945, when N fertilizers became readily available, N recommendation systems have utilized economic considerations, N mass-balance approaches, and in-season monitoring, with most techniques employing adjustments for previous crops in rotated systems, and adjustments for other N sources such as residual nitrate or manure.

Hanway and Dumneil (1955) described one of the first economic-optimum-based approaches, utilizing marginal returns from corn (*Zea mays* L.) and marginal costs of N that were derived from a large number of on-farm N-response experiments conducted in Iowa between 1943 and 1952. Their approach used an exponential equation to summarize the grain fertilizer N response (fertilized yields minus unfertilized yield) with adjustments for soil mineralization capacity, which was estimated from 14-d laboratory aerobic incubations. They considered this approach to be particularly valuable because it predicted whether a soil would respond to N, and estimated the optimum N rate to apply. They also recognized that other factors would affect the need for additional N, such as the crop N requirement and previous legume crops, and that N availability would be affected by soil properties. The work of Heady and others in Iowa (e.g., Heady et al., 1955; Munson and Doll, 1959) led the way in developing the economic approach for fertilizer recommendations.

Over the next decade N recommendation systems were developed from crop fertilizer N-response studies on experiment stations and on-farm trials that included soil-based criteria and crop management systems. In Iowa, continuous corn recommendations were categorized by soil productivity and soil geographic location (Voss, 1969). In Wisconsin, recommendations were based on relative soil-yield potential determined from soil type and farmer management level (Walsh and Schulte, 1970), with recommendations adjusted for manure and previous crop N contributions. For a number of years, Kentucky has based corn N recommendations on soil type and drainage class, tillage, previous crop, and the results of multiyear N responses on representative soils throughout the state (Univ. of Kentucky Coop. Ext. Serv., 2006).

Concern in the early 1970s over agriculture's contribution to the degradation of water quality (e.g., Commoner, 1971) led to a reexamination of the N recommendation procedures based on economic considerations (Parr, 1973). This reexamination led to an expanded use of the N mass-balance approach, which was viewed as an improvement to the generalized large-area economic approaches, into more field-specific estimates (Parr, 1973; Stanford, 1973). Viets (1965) provided one of the first descriptions of a simple mass-balance approach that expressed fertilizer N need as the difference between total N uptake and available soil N, all divided by a fertilizer N availability factor. In Viets's opinion, this approach could only provide crude estimates of fertilizer N need because the crop total N requirement could not be accurately predicted (e.g., poor predictability of total yields due to weather uncertainties), and because the relationship of N content to yield is not linear over the range of the N-response curve (i.e., the N content per unit of yield increases rapidly at the N sufficiency end of the yield curve). These views were not shared by Stanford, who spelled out a direct mass-balance approach to fertilizer N recommendations in a classic 1973 paper (Stanford, 1973). Stanford's approach utilized an internal crop N requirement, and he described approaches for estimating crop N needs from yield data and for estimating soil N supply from soil testing. A detailed discussion of N balance principles for evaluating crop available N was provided by Meisinger (1984) and Meisinger et al. (1992b).

Developing N recommendation systems has been the subject of several excellent reviews. For example, Stanford (1982) and Keeney (1982) described N recommendation systems and focused on methods to estimate plant available N from organic matter mineralization by laboratory incubation and from residual nitrate by preplant soil nitrate tests. Dahnke and Johnson (1990) reviewed N soil testing and concluded that nitrate soil tests are very useful but must be interpreted in light of the soil N cycle of the site. An excellent book on N management was edited by Hauck (1984), which described the importance of N to crop production, sources of N, management of crops and soils for N utilization, and management of fertilizer N for crop production.

The most recent techniques to improve N recommendations utilize in-season monitoring to assess N status and prescribe supplemental N. These new N-management tools can employ global positioning systems to precisely catalog field location, geographic information systems to map soil properties and crop yields, N simulation models, real-time crop N sensors, and variable-rate N applicators. These approaches allow N management to focus down to smaller spatial and temporal scales than traditional preplant approaches based on economics or mass balance. These new technologies were not possible even a decade ago and offer the prospect for improving N management and N use efficiency, by bringing the large spatial and temporal variability of the soil N cycle within the domain of N recommendations.

Principles for Nitrogen Management

All N recommendation systems must come face to face with the challenges of managing N inputs in harmony with the soil N cycle. The goal is to develop N management strategies that produce high crop recoveries of fertilizer or manure N, while avoiding strategies that apply excess N and produce low recoveries and increase the chances of N degradation of our water and air resources. Achieving high N recoveries requires a practical knowledge of the major N inputs and the major soil N-cycle processes within the management zone, and an understanding of the effect of management options on crop N outputs and N losses. Thus, the N mass balance is an undergirding principle for all fertilizer N recommendation systems, whether they are recognized explicitly as source/sink terms with N uptake efficiencies, or recognized indirectly through grouping of similar N-responding soils and the use of N credits, or recognized implicitly through use of within-field N-sufficient reference strips.

The Nitrogen Mass Balance

The classic mass-balance approach estimates fertilizer N needs as a function of crop N requirements, soil contributions (mineralized N and residual N), other N sources (irrigation water, manure, previous crop), and N uptake efficiencies for

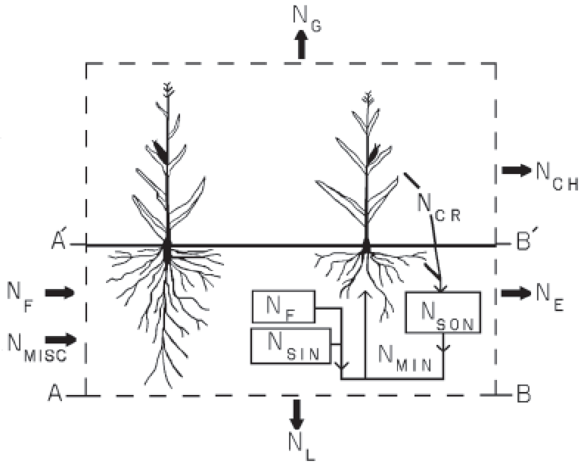

Fig. 14–1. Soil–plant N system for whole-crop approaches (dashed lines bordered by line AB) and aboveground approaches (dashed-lines with bottom line A′B′) (from Meisinger, 1984). Schematic N balance consists of N inputs of fertilizer (N_F) and miscellaneous (wet and dry deposition) N sources (N_{MISC}); outputs of crop harvested N (N_{CH}), N leaching (N_L), erosion (N_E), and gaseous losses (N_G); and internal N pools of crop residue N (N_{CR}), soil organic N (N_{SON}), soil inorganic N (N_{SIN}), and net N mineralization (N_{MIN}).

these sources. The general mass-balance equation for a crop system defined in space and time is

$$N_{\text{inputs}} - N_{\text{outputs}} = \text{change in N stored} \qquad [1]$$

Clear conceptual boundaries are essential for developing a logical N mass balance for crop production systems. Two basic approaches are the whole-crop system and an aboveground system (Meisinger, 1984), which will be discussed separately.

Whole-Crop Approach

A whole-crop system sets the system lower boundary at the bottom of the crop root zone (Fig. 14–1; Meisinger, 1984) and normally employs an annual time step. The whole-crop system contains the N in the aboveground crop, in the root system, and in the soil organic and inorganic N pools. The soil N transformations of mineralization–immobilization and the annual change in soil inorganic N are also within the system and are accounted for by the "change in N storage" term. The N-cycle processes of leaching, denitrification, ammonia volatilization, erosion, and harvested crop removals cross system boundaries and are accounted for as N outputs. The most significant N inputs (e.g., inputs >15 kg N ha^{-1}) are usually fertilizer, manure, legume, and sometimes irrigation water N.

The whole-crop system contains a steady-state condition *if* the change in N storage term is small (see discussion by Meisinger et al., 2008, see Chapter 13). A steady-state condition occurs if the N immobilized in roots, crop residues, and microbial tissue equals N mineralized from organic sources and if the root-zone inorganic N at the end of the year approximately equals inorganic N at the start. Meisinger and Randall (1991) list several characteristics of soil–crop systems that are conducive to using the steady-state approach, which are generally characterized by constant soil–crop management over several years. At steady state, Eq. [1]

simplifies to N_{inputs} (fertilizer and/or manure and legume N) equals N_{outputs} (harvested crop N) divided by the whole-crop efficiency (i.e., $N_{\text{input}} = N_{\text{crop out}}/E$). The whole-crop efficiency is the percent recovery of the N inputs within the whole-crop system and equals 100 minus the percentage losses of N to leaching, denitrification, and ammonia volatilization (see Meisinger [1984] and Meisinger et al. [1992b] for details).

The whole-crop system is rarely used for N recommendations because it uses an annual time step and only crudely accounts for short-term changes in soil inorganic N and soil mineralization capacity. However, it is quite useful for the *long-term evaluation* of a soil–crop system because it allows estimation of the system's N recovery efficiency. Specifically, the steady-state N efficiency is the ratio of the N removed in harvested product divided by the sum of major N inputs (i.e., $E = N_{\text{crop out}}/N_{\text{input}}$). The data of Schlegel and Havlin (1995) and Schlegel et al. (1996) provide an example of a whole-crop system considered to be at steady state. They conducted a 30-yr irrigated corn N-response study in west-central Kansas with six rates of N (0 to 224 kg N ha^{-1}) and two rates of P (0 or 20 kg P ha^{-1}) that disclosed an economic optimum N rate (EONR) of about 180 kg N ha^{-1} with P, and about 160 kg N ha^{-1} without P. Fertilizer N was the major N input > 15 kg N ha^{-1}, and grain N removal was the major N output that was directly measured. The steady-state grain N removals over the last 4 yr of the study at the higher rate (180 kg N ha^{-1}) averaged 117 kg N ha^{-1} for P-fertilized corn, giving a 65% grain-N removal efficiency and leaving about 35% for leaching plus denitrification losses. The corresponding values for the non-P-fertilized corn were 74 kg N ha^{-1} in the grain, which gave a 46% N efficiency and left 54% for other loss processes. Potentially leachable N can be estimated at the end of the study from the nitrate N between the bottom of the 1.5-m-deep root zone and the 3-m depth. These soil data show that the P-fertilized plots contained a total of about 35 kg N ha^{-1}, while the non-P-fertilized plots contained about 90 kg N ha^{-1}. Consequently, the steady-state N balance shows that P fertilization resulted in a 20% improvement in crop N recoveries and a two-thirds reduction in nitrate leaching compared to the non-P-fertilized plots.

The whole-crop approach can also contribute to a holistic evaluation of any N recommendation system, whether based on mass-balance approaches or economic approaches or within-season N management strategies. This is an important aspect that is often neglected by agricultural scientists. For example, all N management systems have economic, environmental, and educational impacts to the farmer and to society. The evaluation of N management systems should therefore be multifaceted, including economic benefits to the producer, environmental value to society, and educational value to the farmer and society. The Kansas study in the preceding paragraph also provides an example of an evaluation of alternative N recommendation systems. The grain N contained about 12 g N kg^{-1} of dry grain (Schlegel and Havlin, 1995) that removed about 10 kg N Mg^{-1} (about 0.57 lb N bu^{-1}) of 15.5%-moisture grain. One N recommendation system evaluated by Schlegel and Havlin (1995) used estimated yield times a crop N factor of about 24 kg N Mg^{-1} (1.35 lb N bu^{-1}) of 15.5%-moisture grain, which would produce a long-term efficiency of about 42%, leaving over half of the fertilizer N subject to losses primarily through leaching and denitrification. In addition, when this yield-based system was compared with the long-term EONR, it recommended about 90 kg N ha^{-1} more than optimal, which would cost the farmer about \$50 ha^{-1} (\$20 acre^{-1}) even with inexpensive N at \$0.55 kg^{-1} (\$0.25 lb^{-1}). An alternative N recommendation system that simply lowered the crop N factor to 18 kg N Mg^{-1} (1.0 lb N bu^{-1}) of 15.5%-moisture grain, as suggested by Schlegel and Havlin (1995), would produce a long-term efficiency of about 57%, would reduce total N losses to about 43%, and would be close to the economic optimum. This evaluation also raises challenges for further improvements in E_{fert} through improved irrigation practices (Randall et al., 2008, see Chapter 23), improved timing of N (Raun and Schepers, 2008, see Chapter 17), within-season monitoring (see "Precision Agriculture Approaches" below), and spatially specific rates from real-time sensors (see "Precision Agriculture Approaches" below; Raun and Schepers, 2008, see Chapter 17). Thus, the steady-state approach identified the crop N factor as a significant area for improving N use efficiency and allowed long-term estimates of the effects of changing this factor on N recoveries and losses. Furthermore, these recovery/loss estimates are in a form that can be easily transferred to educational programs for producers and society.

Aboveground Approach

An aboveground system sets the system lower boundary at the top of the soil surface (see Fig. 14–1) and uses a cropping-season time step. The aboveground approach has been one of the most commonly used N recommendation systems (e.g., Stanford, 1973; Fox and Piekielek, 1978; Magdoff et al., 1984; Dahnke and Johnson 1990; Ketterings et al., 2003; Shapiro et al., 2003). The system in this case is simply the aboveground crop that receives N_{inputs} from fertilizer, soil inorganic N, soil organic N, plus other N sources such as manure N. The system outputs are harvested grain N and crop residue N. The aboveground system for annual crops cannot store N within the system (change in N stored = 0 in Eq. [1]). Equation [1] for the aboveground system therefore becomes $N_{inputs} = N_{outputs}$, or more specifically for N processes greater than approximately 15 kg N ha^{-1} yr^{-1} Eq. [1] becomes:

$$N_{\mathrm{fertilizer}} + N_{\mathrm{soil\ NO3}} + N_{\mathrm{org.\ N}} + N_{\mathrm{other\ N}} = N_{\mathrm{crop\ harvest}} + N_{\mathrm{crop\ residues}} \qquad [1]$$

Notice that the $N_{fertilizer}$, $N_{soil\ NO3}$, and $N_{org.\ N}$ terms are for the sources available for crop N uptake, *not* the total quantities in the soil. Therefore, crop uptake efficiency terms are needed before each of these terms when they are referenced to quantities in the soil. These efficiency terms account for effects of soil N-cycle processes that affect the available N for each source. A common equation for an aboveground system is (Meisinger, 1984; Meisinger et al., 1992b)

$$N_f = [(N_{crop} - e_{min}N_{min})/e_f] - [e_{sin}N_{sin}/e_f] - [e_{other}N_{other}/e_f] \qquad [2]$$

where N_f is fertilizer N input (kg N ha^{-1} $yr^{-1)}$; N_{crop} is crop N, harvested N plus residue N (kg N ha^{-1} $yr^{-1)}$; N_{min} is estimated soil N mineralization (kg N ha^{-1} $yr^{-1)}$; N_{sin} is estimated soil inorganic N (kg N ha^{-1} yr^{-1}); N_{other} is estimated other N inputs (e.g., manure N, legume N, etc.; kg N ha^{-1} yr^{-1}); e_f is the fraction of fertilizer N (N_f) in the aboveground crop; e_{min} is the fraction of mineralized N (N_{min}) in the aboveground crop; e_{sin} is the fraction of inorganic N (N_{sin}) in the aboveground crop; and e_{other} is the fraction of other N (N_{other}) in the aboveground crop.

This equation contains a crop factor (N_{crop}), soil factors (N_{min} and N_{sin}), and climate-related factors (all the efficiency terms). Fertilizer N needs are directly related to the *difference* between N contained in the N-sufficient crop and N contributed by the soil, with the difference divided by the fertilizer efficiency. Some researchers have errantly concluded that the mass-balance approach requires a direct relation between fertilizer N needs and crop N needs, which are often estimated from crop yield. However, Eq. [2] shows that fertilizer N needs are directly related to the *difference* between crop N needs and the soil N sources, that is, the N responsiveness of the site. The remaining terms in Eq. [2] are N credits for soil inorganic N and other N sources such as manure, previous legume crops, or irrigation water N. Another important feature of the aboveground system is that all soil N transformations are outside the aboveground system's boundaries and appear indirectly through the efficiency terms, which reflect the final N available to the crop after leaching, denitrification, and mineralization-immobilization processes. General values for these efficiency terms would be 35 to 75% (Meisinger, 1984; Ketterings et al., 2003), but the values are dependent on management factors and weather conditions. The value of the aboveground efficiency term (e of Eq. [2]) is less than the whole-crop efficiency term (E of Eq. [1]) because the aboveground approach considers only aboveground N uptake and is directly affected by immobilization.

Advantages of the aboveground system include the capability of including local soil N-cycle processes and local N sources, the potential to account for year-to-year variations in soil N processes (e.g., rainfall, temperature), usefulness for short-season crops, and a strong educational value for understanding the soil N cycle. The major disadvantages of the traditional mass-balance approach are a lack of economic considerations and the fact that all soil N transformations are external to the system; this causes the efficiency terms to be complex parameters affected by the N source (e.g., fertilizer vs. manure), climate (temperature and rainfall), and local soil properties (drainage, texture, etc.). As a result, several parameters in Eq. [2] can be difficult to estimate for a given field, although estimates can be used assuming average weather or soil conditions. Furthermore, estimating the availability of N sources, such as soil inorganic N, involves the ratio of the source's efficiency relative to the fertilizer N efficiency (e.g., $e_{\mathrm{sin}}/e_{\mathrm{f}}$ for N_{sin}). Estimating the ratio of efficiencies can be more problematic than estimating individual efficiencies. In practice, the efficiency terms are usually estimated as generalizations derived from field soil fertility trials conducted over several years on representative soil types of a state. For example, the fraction of N_{f} in the aboveground crop is often estimated at 50%, which represents average growing season conditions. Estimation difficulties can also apply to N pools, for example, problems in estimating mineralizable N, or problems from labor shortages that can limit soil-sampling intensities for nitrate N. These difficulties often result in use of indirect estimation procedures, such as the use of nonfertilized crop yield to estimate soil N mineralization in conventional N-response trials. The uncertainties with estimating parameters in the aboveground approach can be reduced with midseason monitoring or real-time monitoring, described below, which monitor crop N status as affected by local soil properties and recent growing conditions. Some scientists consider these limitations to severely restrict the traditional mass-balance approach; but the mass balance does provide a soil-science-based foundation for understanding the N recommendation process, a framework for developing suitable approximations or simplifications, and a basis for identifying and understanding how site-specific soil N-cycle processes affect N recommendations.

Soil–Plant N Resiliency

An important feature of the soil–plant system is its capacity to vary plant available N with the growing conditions; this characteristic will be termed "soil–plant N resiliency." The term "soil resilience" has also been used by Greenland and Szabolcs (1994) in the context of the ability of soils to rebound from degraded or stressed conditions, with the recovery promoted by application of sustainable agriculture practices. The soil stresses noted by Greenland and Szabolcs (1994) resulted from the increased demands for production that have been driven by increasing populations, and from the intensification of modern agricultural practices. Szabolcs (1994) provided a general definition of soil resilience as a soils' tolerance against stress, or the ability of a soil to counteract stress and recover from a degraded condition. This broadspectrum view of soil resilience necessarily includes many components arising from a soil's physical, chemical, or biological processes. Our use of the term "resiliency" differs from that of Greenland and Szabolcs (1994) in that (i) it has a more specific application, as shown by the adjectives "soil–plant N," that focuses attention on the combined effects of soil plus plant, and to a single nutrient, N; and (ii) it describes the ability of the soil–plant system to adjust to favorable growing conditions, rather than recover from a stress. The following discussion will hopefully clarify our use of this term.

Evidence for soil–plant N resiliency can be seen from the observation in multiyear and multilocation N-response studies that the yield of both N-deficient and N-sufficient plots increases in high-yielding years, but decreases in low-yielding years. Figure 14–2 summarizes corn grain-yield versus fertilizer-N input data from Kansas (Schlegel and Havlin, 1995), Pennsylvania (Fox and Piekielek, 1995), and Wisconsin (Vanotti and Bundy, 1994a). Soil–plant N resiliency is illustrated in Fig. 14–2 by the vertical shift of the N-response curves upward in high-yielding years/sites, and the lowering of the response curves in low-yielding years/sites. The soil and plant factors contributing to this resiliency and the effect of soil–plant N resiliency on N recommendations are discussed below. But, it should be clearly stated that N resiliency is a *general characteristic* of the soil–plant N cycle and not a physical law of the soil–plant N cycle (such as the law of conservation of mass, which undergirds N mass-balance principles). Consequently, N resiliency can be observed as a general feature for the *average of N-response curves*, but there will also be individual-year response curves that do not exhibit resiliency because resiliency is thought to be caused by several soil and crop factors that interact with each other and the environment, as discussed below.

The soil–plant N resiliency shown in Fig. 14–2 likely results from environmental effects on the soil N cycle, the physiology of the plant, and the interactions of these two components that produce resiliency. Weather conditions conducive to high yields are characterized by ample, but not excessive, rainfall that produces low water stress, and also by high solar radiation with warm daytime temperatures and cool nighttime temperatures. These weather conditions are likely to contribute to higher N releases from soil organic sources (a larger $N_{\min}$ in Eq. [2]) because it is well known that decomposition rates increase with temperature and adequate moisture. Another factor that could contribute to N resiliency is an increase in N uptake efficiency (a larger e_f in Eq. [2]), which would result from adequate but not excessive moisture, by reducing N losses to leaching and/or denitrification. The summary by Fox and Piekielek (1995) of 57 site-years of data for

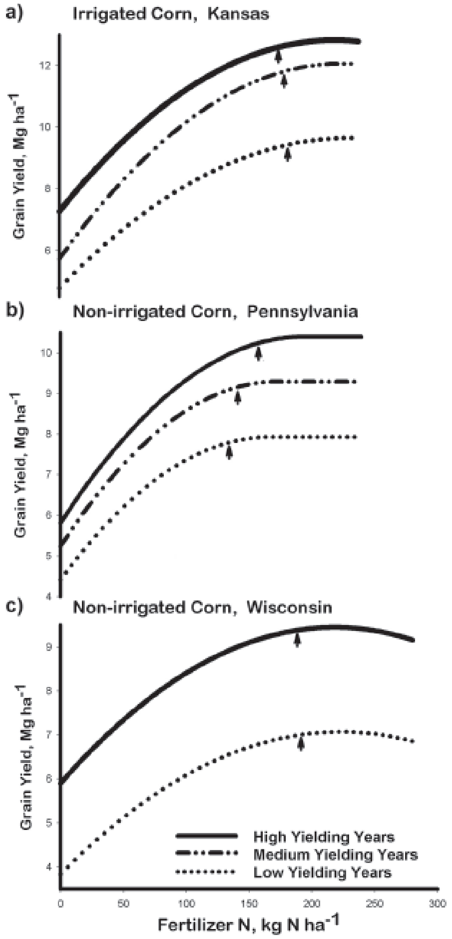

Fig. 14–2. Average corn grain yields versus applied fertilizer N in low-, medium-, or high-yielding years for quadratic response in irrigated corn in Kansas (a) (Schlegel et al., 1996), quadratic-plateau response in nonirrigated corn in Pennsylvania (b) (Fox and Piekielek, 1995), and quadratic response in nonirrigated corn in Wisconsin (c) (Vanotti and Bundy, 1994a). Arrows indicate the estimated economic optimum N rate reported in these studies.

corn with no recent history of organic inputs (no manure or legumes) within 2 yr supports both these explanations. Fox and Piekielek (1995) found that soil N uptake by nonfertilized control plots increased from 71 kg N ha^{-1} in low-yielding years to 83 kg N ha^{-1} in high-yielding years. Likewise, the apparent N fertilizer efficiency increased from 64 to 73% in low- versus high-yielding years (Fox and Piekielek, 1995). To illustrate how these changing factors impact fertilizer N needs in low- versus high-yielding years, they can be substituted into the first term of Eq. [2] ([$(N_{\mathrm{crop}} - e_{\mathrm{min}}N_{\mathrm{min}})/e_{\mathrm{f}}$]) using a crop N factor of 18 kg N Mg^{-1} grain (1.0 lb N bu^{-1}) and the assumption of an average yield of 8.2 Mg ha^{-1} (130 bu ac^{-1}) in low years and 10.5 Mg ha^{-1} (170 bu ac^{-1}) in high years. The resulting calculation produces an estimated aboveground fertilizer N need of about 120 kg N ha^{-1} and 145 kg N ha^{-1} in low- and high- yielding years, respectively. Consequently, although crop N need increased by about 40 kg N ha^{-1} in high-yield years, the fertilizer N need increased only 25 kg N ha^{-1} due to the soil–plant N resiliency resulting from higher mineralization rates and higher fertilizer efficiencies.

Other factors contributing to N resiliency are the effects of good weather on crop growth, and the interactions between crop growth and the soil N cycle. Without water stress, a year with high solar radiation should produce high rates of photosynthesis that could result in a reallocation of the proportion of fixed C between root and shoot tissue, depending on the growth stage of the plant and how it has responded to growing conditions up to that time. For example, good weather may allow the plant to partition a higher percentage of the fixed C into the grain rather than investing it into the root system to meet transpiration or nutrient needs, thus producing N resiliency in the aboveground crop. A positive interaction of the soil and plant components contributing to resiliency might involve higher crop transpiration rates produced by high radiation and ample water in good years. Nitrate N is the main source of plant N, with transport to the root accomplished by mass flow and diffusion, although mass flow is considered to be the primary transport mechanism (Barber, 1995, pp. 86–92). Ample rainfall could increase recoveries of nitrate N by increasing transpiration rates and mass flow, and by maintaining diffusion pathways to the root, with both mechanisms contributing to higher N recoveries as more nitrate is transported to the root surfaces. Thus, adequate moisture and higher transpiration rates would conceivably lead to more complete extraction of NO_3 from the root zone. Field research on corn root growth in contrasting years is rare, but Eghball and Maranville (1993) estimated corn root growth, root-to-shoot ratios, and N flux to the roots in irrigated and nonirrigated field corn in Nebraska. They reported that nonirrigated corn had about 25% more dry matter invested in the roots than irrigated corn, as shown by the mass of dry matter in the roots (26 vs. 20 g DM plant^{-1}), and a higher root-to-shoot ratio (0.18 for nonirrigated corn compared to 0.13 for irrigated). Eghball and Maranville (1993) also estimated a 25% higher N influx to the roots in irrigated corn, amounting to about 20 μmol N m^{-1} d^{-1} with irrigation compared to 16 without irrigation.

Additional factors contributing to soil–plant N resiliency are the weather elements of temperature, water, and energy, with these factors being highly interactive. For example, consider a low water-stress irrigated system, a situation that permits focus on how energy drives resiliency. Clear days (i.e., few clouds) deliver relatively high amounts of solar energy to the vegetation and soil surface. This situation results in above-normal daytime temperatures, but cooler than normal nighttime temperatures. Both conditions are conducive to relatively high rates of dry matter accumulation (high photosynthesis rates in the day and low respiration rates at night). A possible positive consequence of enhanced photosynthesis is greater O_2 production and potentially greater delivery of exudates to roots. These exudates could stimulate mineralization and facilitate nutrient uptake, which serve as a positive feedback mechanism for enhanced biomass production. Conceptually, enhanced O_2 production by plants would be expected to accelerate respiration of soil fauna if positional availability is not a problem. The extent to which enhanced soil respiration contributes to elevated levels of CO_2 within the crop canopy is also open to speculation. In any event, the final result of soil–plant N resiliency is a weather-driven flexible N reserve for the crop. The above explanations are necessarily speculative, because soil–plant N resiliency has not been systematically studied. Hopefully, the acknowledgment of this characteristic within the soil–plant N cycle will encourage future research studies that will expand our understanding of this attribute. An increased comprehension of soil–plant N resiliency would improve the application of this attribute to N recommendations, would outline management strategies to enhance resiliency, and would permit better communication of this characteristic to producers.

In statistical terms, soil–plant N resiliency affects N recommendations because it produces a positive correlation between crop N need and the soil N supply. This positive correlation reduces the variability in the difference between crop N needs and the soil N supply across good- and poor-yielding years and sites. Therefore, soil–plant N resiliency results in fertilizer needs that would not be expected to vary directly with crop N uptake, or to proxy estimates of crop N uptake such as grain yield. The first descriptions of the mass-balance approach to N recommendations did not recognize this positive relationship of soil–plant N resiliency and assumed that crop N needs were independent of soil N supply, thus leading to the use of independent estimates of each of these components. However, the data of Fig. 14–2 illustrate that this positive relationship is common and can significantly influence N fertilizer needs.

Current Preplant Approaches to Crop Nitrogen Fertilization

Concerns about the contribution of agricultural N use to water-quality problems, particularly in the Midwest, has prompted renewed evaluation of the procedures and data used to develop N recommendations. Furthermore, university N recommendations are often used as the technical criteria for nutrient management regulatory policy. These policies generally view university recommendations as a vehicle for achieving environmental objectives; however, a major element in developing most university recommendations is usually the profitability of the producer. Fortunately, the potential conflict between the economic versus environmental objectives can be minimized by applying the well-established fact that N losses are usually low if the N supply does not greatly exceed crop N need, although N losses increase rapidly with N rates on the nonresponsive part of the yield curve (Broadbent and Carlton, 1978; Legg and Meisinger, 1982; Vanotti and Bundy, 1994a; Schlegel et al., 1996; Dobermann et al., 2006; Meisinger et al., 2008, see Chapter 13). Thus, if N rates meet crop needs and avoid the plateau on the N-response curve they will produce profitable yields with low N losses. These issues emphasize the need for implementing N recommendations that are consistent with crop N requirements, farm profitability, and environmental quality.

The various approaches for making N recommendations are discussed in the following sections. These approaches represent seemingly contrasting views of managing the soil N-cycle processes, however, they are based on the direct or indirect application of the principles in the preceding sections. The mass-balance approach uses field-specific information for recommendations and directly utilizes the crop N responsiveness, N efficiencies, and other soil N inputs. The economic approach is based on yield versus N-rate response data from representative soils and cropping systems within a region that are grouped by soil properties and/or cropping systems, and can be expanded to include N mass-balance credits to adjustment for nonfertilizer N contributions from previous legumes or manure. All of these preplant approaches share a common limitation in that none can account for the coming growing season's weather, or the interaction of the coming weather with soil properties, therefore the preplant approaches will always have limited accuracy. However, the within-season monitoring approaches can improve the accuracy of the preplant estimates, by monitoring midseason conditions and adjusting supplemental N accordingly. Some of these within-season methods utilize soil or plant sampling, some utilize soil–crop simulation models, and some use recently developed real-time crop monitoring coupled with variable-rate N applications to optimize crop N utilization.

Mass-Balance Approaches

Mass-balance approaches can be grouped into those that treat crop N requirements independent of soil N supply (i.e., no soil–plant N resiliency) and those that incorporate some form of soil–plant N resiliency.

Mass-Balance Approach without Soil–Plant Nitrogen Resiliency

The mass-balance equation (Eq. [2]) has often been simplified by assuming that the efficiency of soil N mineralization (e_{min}) is equal to fertilizer N efficiency (e_{f}) (e.g., Vanotti and Bundy, 1994b; Schlegel and Havlin, 1995). This assumption separates the N_{crop} term from the N_{min} term of Eq. [2] and produces Eq. [2a], below, with the terms defined as for Eq. [2] above:

$$N_{\mathrm{f}} = [N_{\mathrm{crop}}/e_{\mathrm{f}}] - [N_{\mathrm{min}}] - [e_{\mathrm{sin}}N_{\mathrm{sin}}/e_{\mathrm{f}}] - [e_{\mathrm{other}}N_{\mathrm{other}}/e_{\mathrm{f}}] \qquad [2a]$$

Equation 2a predicts a direct relation between fertilizer N and yield with no direct relationship between the crops N needs and soil N supply, that is, no soil–plant N resiliency. However, the assumption of equal efficiencies for an organic N source, such as soil organic matter, and inorganic N fertilizer is unlikely, because soil organic matter releases N slowly over the course of the growing season while fertilizer N is quickly available and then slowly decreases in availability over the course of the growing season. Furthermore, soil organic N contributes a substantial quantity of N to the crop, commonly supplying 40 to 145 kg N ha^{-1} (Oberle and Keeney, 1990b; Vanotti and Bundy, 1994a; Ketterings et al., 2003; Meisinger et al., 2008, see Chapter 13). Thus, assumptions regarding the soil N mineralization efficiencies can have large impacts on fertilizer N recommendations.

Estimating Crop Nitrogen Needs

The original approach to estimate crop N needs divided the task into estimating the physiologic N need of the crop per unit of dry matter, and the expected dry matter production as suggested by Stanford (1973). The crop N requirement has been defined as the N concentration in the total aboveground dry matter at near-maximum grain yield and has been estimated at about 12 mg N kg^{-1} of aboveground dry matter for corn (Stanford, 1973). The total aboveground N needs of corn can be estimated from this N concentration and the expected total dry matter yield. However, difficulties with estimating total aboveground N produced an alternative approach that employed assumptions about the distribution of total N within the corn crop and expressing the N need in terms of expected grain yield. For example, corn generally contains about 0.55 to 0.75 of its total aboveground N in the grain, with 0.6 being a common value (Hanway, 1962; Oberle and Keeney, 1990b;

Schepers and Mosier, 1991). For corn grain containing 13 g N dry kg^{-1} (0.6 lb N bu^{-1} of 15.5%-moisture grain) the crop N need for the aboveground approach would be 18 g N kg^{-1} (1.0 lb N bu^{-1}) of 15.5%-moisture grain.

After estimating the crop N need per unit of yield, there remains the important, and problematic, issue of estimating the likely yield. Many nutrient management programs use some type of "yield goal". Unfortunately this terminology has a wide range of interpretations that may equate yield goal to (i) maximum yield, (ii) best yield over the past 5 to 10 yr, (iii) average yield over the past 3 to 5 yr, (iv) average yield plus 5%, or (v) average yield with poor years (e.g., drought years) omitted (Wiese et al., 1987; Dahnke and Johnson, 1990; Bock and Hergert, 1991; Schepers and Mosier, 1991). These yield goal interpretation differences can cause serious problems in the application of even the best fertilizer-N recommendation systems and have caused several states to develop non-yield-goal-based N recommendations. For example, a long-term N management project in Hall County, NE (Schepers et al., 1986), showed that farmers commonly overestimated yield by 2 Mg ha^{-1} (32 bu ac^{-1}), which resulted in the application of an average of 35 kg of excess N ha^{-1}. An evaluation of the effectiveness of N management was also conducted by Daberkow et al. (2001) on over 3000 corn fields in the Central Platte Valley of Nebraska for 1989 through 1998. Daberkow concluded that overoptimistic yield goals were the largest contributor to excess N applications, with average yield goals exceeding actual yields by over 15%. In contrast, yields that were within 5% of the yield goal, or had yields that exceeded the yield goal, occurred on only 30% of the fields (Daberkow et al., 2001).

A key element to estimate yields for a given soil–crop system is to acknowledge the effects of non-N-limiting factors such as soil resources, weed control, and timeliness of field operations. The most direct way to integrate all the site-specific yield factors is to use yield data from previous years (e.g., yield monitor data) that are consistent with the scale of the N management zone (whole-fields, soil types within fields, etc.). Adjustments to the previous average yields could consider current growth conditions or new technologies (e.g., current stored soil moisture, variety, new tillage practices, or new irrigation systems). The recognition of the N resiliency characteristic should allow greater use of average yields for estimating the likely yield of a N management zone. A strong education program should also accompany the method chosen to estimate the expected yield, to reduce current problems associated with the yield goal approach.

Estimating Soil Nitrogen Availability Terms

The major plant-available pools of N are soil organic N and soil inorganic N (Eq. [2]). Estimates of these pools have been researched over several decades, with results integrated into N management systems as directly measured soil inorganic N pools or as indirectly estimated soil mineralizable N pools.

Including an estimate of preplant soil inorganic N in fertilizer N recommendations has been conclusively shown to be a beneficial practice in subhumid climates, as evidenced by the use of the preplant nitrate test (PPNT) in most western USA states for the past 30 yr and will not be reviewed (Dahnke and Vasey, 1973; Keeney, 1982; Meisinger, 1984; Hergert, 1987; Dahnke and Johnson, 1990). Extending the PPNT to humid climates has also been shown to be important in many conditions in Wisconsin (Peterson and Attoe, 1965; Bundy and Malone, 1988; Oberle and Keeney, 1990a; Vanotti and Bundy, 1994a), Iowa (White and Pesek, 1959), Georgia (Boswell and Anderson, 1970), Arkansas (Maples et al., 1977), and Pennsylvania (Roth and Fox, 1990). Most recently, Bundy and Andraski (2004) noted the importance of preplant soil NO_3 measurements from the 0- to 60-cm depth for improved N recommendations in winter wheat (*Triticum aestivum* L.) in Wisconsin. Conditions favoring high spring NO_3 levels in humid regions include low-precipitation winters, low-percolation soils, deep-rooting soils, excess N inputs the previous year (e.g., drought years or high N application rates), and high soil mineralization rates (e.g., long history of manure). These conditions contribute to a longer residence time for soil NO_3 or to a large soil NO_3 pool, which can contribute residual N to the next crop even after partial losses of NO_3 during the winter.

Estimating soil mineral N requires an accurate laboratory analysis and the collection of a representative soil sample. Laboratory NO_3–N analysis has been described in detail in publications such as those by Keeney and Nelson (1982), Markus et al. (1985), Gelderman and Fixen (1988), Vendrell and Zupancic (1990), and Bundy and Meisinger (1994). Nitrate analysis presents no major difficulties since this compound is easily extracted from soil and analyzed with modern instruments. Collecting a representative soil sample, however, is a challenging task. The details of sample collection (depth, number of cores, spatial variability, temporal variability, sample handling, etc.) will only be briefly summarized here; readers interested in a detailed description of these topics are referred to publications by Hergert (1987), Gelderman and Fixen (1988), Dahnke and Johnson (1990), and Bundy and Meisinger (1994). The sampling depth for the PPNT usually varies from 60 to 120 cm, with deeper samples suggested on deeply rooted soils. The major problem is the field spatial variability for NO_3. Nitrate variability is characterized by a large small-scale variability that is not uniformly dispersed over a field. It is common to find over 50% of the total variability present within a few square meters. Coefficients of variation for soil NO_3 range from 30 to 120%, with common values falling between 40 and 70% (Beckett and Webster, 1971; Reuss et al., 1977; Meisinger, 1984). Meisinger (1984) concluded that with common sampling intensities (10–20 cores per N management zone) the sample mean would be within ±20% of the true mean in about 75% of the cases. Therefore, precise estimates of the soil NO_3–N content will be possible only with an intense sampling scheme. The sampling time for the PPNT should be as close to planting as practical, to incorporate preceding winter NO_3–N losses due to leaching and denitrification. The results of the PPNT test are usually directly factored into Eq. [2] by subtracting the soil NO_3 content above a background level, from the expected crop N requirement (e.g., Ehrhardt and Bundy, 1995; Shapiro et al., 2003). The direct subtraction of the PPNT from the crop N requirement also indicates that the soil NO_3 availability is equal to fertilizer N ($e_{\mathrm{sin}}/e_{\mathrm{f}} = 1$ in Eq. [2]), as noted by Vanotti and Bundy (1994a).

Including an estimate of soil organic N mineralization in N recommendations has been the goal of soil scientists for nearly 100 yr. Literally hundreds of papers have been written on mineralization methods that have been reviewed in detail by Bremner (1965), Keeney (1982), Stanford (1982), Meisinger (1984), Bundy and Meisinger (1994), and Myrold and Bottomley (2008, see Chapter 5). The traditional approaches to estimate mineralization are microbial incubations, total N analyses, chemical extractants, or analysis of specific N compounds, for example, amino sugars. The general approach with these tests is to correlate several indexes with microbial incubations using a range of representative soils. The most promising indexes are thought to preferentially extract a "mineralizable N pool" from the total soil organic N pool, namely, the N_{min} term of Eq. [2]. However, when evaluations proceed to field conditions with vegetative tests (field crop N uptake) results have been unsuccessful. One reason for the lack of success is that field-testing evaluates N_{min} *plus* $e_{\text{min}}/e_{\text{f}}$. Any difference in uptake efficiency (the e terms) between the N_{min} pool and fertilizer-N pool will complicate the evaluation of any N mineralization index. As pointed out above, these efficiency terms are affected by denitrification, leaching, and immobilization of each N source, with e_{min} being affected differently than e_{f}. Thus, differences in the basic soil N transformations for N_{min} versus N_{fert} can contribute to difficulties in evaluating soil N mineralization indexes. The most successful approach to estimate N_{min} has been the N uptake, or yield, of nonfertilized control plots in conventional N-fertilizer response studies.

Preferred methods for estimating mineralization involve measurements of crop N uptake and soil profile sampling for nitrate in the field (Schepers and Meisinger, 1994; Egelkraut et al., 2003). The most common methods of accounting for mineralization are simple tabulated values of N credits from control plots. A straightforward look-up table is used for each soil series in New York (Ketterings et al., 2003). Missouri (Buchholz et al., 1981) uses an indirect adjustment for mineralization based on soil texture, cation exchange capacity, organic matter content, and crop growing season temperature (cool-season vs. warm-season crops). The N credit approach uses an easily documented local variable that directly affects mineralization. The most common example is the use of crop histories that give a legume N credit of 50 to 200 kg N ha^{-1} for a previous alfalfa (*Medicago sativa* L.) crop (depending on stand, years since alfalfa, and forage harvest management) or 15 to 50 kg N ha^{-1} for previous soybeans (Kelling et al., 1998; Shapiro et al., 2003). Legume credits reflect the systematic oscillations in the soil organic N pool due to crop rotations (Meisinger, 1984). This can result in a release of N temporarily stored in legume residues as the system reverts back to soil organic N levels associated with cereals. It should be noted that legume credits (N-rich residues) are frequently assigned relative to incorporation of N-poor residues such as corn stalks and wheat straw. Indirect methods offer the advantage of easy use but can suffer the disadvantage of being broad generalizations that may be inaccurate for a specific site. They also need to be supported by a field calibration program based on vegetative tests.

Estimating Nitrogen Availability from Other Nitrogen Sources

The N contributed from other sources, such as irrigation water, crop residues, or manure, must also be included in the N mass-balance approach. Credits for irrigation N are usually based on a NO_3–N analysis of the water and projected irrigation quantities; they vary from small credits of 10 kg N ha^{-1} for low-nitrate surface water (e.g., Schlegel and Havlin, 1995) to substantial credits of 50 kg N ha^{-1} for high-nitrate groundwater (>20 mg NO_3–N L^{-1}), as shown by Ferguson et al. (1991) and Schepers et al. (1986). Other credits (positive or negative) are used to account for crop residues such as cover crops. For example, N credits for hairy vetch (*Vicia villosa* Roth) can amount to 50 to 150 kg N ha^{-1} (Clark et al., l995; Ranells and Wagger, 1996).

The N contributed from manures is one of the most important adjustments for N recommendations. But manures are also difficult to credit because they vary in composition and can stimulate several soil N transformations (e.g., ammonia volatilization, denitrification, mineralization, and/or immobilization), which interact with weather and soil properties (texture, internal drainage) over time. The most common approach for crediting manure N begins with a manure analysis, that is, analysis of NH_4–N and organic N fractions, and the estimated application rate based on a calibrated manure spreader. Once the manure NH_4–N applications have been estimated, adjustments for ammonia volatilization are made based on the type of manure (slurry vs. solid), application method (surface vs. incorporated), time until incorporation, and sometimes weather conditions (Meisinger and Jokela, 2000). The NH_4–N remaining after ammonia losses is usually considered equal to fertilizer N. The manure organic N input is usually credited through a decomposition coefficient based on the type of manure. For example, a typical first-year decay coefficient for organic N in liquid cattle slurries is 35%, for solid beef feedlot manure is 25%, and for broiler litter is 50% (Evanylo, 1994; Koelsch, 1997; Meisinger and Jokela, 2000). Allowances are also usually made for manure N applied in previous years by reducing the decay coefficient through a time series (e.g., the second-year coefficient might be one-third of the first-year value and the third-year coefficient might be one-half of the second-year coefficient). Estimating manure N credits remains as one of the most challenging areas in the N recommendation process, although use of within-season tests such as the presidedress nitrate test can improve N management in manured systems (see later discussion).

Mass-Balance Approach including Soil–Plant Nitrogen Resiliency

Including the concept of soil–plant resiliency in the mass-balance equation (Eq. [2]) allows the soil mineralizable N to be related to crop N requirement. The N resiliency characteristic can either be included indirectly, as exemplified by the New York system described below, or directly, as illustrated below in the Nebraska system.

Mass Balance with Indirect Resiliency

The N recommendation system in New York illustrates the indirect inclusion of soil–plant N resiliency. The New York approach directly applies Eq. [2] to each of the 594 soil types within the state (Ketterings et al., 2003) and includes N contributed from soil mineralization and previous forage crops (N_{sod}) within the equation $N_{\mathrm{f}} = [(N_{\mathrm{crop}} - N_{\mathrm{min}} - N_{\mathrm{sod}})/e_{\mathrm{f}}]$. Ketterings et al. (2003) list tabulated values for this equation for each soil type that contain estimates of soil N supply commonly varying from 55 to 100 kg N ha^{-1}, N uptake efficiency (commonly 50–75%), and corn yield potential that varies from 4.5 to 9 Mg ha^{-1} (70–140 bu ac^{-1}), which is used to estimate crop N need by multiplying yield potential by 21.4 kg N Mg^{-1} (1.2 lb N bu^{-1}). These three basic elements can be further adjusted within each soil type to account for one of four soil drainage conditions, varying from the native undrained condition through excellent artificial drainage. Difficulties with the yield goal approach described above are avoided in the New York system by using the tabulated yield potential for each soil type. The individual soil-type databases are also classified into soil management groups, which reflect six categories of soil texture and soil parent materials, and also into the soil hydrologic group that is used to estimate a local nitrate leaching index (van Es et al., 2002).

The resiliency property within the New York approach is illustrated by a highly significant correlation coefficient ($r = 0.45$, $n = 380$) between soil N supply and crop N requirement across all soil types. More importantly, resiliency changes

Table 14–1. Example mass-balance fertilizer N calculation for irrigated corn harvested for grain on a silt loam soil in Nebraska following a soybean crop, with an application of 11 t ha^{-1} solid beef manure (30% dry mater) containing 3 kg NH$_4$-N and 5 kg organic N per 1000 kg fresh manure. Details of fertilizer N calculation algorithm given by Shapiro et al. (2003) and manure N calculations by Koelsch (1997).

Description of N source	Estimated value†		Notes and observations
	kg N ha^{-1}	lb N acre^{-1}	
Corn N requirement	336	300	Exp. yield 13,800 kg ha^{-1} (220 bu ac^{-1})
Soil NO$_3$-N	–27	–24	Soil test results, avg. 3 ppm NO$_3$-N to 3 ft.
Soil organic N	–70	–62	Soil test 2% org. matter and exp. yield
Legume N	–50	–45	Previous soybean crop
Irrigation N	–58	–52	Water 18 mg NO$_3$-N L^{-1}, 32 cm irrigation
Manure NH$_4$-N	–17	–15	Incorporation 1 d after application, 50% loss
Manure organic N	–14	–12	Organic N mineralization 25%
Fertilizer N need	100	90	Summing values in column

† Estimated from N recommendation algorithm of Shapiro et al. (2003), all in English units: Fert. *N* = [35 + (1.2 * Exp. Yld.)] – (0.14 * Exp. Yld. * Soil Org. Matter) – (8 * Soil NO$_3$–N) – (Leg. Credit) – (Irrig. Water NO$_3$-N * Exp. Irrig.) – (Manure NH$_4$-N * NH$_4$-N Ret'n. %) – (Manure Org.-N * Mineralization %).

across soil management groups, for example, the correlation coefficient between crop N need and soil N supply is 0.82 ($P < 0.01$, $n = 58$) for the high-yielding soil management group of medium- to fine-textured soils derived from calcareous glacial till or from recent alluvium, while the correlation declines to less than 0.15 (ns) for the lower-yielding coarse-textured soils derived from glacial outwash. Thus, the New York approach also recognizes the interaction of resiliency with yield potential, so that high yield potential soils display higher resiliency than low yield potential soils that contain yield restraints other than N.

Mass Balance with Direct Resiliency

It is also instructive to consider an example of a mass-balance approach to show the importance of accounting for site-specific N sources and to illustrate the direct use of resiliency. This scenario is for irrigated corn grown for grain, with a preceding crop of soybeans in central Nebraska (Table 14–1). This setting represents an environment where yield-based crop N need is likely to perform well, because corn yields and N use efficiency are likely to be less variable under irrigated conditions compared to rain-fed conditions. The Nebraska mass-balance approach of Shapiro et al. (2003) translates Eq. [2] into an algorithm that contains a crop requirement term, a residual soil-nitrate term, a soil organic N mineralization term, and other N credits for N inputs from legumes, irrigation water, and manure (see footnote of Table 14–1).

The crop requirement factor of the algorithm, designated expected yield, is calculated from the 5-yr average yield plus 5% to allow for increasing variety performance or increasing corn N use efficiency as suggested by Cassman et al. (2002). The soil terms of Eq. [2] (N_{sin} and N_{min}) are accounted for through preplant soil nitrate tests and soil organic matter analyses. The calculation for mineralization (in lb N ac^{-1}) multiplies percent soil organic matter by expected yield and by the empirical factor 0.14 (see footnote of Table 14–1). The rationale for including the expected yield component within the organic matter adjustment is a direct adjustment for soil–plant N resiliency and recognizes that soil N mineralization is favored by conditions that favor high yields. This mineralization credit translates into the release of about 2% of the total organic N in the surface 20 cm (8 in) of the example soil.

The mass-balance calculation also accounts for N credits from legume residues, manure applications, and irrigation inputs (Table 14–1). The Nebraska system assigns uniform legume credits for soybeans and varying credits for alfalfa of 80 to 170 kg N ha^{-1} (70–150 lb N ac^{-1}) depending on alfalfa stand density (three levels of stand density) and soil texture (sandy soils vs. finer-textured soils). Irrigation credits can also be significant; in our example for central Nebraska, the average irrigation of 32 cm (12.6 in) containing 18 mg NO_3–N L^{-1} (Daberkow et al., 2001) would add about 58 kg N ha ac^{-1} (52 lb N ac^{-1}).

The last N credit to estimate for this example is for the manure. This credit contains the most uncertainty because of the variable composition of manures, variable application rates, and variable losses due to volatilization and the net mineralization rate. The NH_4–N fraction is subject to large ammonia losses as long as the manure remains on the surface, the Nebraska system estimates a 50% loss for a 1-d delay in incorporation. If the manure was left unincorporated for 2 d the credit for manure NH_4–N would decline to 25%, indicating an estimated 75% loss over 2 d. These estimates emphasize the importance of rapid incorporation of manures for conserving NH_4–N, and provide an opportunity for educating the producer about soil N-cycle processes. The mineralization coefficient for first-year beef manure is 0.25 (Koelsch, 1997). The concluding N credit for the beef manure example in Table 14–1 is 31 kg N ha^{-1} (28 lb N ac^{-1}) from the total manure N application of 88 kg N ha^{-1} (80 lb N ac^{-1}).

The final fertilizer N calculation involves subtracting the various N source credits from the crop requirement (Table 14–1), resulting in an estimated fertilizer N rate of about 100 kg N ha^{-1} (about 90 lb N ac^{-1}). This example clearly illustrates the importance of accounting for other site-specific sources of N. One of the important benefits of the mass-balance approach is the educational value concerning the soil N cycle that is derived from managing the various N sources and sinks. However, including the site's N sources in this example also carries with it the need for documenting these sources through analysis of soil, water, and manure.

Grouped Economic Approaches

The grouped economic approaches apply economic principles to large N-response data sets and groups the response data into classes of soil resources, cropping history, or other groupings. The groupings reflect similar fertilizer N responses as affected by agronomic practices, soil resources, or soil N transformations. For example, well-drained soils with deep root zones might be expected to have similar N transformations compared to poorly drained soils or shallow-rooted soils. Because of the similarity of soil properties and N processes within a group, the fertilizer N rates that optimize the economic constraints would also be expected to be similar. The soil-grouped economic approaches were some of the first methods used to manage fertilizer N (e.g., Hanway and Dumneil, 1955), as discussed above in the "Historical Perspectives" section.

Table 14–2. Examples of N-rate response data sets showing weak relationships between simple corn yield and the economic optimum N rate (EONR).

Location	Years	Number site-years	Yield vs. EONR, R^2	Reference
Wisconsin	1959–1989	117	0.02	Vanotti and Bundy (1994a, 1994b)
Illinois, Minnesota, Missouri, Pennsylvania, Wisconsin	1982–1999	193	0.03	Lory and Scharf (2003)
Ontario, Canada	1962–1992	300	<0.15	Kachanoski et al. (1996)
Pennsylvania	1982–1994	57	0.08	Fox and Piekielek (1995)
Wisconsin	1989–1999	101	<0.003	Andraski and Bundy (2002)
Iowa	1987–1999	25 corn–corn	0.21†	Blackmer et al. (1991)
		25 soybean–corn	0.06†	

† R^2 values are for the relationship between yield-goal-based N recommendations and observed EONR.

Simple Yield- and Economic-Based N-Rate Relationships

The economic-based systems have been compared to the yield-based systems by several investigators (Blackmer et al., 1991; Vanotti and Bundy 1994b; Andraski and Bundy, 2002; Lory and Scharf, 2003). These comparisons have generally used the simplest yield-based N recommendation system arising from Eq. [2a] after applying the assumption of equal efficiencies for soil N mineralization (e_{min}) and fertilizer N (e_f). In practice, Eq. [2a] is usually simplified into a form that involves multiplying the expected grain yield (bu acre^{-1}) by a factor reflecting the amount of available N per unit of yield required to achieve the yield goal. Factors for available N per unit of grain yield vary among states but have typically range from 19 to 25 kg N per 1000 kg of expected corn grain yield (1.1 to 1.4 lb N/bu). For wheat these values are higher due to the increased protein in the grain (Mullen et al., 2003) and average 33 kg N per 1000 kg of expected wheat grain yield (2.0 lb N bu^{-1}). States that have used this approach include Illinois (Hoeft and Peck, 2001), North Dakota (Dahnke et al., 1992), Pennsylvania (Beegle and Wolf, 2000), and Michigan (Vitosh et al., 1995).

Studies comparing the simplified yield-based approach with the economic-based approach have shown poor relationships between corn yields and EONR, as determined from N-rate response experiments (Table 14–2). The poor relationship can result from the inaccurate assumption of equal efficiencies of fertilizer N and soil N mineralization, a lack of accounting for residual N, legume N, or manure N, or a lack of inclusion of the soil–plant N resiliency. For example, 101 N-response experiments in Wisconsin covering a wide range in cropping systems and management groups showed no relationship between yield and EONR (Andraski and Bundy, 2002), but they illustrate the value of separating soils into specific groups that reflect N-response characteristics. A careful evaluation of yield and EONR was reported by Fox and Piekielek (1995), who conducted over 275

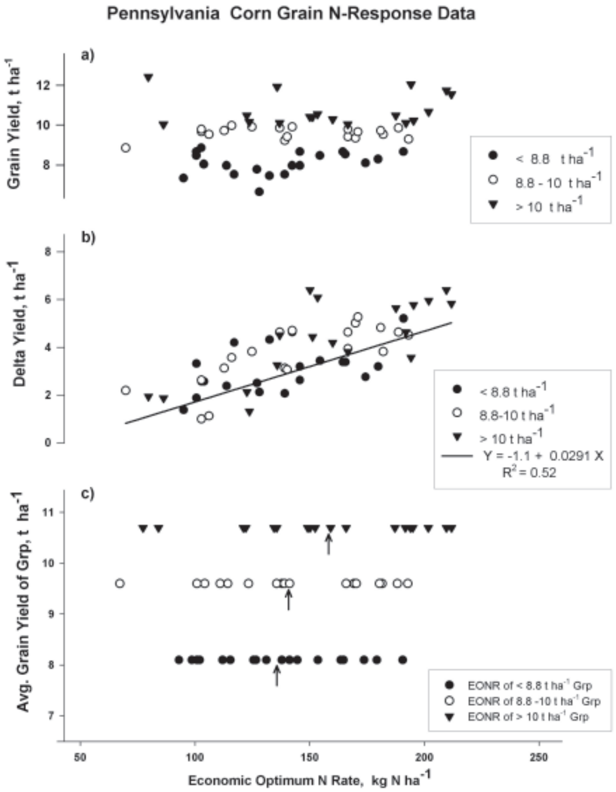

Fig. 14–3. Relationships between the economic optimum N rate (EONR) and corn grain yield (a), the difference in yield (delta yield) of adequately N fertilized and non-N-fertilized plots (b), and the average yield of productivity grouped N-response studies (c) conducted in Pennsylvania (Fox and Piekielek, 1995). Arrows in (c) indicate average EONR for each yield productivity group. Data are a summary of 57 corn N-response studies conducted between 1982 and 1994 at sites with no manure or legume crops within the previous 2 yr.

N-response studies in Pennsylvania that contained 57 trials that did not receive manure or grow a legume the previous 2 yr. By focusing on these 57 trials the interfering effects of manure N and legume N could be avoided. Their summary (Fig. 14–3a) also showed a lack of association (R^2 = 0.08) between yield and EONR but suggests that sites could be broadly grouped into productivity classes (note grouping of similar symbols in Fig. 14–3a). Figure 14–3a supports the view that absolute yield is not significantly related to the EONR; however, when the same data are summarized as the *yield response* to N (non-N-limited yield minus the control plot yield) and compared to EONR (Fig. 14–3b) there is a significant relationship (R^2 = 0.52), as expected from the correct version of Eq. [2], which focuses on crop N response rather than absolute yield. The significance of the relationship between yield response, later termed delta yield, and EONR is also supported by the analyses of Kachanoski et al. (1996) and Lory and Scharf (2003) (see discussion below).

Several studies have also shown that the EONRs on a specific soil or group of soils are similar, although actual yields may vary substantially. Figure 14–2 shows three examples of substantial year-to-year yield variations that are accompanied by only minor variations in EONR (shown by the arrows on each response curve). This situation arises from soil–plant N resiliency, as previously discussed. For example, Schlegel et al. (1996) found that EONR values for high- and low-yielding years in a 30-yr irrigated corn N-response experiment in Kansas ranged from only 172 to 180 kg N ha^{-1} while the corresponding yields ranged from 9.7 to 12.7 Mg ha^{-1}. This work also showed that long-term P fertilization increased average yields by nearly 3.7 Mg ha^{-1}, but the EONR with and without P additions differed by only 17 kg N ha^{-1}. Randall et al. (2003) determined optimum N rates for corn following soybean in southern Minnesota. Using a quadratic-plateau model, they identified EONR values of 118 and 111 kg N ha^{-1} for 13 small-plot and 13 field-size strip studies, respectively. Average yields were about 1.25 Mg ha^{-1} higher in the small-plot studies, but EONR was similar in both types of experiments, demonstrating a lack of sensitivity of EONR to attained yield. Murdock et al. (2002) found that optimum N rates for corn in Kentucky were the same across several levels of within-field yield variation mapped during the previous 3 yr. The Kentucky scientists concluded that corn yield response to N is independent of within-field yield variation and that N recommendations could continue to be based on N-response data, soil characteristics, and management practices.

Nitrogen Recommendations Using a Grouped Economic Response

Several states have implemented the grouped economic approach due to the increasing price of N fertilizer, the poor relation between simple yield and EONR, and the desire for a simpler recommendation system requiring less data collection. For example, Iowa offers two approaches for making N-rate recommendations. One approach uses a reduced rate of preseason N based on suggested rate ranges for different cropping systems, and then uses an early-vegetative soil nitrate test to prescribe additional N. The second is for producers not planning on soil testing, who would apply a suggested N rate from a table that gives ranges based on the cropping system (Blackmer et al., 1997). Kentucky has continued its approach of basing N recommendations on soil characteristics, cropping system, and the results of N-response experiments on representative soils (Univ. of Kentucky Coop. Ext. Serv., 2002). In Wisconsin, N recommendations were revised in 1990 using a soil-grouped economic approach based on the results of numerous N-response experiments conducted on the major soils in the state. These recommendation approaches rely heavily on soil–plant N resiliency as illustrated by the Wisconsin data in Fig. 14–2. The soil-grouped economic recommendations require a large database, preferably several hundred fertilizer N response studies, that represent the main soil types, the common agronomic practices, and a common fertilizer management system including N source, timing, and placement. The individual soil data were then grouped into statistically similar N-response classes, which reduce the need for N-response data from each soil type (Vanotti and Bundy, 1994b). The recommended N rates in Wisconsin are similar for three of the six major soil groups used for corn production (Table 14–3). Consequently, a smaller N-response database from representative soils can provide enough information for the soil-grouped economic recommendations. Further details on the rationale and approach for the soil-grouped economic recommendations are described by Vanotti and Bundy (1994a, 1994b). The development of a fertilizer N-response database need not be limited to response data from public institutions, because thousands of N-response experiments with corn have been conducted in the USA between

Table 14–3. Model selection for describing corn economic optimum N rate (EONR) on six soil groups in Wisconsin.†

Soil group	Representative soil(s)	Residual nitrate N‡	Response model	EONR
		kg ha^{-1}		kg ha^{-1}
Southern prairie–derived	Plano	86	Quadratic	161
			Quadratic plateau	125
			Quadratic surface§	186
Southern forest–derived	Fayette	91	Quadratic	151
			Quadratic plateau	78
			Quadratic surface§	179
Eastern red	Manawa and Kewaunee	77	Quadratic	160
			Quadratic plateau	99
			Quadratic surface§	176
Northern silty and loamy	Withee	57	Quadratic	130
			Quadratic plateau	106
			Quadratic surface	NS¶
Western coarse-textured	Meridian	119	Quadratic	128
			Quadratic plateau	99
			Quadratic surface§	138
Sands and loamy sands, irrigated	Plainfield	26	Quadratic	231
			Quadratic-plateau	218
			Quadratic surface	NS

† Adapted from Vanotti and Bundy (1994b).

‡ Mean preplant soil nitrate N (0- to 3-ft depth).

§ Model selected for recommendations, quadratic-surface model includes independent variables for fertilizer N and residual N (Vanotti and Bundy, 1994b).

1980 and 2000 (see examples in Table 14–2). Voss (1993) noted that environmental concerns about N use have greatly stimulated corn N-response trials. Using these field N responses within the soil-grouped economic approach can produce N recommendations for a site with a minimum of site-measured data; although the direct transferability of these minimal data sets to new sites will be limited because they are based on simple regression models that have a history of limited transferability to environments not included in the original database. It should also be noted that this large-scale field approach for N-response databases does not diminish the need for continued comprehensive N studies at research institutions, due to societies' concern with the environmental impacts of the unrecovered N.

Specific Development of Grouped Economic N Recommendations

Grouped economic N recommendations are based on economic criteria that are developed from multiyear N-response studies at research farms (e.g., Vanotti and Bundy, 1994a, 1994b), or from multilocation producer N-response studies performed on a regional basis (e.g., Nafziger et al., 2004; Sawyer and Nafziger, 2005; Sawyer et al., 2006). Sawyer et al. (2006) have described this economic approach that produces a population of response functions for estimating economic returns and costs from fertilizer. The basic economic approach does not suggest the use of site-specific variables within the groups but could delineate other grouping categories (i.e., other soil–crop management groups) if justified by the population of response functions. The specific steps in this approach are to (i) collect yield data from replicated multirate N-response trials from representative soil–crop systems, (ii) fit a yield versus N-rate response function to each year or site, (iii) divide the data set into subgroups representing similarly responding groups such as cropping systems, soils, or other factors affecting N response, (iv) use the N-response function to calculate the economic data using a series of fertilizer N costs and grain prices, that is, determine the total dollar return from N fertilizer (usually an interval estimate), or the EONR from marginal returns (a point estimate), (v) summarize the economic data, usually an average across the data sites within each subgroup, and then identify the N rate, or interval, that produces best economic returns.

An example of this approach is given by Nafziger et al. (2004) and Sawyer and Nafziger (2005), who led a regional N-response project that summarized 698 replicated N-rate experiments on high-yield-potential soils from 1984 to 2004 primarily in Illinois, Iowa, Minnesota, and Wisconsin. Corn yield-response data were accumulated for N responding sites receiving spring-applied, or sidedress-applied N for corn-corn and soybean-corn cropping systems in each state. Most of these sites were on medium- and fine-textured soils under rain-fed conditions in the humid portion of the Corn Belt that received excellent agronomic management (e.g., date of planting, weed control, etc.) and where residual N was expected to be minimal. The N-response data from each site were fit to a response function, usually a quadratic plateau, and a series of total product values was calculated in increments of 0.5 kg N ha^{-1} from 0 to 270 kg N ha^{-1}, using the predicted yield and a series of possible corn prices. This process gives estimates of the yield increase (yield above the nonfertilized treatment), and the gross dollar return from the yield increase for all sites in the data set. This information, combined with fertilizer cost, allows calculation of the net return to fertilizer N with values calculated for specific costs of N fertilizer and corn grain prices. Next the net returns are accumulated across all sites in the subgroup (e.g., each crop rotation), producing an average economic return to fertilizer N versus the fertilizer N rate (Fig. 14–4). The fertilizer rate with the largest net return is the maximum return to N (MRTN) with an acceptable interval around this point estimated to be N rates with net returns within \$2.50 ha^{-1} (\$1 acre^{-1}), as shown in Fig. 14–4. The MRTN in Fig. 14–4 can be described as an economic returns curve with a broad maximum, showing that as the N–to–corn-

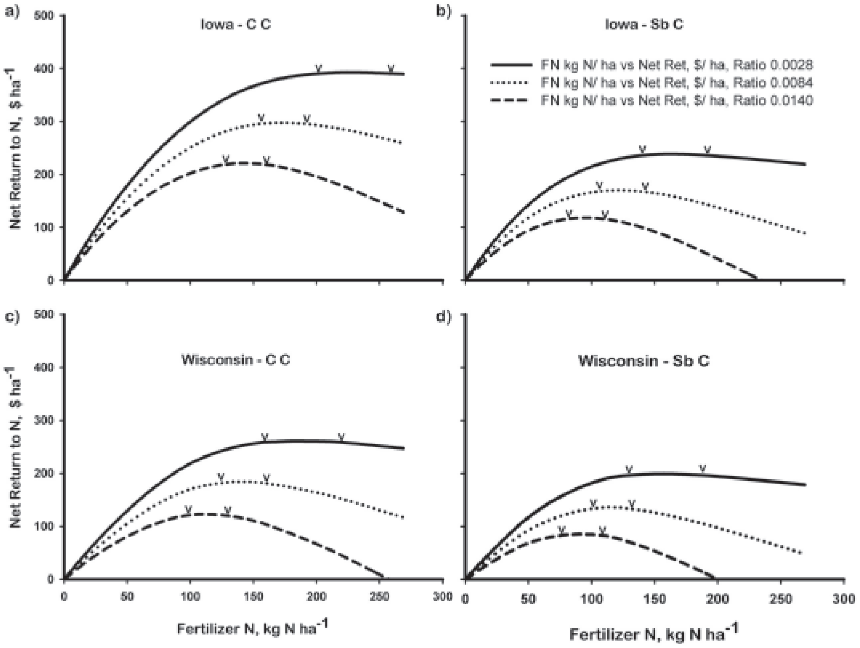

Fig. 14–4. Example of economic results derived from the maximum return to N (MRTN) calculations (Sawyer et al., 2006) derived from 196 corn N-response studies in Iowa and 73 studies in Wisconsin between 1983 and 2004 on continuous-corn or soybean-corn cropping systems (see text for details). Arrows on each curve indicate points that are within ±\$2.50 ha^{-1} (±\$1.00 acre^{-1}) of the MRTN.

price ratio increases (fertilizer is more expensive relative to the price of corn), the total dollar return from fertilizer N declines (the curves reach lower MRTN values). The broad maximum suggests a small yield change near the optimum N rate, indicating that choosing an exact N rate is not critical to maximize the net return to N on this population of soils and cropping systems. A more in-depth discussion of these curves is given by Sawyer et al. (2006). Figure 14–4 also shows that as fertilizer becomes more expensive the rate producing the MRTN decreases, although there is substantial overlap in N rates across the price ratios that are within \$2.50 ha^{-1} of the MRTN. The panels of Fig. 14–4 illustrate the differences in MRTN between continuous corn and corn after soybeans in both Iowa and Wisconsin. In addition, differences in MRTN are shown between Iowa and Wisconsin for the same cropping systems, which likely result from a greater number of growing degree days in Iowa, as well as differences in soils and precipitation. Minnesota (Rehm et al., 2005) and Wisconsin (Laboski, 2006) have recently implemented the MRTN approach by subdividing their state data sets according to previous crop (corn or soybean) and according to production characteristics (high yield potential, medium yield potential, and irrigated sands).

The second type of common economic analysis fits a fertilizer N-response function and estimates the EONR by equating marginal returns to marginal costs, namely, the point where the last dollar invested in fertilizer N equals a dollar returned from added yield. This point is found by calculating the first derivative of the response function and setting it equal to the specific fertilizer–to–corn-price ratio (Heady et al., 1955), which produces a point estimate of the EONR, as exemplified by Cerrato and Blackmer (1990), Vanotti and Bundy (1994a, 1994b) and Dobermann et al. (2006). Finally, it should be noted that there is a close relationship between the MRTN approach and the EONR approach, with the average MRTN rates generally being somewhat higher than determining the average of the individual site EONRs (Nafziger et al., 2004; Sawyer and Nafziger, 2005).

Advantages of Using the Grouped Economic Approach

There are several advantages to the economic-based approaches. Of course, they provide an economic perspective to fertilizer management, but they also provide a defined "stopping point" for the EONR approach or a range of N applications for the MRTN approach, which is based on economic criteria. By defining the stopping point as the economic optimum, the producer is meeting crop N needs and also avoiding excess N applications that promote high N losses, because the economic optimum is usually just before the nonresponding part of the yield curve. Many studies have shown that excess N and potential N losses increase rapidly once N rates exceed crop assimilation capacity (e.g., Legg and Meisinger, 1982; Vanotti and Bundy, 1994b; Schlegel and Havlin, 1995; Dobermann et al., 2006; Meisinger et al., 2008, see Chapter 13). The economic-based approach also provides a greatly simplified N recommendation scheme that does not rely on documenting several site variables. This simplified scheme would be most beneficial for large grain farms where manures are seldom used, or where residual nitrates are unlikely, or where labor demands preclude sampling for soil nitrate. However, traditional N credits for nonfertilizer N sources such as manures, previous forage legumes, or residual nitrate can be added to the economic approach (e.g., Bundy, 2006; Laboski, 2006) to broaden the applicability to manured systems or where residual nitrate is expected. An expanded discussion on these approaches that combine economics with mass-balance credits is provided below.

Challenges for Using the Grouped Economic Approach

Developing grouped economic N recommendations appears to be straightforward, requiring only corn yield versus N-rate response data from the major soil or cropping system groups, but there are also challenges with this approach. The mathematical functions fit to the yield versus N-rate data are greatly influenced by the statistical model chosen to summarize these data, as shown by the differing EONRs for the response models in Table 14–3. Cerrato and Blackmer (1990) found that the average EONR determined from 12 site-years of data from Iowa corn varied from 184 kg N ha^{-1} for the quadratic-plateau model to 225 kg N ha^{-1} for the quadratic model, with the exponential model estimating EONR of 252 kg N ha^{-1}. Furthermore, the "best" statistical model for describing the yield response function could not be identified using conventional statistical tests, although the quadratic-plateau model best described the data from Cerrato and Blackmer's (1990) study. Another challenge to model selection is that the "best" statistical model can change from year to year at the same site due to soil–crop–weather interactions. Iback and Williams (1971) and Bock (1984) have noted that benefits from being able to accurately forecast N–to–corn-price ratios are substantially less than gains to be made from foretelling the best response model. Thus, uncertainties in model selection due to statistical uncertainties or weather uncertainties can be problematic for economic approaches. The underlying fact contributing to these problems is the experimental uncertainty in yield versus N-rate experiments, that is usually about 5 to 10% of the average yield (8 to 15 bu ac^{-1}), which is sufficient to buy about 60 to 110 kg N ha^{-1} (assuming corn at $2.35 per bu and N at $ 0.35 per lb, or a N–to–corn-price ratio of 0.15). Model selection is also open to other subjective influences, such as the desire to minimize economically damaging N deficiencies, which results in higher N recommendations than suggested by selecting a conservative model. Avoiding N deficiencies is usually considered important for maintaining producer confidence in the recommendations, since producers will be unwilling to use recommendations that sometimes result in N deficiencies and yield reductions (Vanotti and Bundy, 1994b; Fox and Piekielek, 1995).

An additional underlying assumption with economic approaches is that the producer has unlimited capital. This is shown in Fig. 14–4 by the suggested addition of N until maximum returns to N are achieved. Or in marginal product terms, the addition of N until the last dollar invested in fertilizer returns one dollar in yield. Undoubtedly, the producer has alternative investment options, namely, investing in upgraded machinery, new varieties or herbicides, or hiring a marketing consultant. In the end, the producer must decide which production inputs are likely to give the highest return per dollar invested and allocate limited capital accordingly (Iback and Williams, 1971; Bock, 1984). However, the underlying economic assumption of unlimited capital and alternative investments is often minimized in the economic approach.

Another challenge to grouped economic approaches is that the soils or cropping systems within a group are assumed to behave similarly. The widespread recognition of spatial variability within seemingly similar soil types raises questions about the accuracy of this approach for a specific site. Lory and Scharf (2003) concluded that N recommendation systems that ignore yields entirely would likely explain less than 50% of the variation in EONR for corn. This within-group soil/site variability is illustrated in Fig. 14–3c by the range of EONRs among the individual sites within a yield productivity group; if the variability within productivity group is compared to the average EONR of the group (shown by the arrows in Fig. 14–3c), an average coefficient of variation (CV) of about 25% is calculated. This CV is somewhat smaller than the 40% CV of EONRs within the soybean-corn database from Illinois, or the corresponding 36% CV for EONRs from the soybean-corn database from Iowa, that were estimated from the EONR frequency distribution of Nafziger et al. (2004). Thus, the grouped economic approach should be expected to have limited accuracy for estimating optimum rates for specific fields. This limitation has been acknowledged by Sawyer et al. (2006, p. 16) who state, "It must be recognized that [N] rate guidelines from analysis of trials conducted across a wide geography will be general in nature. Those guidelines reflect the research data and provide insight into general fertilizer N needs. However, they cannot predict site-specific N requirements, and they are unlikely to provide an accurate estimate of the optimum N rate needed in each specific environment." However, Sawyer et al. (2006, p. 16) weigh this against the view that "the guidelines should provide an N rate that reflects economic value and probability of achieving expected economic return across a range of locations and period of time." Discussion in a following section will describe how the grouped economic approach can be more site specific by augmenting it with mass-balance N credits. Although the grouped economic approach has limited site specificity by itself, it could provide more useful general N guidelines than an incompletely formulated mass-balance approach that ignores significant nonfertilizer N sources (e.g., manure, residual nitrate) or that uses overly optimistic yield goals.

Commonalties between the Mass-Balance and Soil-Grouped Economic Approaches

An initial comparison of the mass-balance approach and the grouped economic approach would appear to contain little common ground. However, there are areas in the mass-balance approach that could benefit from information in the economic approach, and the economic approach could benefit from information in the mass-balance approach.

Mutual Areas within Nitrogen Recommendation Approaches

One common area shared between these approaches is the estimation of the crop N requirement. Specifically, the yield versus fertilizer–N relationship in the EONR approach can also supply information for the mass-balance approach (Eq. [2]) because the first term within the brackets of Eq. [2] $[(N_{\mathrm{crop}} - e_{\mathrm{min}}N_{\mathrm{min}})/e_{\mathrm{f}}]$ is related to information contained in the EONR, and by equivalence in the MRTN approach. The EONR is a creditable substitute for the first bracketed term of Eq. [2] because the EONR utilizes the first derivative of the yield versus fertilizer N function—the instantaneous change in yield (dY) per unit change in fertilizer N (dN). The derivative combines a measure of the crop responsiveness of the site to N (the dY component) that can be considered a proxy for $N_{\mathrm{crop}} - e_{\mathrm{min}}N_{\mathrm{min}}$, with information related to the fertilizer efficiency (e_{f}) being contained in the first derivative (the dY per unit dN) through the regression coefficients of the response model. Thus, the EONR derived from a N-response function contains information directly related to the site's fertilizer N responsiveness and the fertilizer efficiency for the specific N management practices embodied within the response database. These are the same elements needed for the first term of the mass-balance approach and could logically substitute for these elements with the remainder of Eq. [2] estimated by the conventional soil tests and N credits.

A common area that the mass-balance approach can contribute to the grouped economic approach is through the N budgeting credits for forage legumes, manures, or residual nitrate N. The N-response equations derived from the yield versus fertilizer-N trials empirically contain the average N-management (e.g., N timing and placement) and average site-N conditions (e.g., soil residual nitrate) within each subgroup. For example, the regression coefficients derived from the soybean-corn cropping system contain information expressing the greater availability of soil N after soybeans. However, these same coefficients should not be expected to provide information on soil N availability following a forage legume such as alfalfa, or following manures, or from high residual nitrates, unless these specific available-N factors are separated into different N-response database groups as suggested by Sawyer and Nafziger (2005). As a result, most traditional economic approaches can benefit from incorporating N crediting methods that are similar, or identical to, those used in mass-balance approaches, as exemplified by the Wisconsin approach (e.g., Bundy, 2006; Laboski, 2006).

The regression coefficients derived from the economic approach are also linked to the fertilizer management practices within the groups, such as time of N application, N source, and N placement. Bock (1984) has illustrated how fertilizer

N management can effect crop N response. Accordingly, N-response databases can also be affected by fertilizer management factors such as timing (e.g., spring vs. early-vegetative applications), or fertilizer N source and placement (e.g., anhydrous ammonia vs. surface-applied urea ammonium nitrate), or inclusion of fertilizer additives (e.g., urease inhibitors or nitrification inhibitors). Ideally the preplant N recommendations should also include factors for fertilizer N management practices, for example, spring application versus sidedress application. However, due to our inability to forecast weather, any preplant N recommendation approach must employ management factors that represent average weather conditions, or the average weather across sites contained within a multisite database. Therefore, approaches that utilize within-season monitoring of soil or plant N will have an advantage over preplant approaches, because they can adjust for early-season weather. These within-season approaches are discussed below.

Comparison of Mass-Balance and Economic-Optimum Approaches

Comparisons of the mass-balance approach with the economic approach have been made by Vanotti and Bundy (1994b) and Dobermann et al. (2006). Vanotti and Bundy (1994b) found that the two methods converge into similar recommendations *if* the expected yields are estimated by the multiyear average of non-N-limiting yields, rather than the yield goals of the optimistic producer, and *if* the economic approach is adjusted for credits such as residual N. The Wisconsin comparison assumed an average N efficiency of 0.7 and an N requirement of 20 kg N ha^{-1} per Mg of expected corn grain yield (1.13 lb N bu^{-1}) for the mass-balance approach. The use of average yields in place of yield goals invokes soil–plant N resiliency, which allows the use of average yield within the mass-balance approach to be equivalent to the results from the grouped EONR.

A recent comparison of the two N recommendation approaches was also reported by Dobermann et al. (2006) who summarized 34 fertilizer-N yield-response studies conducted with irrigated corn in Nebraska, covering the major irrigated corn areas and the continuous-corn and corn-soybean cropping systems. Dobermann et al. (2006) conducted an economic analysis that evaluated several response models and calculated the EONR using marginal returns for varying ratios of N cost to corn price . In addition, data were also collected at each site for the mass-balance algorithm of Shapiro et al. (2003, see Table 14–1), including expected yield based on previous yields of the site, soil organic matter and residual NO_3, irrigation water N, and previous crop. The algorithm-calculated N rate was then substituted into the economic response model for each site and the net return to N calculated and compared to the EONR for different cost-to-price ratios. The mass-balance algorithm and the economic approach compared well at cost-to-price ratios representing inexpensive N, with the average difference being only about 2 kg N ha^{-1} and the average profit from the mass-balance approach being within 99% of the maximum profit, as calculated with perfect hindsight by the economic approach. However, for cost-to-price ratios representing expensive N, the mass-balance approach overpredicted N rates by about 10 kg N ha^{-1} and profits decreased rapidly as the cost of fertilizer increased. This is to be expected since the original mass-balance algorithm considered only soil–crop N factors, not economic factors.

Dobermann et al. (2006) concluded that the mass-balance algorithm should be modified to incorporate an economic component, as described in the next section.

Combined Mass-Balance and Economic-Optimum Approaches

The prospect of expensive fertilizer N, driven by expensive energy, and the need to provide accurate site-specific recommendations, driven by environmental concerns, has prompted the development of combined approaches. These approaches incorporate elements from both the mass-balance and the economic approach into a combined system.

An early version of the combined approach was used for corn in Wisconsin after 1990 (Vanotti and Bundy, 1994b; Kelling et al., 1998) and was based on a soil-grouped EONR. It placed the state's nearly 700 soil types into yield potential categories based on the soil's ability to retain adequate water and N in the crop root zone during the growing season (Bundy and Andraski, 1995). Corn N-response functions derived from long-term studies of EONR experiments on soils representing each yield potential category were used to provide estimates of crop N need. The estimated crop N need was then merged with mass-balance N credits for previous crops, especially alfalfa (Kelling et al., 1998), for residual N (Vanotti and Bundy, 1994a), and for manure. This combined approach has been updated by employing the MRTN method to estimate crop N requirement with N credits for forage crops, residual nitrate, and manures (Laboski, 2006) to adjust for site-specific factors not contained in the MRTN yield-response database.

An approach for adding an economic element into the mass-balance approach has been described by Dobermann et al. (2006) based on the comparison of the mass-balance and economic-optimum approaches on 34 irrigated corn sites between 2002 and 2004. The technique multiplies the N recommendation from the mass-balance algorithm (Shapiro et al., 2003) by a simple economic adjustment factor. The adjustment factor is based on the fact that the recommended N rates forecast from the algorithm agree well with the EONR if fertilizer N is inexpensive, that is, until the cost-to-price ratio reaches about 0.125 (e.g., fertilizer N at \$0.30 lb^{-1} and corn selling at \$2.40 bu^{-1}). But the agreement decreases rapidly and nonlinearly as the cost-to-price ratio increases above 0.125, that is, as fertilizer N becomes more expensive relative to the value of corn. Dobermann et al. (2006) calculated the economic adjustment factor by dividing the EONR at a given cost-to-price ratio by the EONR at 0.125, which effectively re-scales the EONR to a baseline of 0.125. The economic adjustment factor was then plotted against cost-to-price ratios and an exponential function was fit to provide estimates of the adjustment factor for any cost-to-price ratio. Values of the economic factor vary from about 0.78 for expensive N (e.g., cost-to-price ratio of 0.200), to a value of 1.00 for a ratio of 0.125, to a value of 1.20 for inexpensive N (e.g., cost-to-price ratio of 0.075). The final calculation simply multiplies the N rate calculated from the mass-balance algorithm by the economic adjustment factor, resulting in lower fertilizer N rates for expensive N and higher rates for inexpensive N (Dobermann et al., 2006).

The above examples of combined approaches show that the traditional mass-balance strategies can be modified to accommodate economic conditions, and traditional grouped economic approaches can accommodate site-to-site variability through N credits. An essential element for each approach is maintaining a field

N-response database for calculating the EONR and identifying site-specific factors affecting the crop response to N.

Final Thoughts and Viewpoints

The above lengthy discussion of preplant N recommendations indicates that both the traditional mass-balance approach and the soil-grouped economic approach have strengths and weaknesses. Yet, both approaches seek to improve N use efficiency for specific fields, or management zones within fields, by estimating fertilizer N needs. Economic conditions of expensive energy will encourage the incorporation of economic factors into N recommendations, but the environmental concerns of society will increase the need for better budgeting of agriculture's N inputs from fertilizers, manures, or legumes. The authors suggest that each method would benefit from a factual reexamination, giving due regard to current economic conditions and environmental concerns. This examination should consider the important soil–crop–livestock systems of the state, the economic concerns of the producer, the environmental concerns of the public, preplant versus within-season approaches, and the attainable level of spatial resolution. Such a review should reveal areas where each preplant recommendation approach could be improved and where within-season approaches are advantageous. This should contribute to improving N use efficiency by developing more accurate estimates of crop N requirements and fertilizer N needs.

Within-Season Methods for Improved Crop Nitrogen Utilization

Both the grouped economic approach and the mass-balance approach for N recommendations are targeted to preplant estimates of fertilizer N needs, and to large spatial resolutions covering groups of similar soils or several hectare-sized N management units. However, the well-known large spatial variability and temporal variability of soil N processes places a limit on the accuracy of these approaches. For example, in evaluating the performance of soil nitrate tests and organic N crediting, Bundy and Andraski (1995) and Andraski and Bundy (2002) measured success as being within ±35 kg N ha^{-1} of the EONR. A north-central regional study to evaluate soil nitrate tests considered predictions of N response correct if predicted relative yields were above 90% (Bundy et al., 1999). These levels of inaccuracy result from (i) the large N increment that is needed to produce a detectable yield response in field experiments; (ii) errors associated with model selection to describe the relationship of yield versus N rate; and (iii) a realistic estimate of the in-field accuracy attainable with conventional fertilizer N application equipment. These levels of accuracy and sources of uncertainty are typical for traditional preseason, large-resolution N recommendation systems based on conventional field-scale application methods.

Over the past 10 yr, however, there has been a marked improvement in the tools and methods available to soil scientists for improving crop N requirements and fertilizer N needs. Some of these new approaches include in-season monitoring techniques, geographic information systems, global positioning systems (GPSs), yield monitors, N simulation models, real-time crop N sensors, and variable-rate N applicators. Several of these approaches will be discussed in the following sections. Some methods have been extensively evaluated over a wide range of crops and environments, other newer approaches are still being evaluated. Our ability to assess the newer approaches is therefore limited, but the great potential of these new methods is apparent, although a full assessment of their impact must be entrusted to future research.

Within-Season Monitoring Approaches

Within-season monitoring strategies measure the N status of the soil or the developing crop and assess the need for additional N, or prescribe specific rates of supplemental N. They typically rely on use of split, or multiple, applications of N and thus combine two elements of N management: estimating the proper rate of N and applying N in phase with crop need. They are successful because they monitor soil or crop N status after the growing season has begun and thus include aspects of the season's weather and the weather's effect on N availability. Early-season precipitation effects have been shown to be significantly related to yield in several N-response studies from Wisconsin (Oberle and Keeney, 1990a) and New York (Sogbedji et al., 2001). Within-season approaches typically use limited preplant N applications and seek to confirm N adequacy or to add supplemental N. Two of the most widely used in-season tests are the presidedress soil nitrate test (PSNT) developed by Magdoff et al. (1984) and the leaf chlorophyll meter (LCM) for corn developed by Schepers et al. (1998, 1992b). In their own specific way, N applications that are based on in-season soil or plant monitoring incorporate soil–plant N resiliency, which is thought to be largely driven by weather conditions.

Pre-Sidedress Nitrate Test

The PSNT measures the soil NO_3–N concentration in the surface 30 cm of soil when the corn is 20 to 30 cm tall. Bundy and Meisinger (1994) have described the principles underlying the PSNT and the details of its use. Basically, the PSNT is a point-in-time assessment of the spring accumulation of soil NO_3–N, just before a warm-season crop begins its period of rapid N uptake (Magdoff, 1991; Meisinger et al., 1992b). The NO_3–N content of a typical agricultural soil represents the net balance between nitrate production processes and nitrate loss processes. Bundy and Meisinger (1994) have illustrated the seasonal soil nitrate concentrations for a typical silt loam soil in a humid-temperate climate and show that soil nitrate concentrations are lowest in winter (due to leaching in humid climates), rise two- to sixfold in the spring and early summer depending on recent additions of manure or crop residues (due to commencement of mineralization), decrease quickly during summer (due to crop uptake), and slowly increase again in the fall (Harmsen and Van Schreven, 1955; Magdoff et al., 1984; Stevenson, 1986; Fox et al., 1989; Meisinger et al., 1992a). The PSNT exploits the close juxtaposition of the early-summer soil NO_3–N maximum and the onset of rapid corn N uptake; however this can also cause logistical problems because only 2 to 3 wk are available to measure the soil NO_3–N and to apply the appropriate sidedress N. The PSNT has been extensively evaluated; some have found it to be especially useful for high-mineralizing sites (Magdoff et al., 1984, 1990; Blackmer et al., 1989; Fox et al., 1989; Meisinger et al., 1992a),while others consider that a preplant soil nitrate test is more appropriate for their conditions (Schmitt and Randall, 1994; Bundy et al., 1999).

The PSNT evaluations have involved over 350 site-years of data (Blackmer et al., 1989; Fox et al., 1989; Magdoff et al., 19984, 1990; Meisinger et al., 1992a; Andraski and Bundy, 2002) and have convincingly shown that the PSNT can successfully identify N-sufficient sites. There is a remarkable consensus that PSNT soil NO_3–N concentrations of 20 to 25 mg NO_3–N kg^{-1} or more are associated with N sufficiency for corn. However, using the PSNT as a quantitative index of fertilizer N needs has met with varied success. For example, Pennsylvania, Iowa, Vermont, and Wisconsin use PSNT values below the critical level as a direct input into fertilizer N recommendations (Beegle et al., 1989; Jokela, 1989; Blackmer et al., 1991; Bundy and Sturgul, 1994). Others have concluded that variability in the relation between PSNT and relative yield limits its usefulness as a quantitative index (Fox et al., 1989; Meisinger et al., 1992a; Klausner et al., 1993). Part of this variation in PSNT performance may be due to annual variations in temperature or rainfall during the period just preceding soil sampling, and the resulting effects of these weather conditions on soil nitrate. Andraski and Bundy (2002) found that N recommendations based on the PSNT frequently resulted in excess N additions when May and June temperatures were more than 0.5°C below average. These weather impacts on the PSNT suggest that the recommendations could be improved by developing interpretation schemes that included the influences of deviations from normal weather conditions.

The PSNT has been shown to provide significant environmental benefits, as documented by the direct leaching estimates of Guillard et al. (1999). These investigators compared corn-silage N management systems of a standard 196-kg N ha^{-1} preplant application (no PSNT), a PSNT-based system that received 90 kg N ha^{-1} preplant with sidedress N determined by PSNT test, and a PSNT-based system that received all the N at sidedress. The study used zero-tension lysimeters beneath these treatments that provided flow-weighted NO_3–N concentrations (in mg NO_3–N L^{-1}) of 20 for the standard preplant treatment, 7 for the PSNT receiving preplant N, and 5 for the PSNT receiving all sidedress N. The corresponding quantities of N lost by leaching were 50, 19, and 15 kg N ha^{-1}, respectively. Guillard et al. (1999) found no significant difference in corn yields among the three treatments. The main factor contributing to the leaching reduction was the avoidance of excess N, because the average fertilizer N rate was 196 kg N ha^{-1} for the standard preplant, 113 kg N ha^{-1} for the PSNT with preplant N, and 80 kg N ha^{-1} for the sidedress N treatment. Similar results have been reported for PSNT use in New York (Sogbedji et al., 2000) that monitored tile drainage from large corn-silage plots and concluded that compared to conventional N management, the PSNT reduced the mass of N leached and NO_3–N concentrations by about 50% with no significant effect on crop yields. The above results show that the PSNT can be a useful within-season monitoring tool to avoid excess N applications, with attendant reduction in N leaching.

The PSNT and the PPNT were evaluated in a large 5-yr regional study that was summarized by Bundy et al. (1999) and included 307 site-years across the Midwest. The study utilized the relative yield of a site (yield without N divided by non-N-limited yield) in relation to the PPNT or PSNT soil nitrate concentrations using a linear-plateau response model. Site factors such as depth of sampling, cropping history, and soil properties were evaluated and showed that the PSNT was improved with a 0- to 60-cm (0–2 ft) sample rather than the traditional 0- to 30-cm sample. This study used an indirect environmental evaluation of these nitrate tests by counting the number of sites that did not respond to N but had soil nitrate N concentrations below the critical value, which would have resulted in additional fertilizer N applied to a nonresponding site. The study found that across all sites a 0- to 60-cm-deep sample resulted in a PPNT-responsive-site detection rate of 70%, and a PSNT detection rate of 77%. However, when the PSNT and the PPNT tests where applied to sites where the previous crop was corn, the detection rate of the 0- to 60-cm PSNT increased to 83 to 90% while the PPNT detection rate was 75 to 89%. The study also showed that the PSNT performed best on medium-textured soils (7–27% clay), in years with high yield potential, and when local weather conditions favored nitrate retention (low leaching and/or low denitrification). Schmitt and Randall (1994) also summarized the 54 site-years of Minnesota data that contributed to the larger regional study. They found somewhat higher correlations between relative yield and the 0- to 60-cm PSNT ($r^2 = 0.57$) than with the PPNT ($r^2 = 0.52$), and that the PSNT correlation increased to 0.63 if nitrate plus ammonium was included. However, Schmitt and Randall (1994) selected the PPNT for upgrading the Minnesota recommendation system due to its direct link to residual nitrate, the ease of incorporating it into the Minnesota system, the expectation that the PPNT would be more readily accepted by growers and dealers, and the fact that the PSNT required a sidedress N management system that was considered to be risky on fine-textured soils due to positional unavailability of the N (Randall and Schmitt, 1993). The above regional evaluations of the PSNT indicate that it has a somewhat higher success rate than the PPNT, and that it can be improved with deeper sampling and the inclusion of ammonium N. However, adoption of the PSNT requires a sidedress N management system and a commitment to timely soil sampling.

A nearly universal caution raised in all of the above studies is that the PSNT results are influenced by the residence time of nitrate N under the local soil and weather conditions of the site. Thus, local weather conditions such as abnormal temperatures or rainfall, or local soil properties such as coarse textures or tile drainage can affect the interpretation of the PSNT. On the other hand, these factors also indicate areas where the PSNT can be improved. For example, the PSNT would benefit from incorporating recent weather and soil properties into the interpretations, as shown by the simple, decision flow chart in Maryland's approach (Coale et al., 1995). Nevertheless, the PSNT's requirement for soil sampling and the narrow time window will limit its application to areas requiring prudent N management.

Leaf Chlorophyll Meter

A direct measurement of plant N content has long been a goal of scientists because leaf greenness is intuitively recognized as a sign of N status, that is, the pale green appearance of leaves is associated with low chlorophyll and N content. The LCM was developed to quantitatively monitor the N status of rice (SPAD 502 chlorophyll meter, Minolta Camera Col., Osaka, Japan). Subsequently, the meter was adapted for use on corn (Schepers et al., 1992a, 1992b; Wood et al., 1992a), cotton (Wood et al., 1992b), wheat (Follett et al., 1992), and scheduling fertigation of irrigated corn (Blackmer and Schepers, 1995). Measurements are taken by pressing the device against the leaf, which then quantifies transmittance through the leaf at 650 and 950 nm, thus producing a measure of leaf "greenness." The meter basically quantifies potential photosynthesis for a small portion of the leaf under existing nutrient conditions because excess light is provided to stimulate photosynthesis. The LCM readings are typically used to calculate a "N sufficiency index" by dividing the meter reading for a leaf in question by the reading in a nearby N-sufficient reference area to standardize for factors such as variety, growth stage, water stress, and cultural practices. The approach of using non-N-limiting reference strips was a benchmark for later precision agricultural methodologies that have targeted improved within-season N management in cereal production.

Further research by the Nebraska group developed the N sufficiency index as a guide for applying in-season N (Peterson et al., 1993; Blackmer and Schepers, 1995; Varvel et al., 1997a). Using this approach, maximum yields were attained when early-season N levels were adequate to maintain sufficiency indexes above 95% at the V8 growth stage of corn. If the sufficiency index at V8 was below 95%, maximum yields could not be achieved with in-season fertilizer N applications. Sawyer et al. (2004) calculated the EONR for a large number of rain-fed N-response trials in Iowa and noted that the EONR corresponded to an average sufficiency index value of 0.97 for corn (V15 to R1 growth stages) following soybean. They found the sufficiency index value was 0.98 for a smaller number of fields under continuous corn. Possible reasons for different sufficiency index values between Nebraska and Iowa are (i) the Iowa data included many fields compared to a limited number in Nebraska, (ii) fields in Nebraska were irrigated, (iii) the Nebraska study involved corn plants at an earlier growth stage, or (iv) the irrigation water in Nebraska contained up to 30 mg NO_3–N L^{-1} even though little was usually applied until after the V12 growth stage. It should also be noted that the CVs within a group of 30 SPAD meter readings from a plot are typically 5 to 8%, so triggering remedial N applications based on LCM readings involves some uncertainty. Studies by Blackmer and Schepers (1995) noted that early N deficiencies could be corrected using LCM readings when deficiencies were not severe. The LCM is especially useful in irrigated systems where readings can be taken throughout the growing season and N can be added as needed through overhead sprinklers. Caution should be exercised when collecting LCM data from plants under water stress because the near-infrared light band (950 nm) is much more sensitive to water stress than the red band (Schepers et al., 1996).

Chlorophyll meters have been widely used in research settings in many parts of the world since commercialization in 1990, but field applications have been limited because of the manual nature of the measurements. The nondestructive attribute of LCM measurements allows the device to be used as a proxy for leaf chlorophyll content (Markwell et al., 1995) and leaf N concentration up to the point of luxury consumption of N by plants (Schepers et al., 1992a; Fox and Walthall, 2008, see Chapter 16, for additional details). Normalizing LCM data or related data to a non-N-limiting area makes it possible to compare results across physiological growth stages, cultivars, fields, and years. For example, Varvel et al. (1997a) found relative LCM values for irrigated corn were significantly correlated with relative yield over multiple growth stages. Although LCMs are largely used as a research tool, their use has made it possible to nondestructively monitor plant N status as it relates to stalk nitrate concentration (Varvel et al., 1997b) and yield (Varvel et al., 1997a) in corn. As a comparative tool, LCMs have proven their value for assessing interplant competition (Blackmer et al., 1993) and calibration of remote-sensing imagery (Blackmer et al., 1994) and ground-based sensors. From an environmental perspective, application of fertilizer to N-deficient plants according to relative LCM values should have the potential to increase N use efficiency and reduce nitrate leaching by better synchronizing N application with crop need. A 12-yr study where LCMs were used to schedule “spoon-feeding” of irrigated corn in Nebraska showed an average relative yield of 0.95 (11.3 Mg ha^{-1}) and N use efficiency of 65% (N removed in grain for treatment, minus grain N removed in the check, divided by N applied), compared to a N use efficiency of 50% for the reference plants (unpublished). The average N rate applied using the spoon-feeding technique was 108 kg ha^{-1} compared to 200 kg ha^{-1} for the adequately fertilized reference area.

Precision Agriculture Approaches

Precision agriculture includes a wide range of georeferenced technologies that have become available to agriculture since the mid 1990s. These technologies have been made possible by low-cost GPS units and mobile data processing equipment capable of storing and retrieving large databases. Some of these developments have provided detailed spatial databases for traditional elements of the N recommendation algorithms, such as soil survey maps, yield maps, previous crops, and soil test results. Satellite and aircraft can also provide remotely sensed data on soil moisture content, residue cover, and crop stress. On-the-ground soil sensors have also been developed for assessing electrical conductivity, subsoil compaction, and soil organic matter. Real-time crop sensors have also become available utilizing passive and active technologies to measure crop stress (apparent N status) through reflectance in the visible and near-infrared wavelengths. It is beyond the scope of this chapter to discuss how each of these methods could improve estimates of fertilizer N needs (see Randall et al., 2008, Chapter 23, for a full discussion). But several of these technologies offer important opportunities to improve estimates of crop N responsiveness, crop N status, and new algorithms for estimating fertilizer N needs within N management zones.

Within-Field N-Response Measurements Using Two Rates, Delta Yield

Delta yield is defined as the difference between the yield at a non-N-limiting rate and the yield without added N. Kachanoski et al. (1996) concluded that delta yield was better correlated with EONR than actual yield, a result that is also illustrated by the Pennsylvania data in Fig. 14–3b (Fox and Piekielek, 1995). The conclusion of Kachanoski et al. (1996) was derived from an analysis of over 300 corn N-response experiments in southern Ontario that showed no significant relationship between measured yields and EONR, but that 50 to 75% of the EONR variability could be accounted for by delta yield. Lory and Scharf (2003) applied the delta yield approach to an extensive corn N-response database from five states (Illinois, Minnesota, Missouri, Pennsylvania, and Wisconsin). This study found that yield by itself was poorly correlated with EONR, due to N supplied from the soil due to previous legume crops, manure, or possible residual N, but that delta yield was a much better predictor of EONR at these same locations. Lory and Scharf (2003) concluded that N recommendation systems that rely solely on yield, or that ignore yield entirely, are limited to explaining less than 50% of the variation in corn EONR. It should be noted that the above observations were from regions where water availability is not usually limiting. Situations where a water deficit impacts mineralization as well as crop growth can render the delta yield concept problematic.

Appealing features of the delta yield approach are that it is highly site specific, it can provide estimates of the fertilizer N needs, and the yield data could be readily collected with current yield monitors (Lory and Scharf, 2003). By monitoring yields on nonfertilized areas and well-fertilized areas of a field the producer would have a direct local estimate of the N responsiveness, which is the central component for estimating the crop N requirement. Delta yield is directly related to EONR because both parameters measure the N responsiveness of a site, the former by simple subtraction and the latter through a regression equation. While the extent of year-to-year variation in delta yield needs to be determined, its close relationship to the EONR and the robustness of the EONR to year-to-year variability through soil–plant N resiliency (see Fig. 14–2) make it worthy of more in-depth evaluations. The delta yield approach is also directly related to the mass-balance Eq. [2], with delta yield being a proxy for the numerator in the first term of this equation, as previously discussed.

Lory and Scharf (2003) have described a preliminary fertilizer recommendation approach using delta yield. It is based on the fact that the nonfertilized yield reflects all N contributed from mineralization, residual N, manure N, and so forth and that the delta yield value represents the total crop N requirement that the fertilizer must supply. The delta yield is first converted into a total aboveground N requirement. For example, corn grain contains about 12.5 g N kg^{-1} oven dry grain (~0.6 lb N bu^{-1} of 15.5%-moisture grain) and would require about 18 g N kg^{-1} oven-dry grain (~0.85 lb N bu^{-1} at 15.5% moisture) to produce the total aboveground crop; then assuming a fertilizer efficiency of about 55%, a fertilizer N need of 33 g fertilizer N kg^{-1} grain (1.6 lb N bu^{-1} at 15.5% moisture) is calculated. These approximations agree well with the slope of Fig. 14–3b, which converts to about 34 g fertilizer N per kg of grain increase. This approach could be implemented by conducting the delta yield measurements over several years across the soil resources of selected fields. Such a multiyear approach would evaluate the consistency of the N response over time (i.e., evaluate soil–plant N resiliency), as well as how delta yield varies with other N-management-zone factors such as soil type, previous legume crops, or manure applications. Producers and consultants frequently resort to an N recommendation strategy that applies 21 to 25 g N kg^{-1} oven dry grain (1.0 to 1.2 lb N bu^{-1}), which is less than the amount needed assuming a 55% fertilizer efficiency. This difference is attributed the realization that soil N mineralization contributes to the N supply with an N-use efficiency greater than 55%.

Thus, a consistent application of the simple delta yield approach could provide the producer with information to estimate fertilizer N need, soil N supply, and validate the conventional legume credits or manure credits on his own farm. It would be difficult for either of the traditional preseason N recommendation approaches to provide more site-specific estimates of fertilizer N needs than a repeated measure of the crop N responsiveness of specific N management zones. This type of on-farm validation would also have substantial educational value for the producers and scientific value to farm advisors. Furthermore, this type of N recommendation is entirely within the scope of current production practices due to the availability of yield monitors and variable-rate N application equipment.

Within-Field N-Response Measurements Using Multiple Rates

The concept of evaluating N recommendations within a specific field can be expanded beyond simple N-sufficient versus nonfertilized strips by use of programmable variable-rate N application equipment. The availability of GPS-referenced variable-rate-N applicators coupled with yield monitors could allow a producer to verify or refine traditional preplanting N recommendation approaches.

It can also help identify the proper rate of midseason supplemental N, which can potentially improve N use efficiencies.

An example of this approach is the development of the "ramped N reference strip" (also referred to as a ramped calibration strip) approach by engineers and soil scientists at Oklahoma State University. These researchers have developed an automated programmable N-fertilizer-strip applicator that can be retrofitted on common fertilizer applicators, similar to the "calibration stamp applicator" (Raun et al., 2005). However, unlike the calibration stamp applicator, this applicator can apply preplant rates ranging from 0 to 300 kg N ha^{-1}, in progressively incremental rates of 20 kg N ha^{-1} over user-defined distances (50–300 m). The highest N rate and the rate increments can be adjusted to the crop and the expected N need by using different nozzles. The system has been used in winter wheat with N ramps from 0 to 150 kg ha^{-1} in increments of 10 kg N ha^{-1} that change every 3 m. The ramped N reference strip is specifically designed to assist producers in estimating the optimal midseason fertilizer N rate by visually, or electronically, inspecting differences in growth and color during the season across the range of preplant N rates. This approach will be especially useful with real-time sensors and should substantially improve the identification of the N rate where in-season growth is maximum, which should improve the forecasting of optimal rates of supplemental N. The ramped N reference strip approach offers particular advantages for large acreages where preplant soil tests and in-season soil tests are simply too labor intensive for the producer. For example, if no in-season growth differences were measurable across the ramped N reference strip (0–150 kg N ha^{-1}), it is unlikely that there will be added response to fertilizer N. However, if growth peaked at 100 kg N ha^{-1} with discernable differences from 0 to 100 kg N ha^{-1} (no differences from 100 to 150 kg N ha^{-1}), then the topdress rate would be around 100 kg N ha^{-1}. It is important to note that the ramped N reference strip must be applied in addition to the normal farmer practice and would thus incorporate the N contributed from other sources such as residual nitrate, manure, soil mineralization, and so forth. However, to be useful for applying supplemental N for long-season crops (e.g., corn) based on early-season observations, it is likely that crop developmental stage and total crop N need will also need to be considered.

The ramped N reference strip has been evaluated on winter wheat by Raun et al. (2005) and was shown to be useful when adjusting in-season fertilizer N rates because the crop is responsive to environmental conditions encountered from planting to the time of N topdressing. Their work employed the use of normalized difference vegetative index (NDVI) active sensors whereby readings collected from the N-rich strip were divided by NDVI readings from the farmer practice to determine the response index. The response index determined soon after breaking dormancy in winter wheat using NDVI readings was highly correlated with the response index determined at harvest (grain yield in the N-rich strip divided by grain yield in the farmer practice). This finding allowed researchers to predict the relative fertilizer N response of winter wheat in each field from year to year by measuring the response index at midseason (Mullen et al., 2003). A useful attribute of the ramped N reference strip is that it can easily be applied and marked within each field at the time of planting, and then used as a visual guide for determining the appropriate topdress N rates without the requirement of a crop sensor or chlorophyll meter. However, the use of hand-held real-time sensors or LCM readings across the range of N rates will be more accurate in assessing crop N status. Use of this within-field variable N-rate calibration approach can also serve as a strong educational tool because producers find it easy to recognize signs of N stress or N adequacy. In essence, a ramped calibration strip provides a temporal moving target to delineate the appropriate sidedress N rate in that general part of a field. Several such strips across a field, each including multiple rate sequences, can help producers determine the appropriateness for changing the application rate by management zone or using real-time sensors to account for spatial variability.

Real-Time Crop Nitrogen Sensors

A fundamental question faced by all N recommendation systems is how to manage the interaction of the large year-to-year weather variability with the spatial variability of the soil N cycle. The spatial variability of soil N has been characterized by a large small-scale component (large "nugget effect" in spatial statistics terms) with over 50% of the total variability present within a few square meters (Beckett and Webster, 1971; Reuss et al., 1977; Meisinger, 1984). The most detailed management of this variability would require fertilizer application equipment and crop or soil sensors with submeter resolution.

Variable-rate N-application strategies have received considerable attention as an approach for addressing within field variation in crop N response. But, adoption of variable-rate N application strategies have been limited by lack of diagnostic criteria that can be used as the basis for varying the rate of N applied (Doerge, 2001). Strategies using within field variation in expected yield, or mapped previous yields, have not been successful due to the weak relationships between simple yield and EONR described earlier, and because the mapped yields can change substantially from year to year in the same field. Indeed, several studies have concluded that variation in expected or historic yield is not a valid basis for guiding variable-rate N applications (Katsvairo et al., 2003; Murdock et al., 2002). In-field variation in soil organic matter content (Schmidt et al., 2002), soil nitrate concentrations (Ferguson et al., 2002; Katsvairo et al., 2003), and soil type or drainage class (Sogbedji et al., 2001) have also been shown to be of limited usefulness in predicting optimum N rates in variable-rate application strategies.

Indirect plant measurements for determining variable-rate N application rates have met some degree of success. Using active sensor reflectance measurements (NDVI) to calculate a response index (determined by comparing to a non-N-limiting reference strip), Raun et al. (2002) showed that early-season sensing and treating each 1 m^2 in winter wheat resulted in N use efficiency increases of 15% over traditional whole-field techniques based on mass-balance approaches. The Greenseeker sensor (NTech Ind. Inc., Ukiah, CA) used in this work is self-illuminated in red (650 ± 10 nm FWHM) and near-infrared (770 ± 15 nm FWHM) bands. The sensor measures the fraction of the emitted light in the sensed area that is returned to a detector, which is then used to compute NDVI, virtually instantaneously. The NDVI is the difference between the near-infrared and red reflectance divided by the sum of these two reflectance values. The real-time crop sensor coupled directly to a variable-rate N applicator resulted in the highest revenue when compared to other conventional practices, even using inexpensive N priced at \$0.55 kg^{-1}, which is roughly half the cost of N at the time of this writing. The methodology developed for wheat and corn by Raun et al. (2002) relies on the demonstrated ability to estimate yield potential early in the season. This is done by dividing NDVI by the days from planting to sensing (www.nue.okstate.edu), which is essentially the early-season growth rate or biomass production per day. The in-season method for estimating topdress N rates is based on yields estimated from early-season sensor data rather than a preseason forecasted yield. The in-season topdress N rate is estimated by subtracting the projected N uptake for the predicted yield in the sensor area, from the projected N uptake in the non-N-limiting reference strip, and then dividing by an efficiency factor (usually between 0.6 and 0.7 for in-season N applications). The main differences between the traditional preplant approaches and the within-season real-time sensor approach are the spatial resolution of the sensors (submeter resolutions) and that the sensor is based on site-specific climatic conditions encountered from planting to the time of measurement. This approach allows environmental conditions from planting to sensing to influence N rate. These environmental conditions can change substantially from year to year and are known to alter available N from mineralization or from residual N.

Predicting N inputs and losses with simulation models is another way to adjust in-season N application rates. Sogbedji et al. (2001) showed that including a N simulation model (LEACHMN) and early-season weather conditions into N management plans can substantially improve yearly adjustments to supplemental N, while conventional soil series and drainage information provided little benefit. The model-aided approach focuses on soil–climate interactions that affect N mineralization and N losses up to the time of in-season N application. Practical limitations to using such a soil-based model are that spatial data inputs are required if the intent is to utilize within-field N applications (e.g., use of variable-rate N applications). A different model-based approach involves a crop-simulation model (e.g., Hybrid Maize) to estimate yield potential based on actual weather conditions up to the point of in-season N application and local long-term weather records until harvest (Yang et al., 2004; Lindquist et al., 2005). The Hybrid Maize model assumes N supply is not limiting up to the time of in-season N application. The amount of starter fertilizer, residual N, and other credits could be subtracted from the total N requirement based on site-specific predicted yield. This crop–climate approach does not involve a spatially variable soil component. Runge and Hons (1998) developed a strategy and user-friendly spreadsheet to make in-season adjustments to yield estimates from 6 wk before pollen shed until 4 wk into the grain-fill period based on limiting factors such as antecedent soil water, precipitation, and evapotranspiration. Their approach also assumes adequate N availability and has the same spatial limitations as other crop-climate-based simulations. For purposes of making within-season N recommendations, the soil–crop–climate simulations should provide very useful information, especially if supplemented with appropriate spatial data. In the meantime, the paucity of spatial data and the need to verify simulation models for local conditions provide a strong incentive to consider using the sites' crop as an indicator of growing conditions and N needs.

The in-season crop-sensing methodology allows N rates to be tailored to adjust for N-responsive or non-N-responsive conditions. Using contributions from scientists all over the world, 14 specific algorithms have been developed for various regions that include irrigated corn, dryland corn, winter wheat, spring wheat, sorghum (*Syricum granum* L.), and bermudagrass (www.nue.okstate.edu). Each algorithm requires preplant establishment of the non-N-limiting reference strips as proposed by Schepers et al. (1992a, 1992b), in-season NDVI sensor readings from the N-rich strip and farmer practice, knowledge of planting dates, and regional yield limits (www.soiltesting.okstate.edu/SBNRC/SBNRC.php). All algorithms are free over the Web, and all mathematical components of each algorithm are public property.

Future Opportunities

The movement from uniform field-scale N applications based on preplant estimates from mass-balance or economic approaches, to within-season variable-rate applications based on sensing of crop growth offers the prospect for significant improvements in estimating the crop N requirement and fertilizer N needs. Timely and inexpensive accessibility to adequate spatial soils data is currently a major constraint to making variable-rate N applications, but one that may be eliminated over the next decade. Another constraint is having robust algorithms for making N recommendations that are appropriately responsive to soil–climate interactions. The fact that crop N uptake patterns are poorly synchronized with one-time fertilizer N applications is evidence that improvements in N synchronization can reduce environmental risks. This is consistent with the well-established principles that N should be applied at a rate consistent with crop N requirements and in phase with crop demand. Delayed or multiple applications of N that are tailored to the site's crop N requirement reduce the potential for N losses to the environment driven by excessive water, for example, leaching and denitrification.

In-season N management involving sensors (aircraft or ground-based) will also need to be flexible to accommodate equipment availability and weather uncertainties. Managing winter- versus summer-annual crops or perennial forages involves different approaches to interpreting sensor data because of the need to assess factors such as bare soil color, vegetative cover, chlorophyll content, leaf area index, biomass, anthocyanin concentration, plant height, and so on. As such, in-season technologies and management decisions will need to accommodate variable amounts of vegetation at different growth stages and will likely be best served by a variety of vegetative indices developed for specific crops under specific production practices (tillage practices, soil drainage, etc.). The future should also see a better understanding of soil–plant N resiliency, which should allow further incorporation of this characteristic into within-season N management technologies.

The next generation of N management strategies involving crop sensors (reactive management) is now in the research and development stage, but the widespread use of these sensors will likely require more convincing reasons for adaptation, that is, reasons arising from environmental plus economic issues. Future N management practices will likely function in an arena of some form of N directive. Daberkow et al. (2008, see Chapter 22) concluded that “the question now is not whether there will be additional policies addressing concerns with N pollution, but what policies will be adopted.” Likewise, future N management practices will function in an arena of more expensive energy, which necessarily means more expensive fertilizer N.

Summary and Conclusions

This chapter has reviewed the principles undergirding N recommendations and the N mass balance and introduces the concept of soil–plant N resiliency. It has also summarized various approaches for making fertilizer N recommendations for cereal crop production, with the main categories being preplant approaches of the N mass balance and the grouped economic optimum, and within-season monitoring such as real-time sensing. In the final analysis, all N recommendation methods seek to prescribe fertilizer N that harmonize with the sites' soil N cycle and produces high crop N use efficiency with minimal environmental loss. A brief summary of the major advantages and disadvantages of these recommendation approaches are given in Table 14–4.

If reliable yield estimates can be made before planting, or if soil–plant N resiliency allows use of average yields, the N mass-balance approach utilizing the difference between crop N need and soil N mineralization, along with N credits from soil nitrate (mostly in subhumid areas), legume credits (soybeans or forage legumes), manure credits (with manure analyses), and credits for other significant sources (e.g., irrigation water), is a viable option utilizing site-specific data and provides a clear educational value to the producer. However, this method requires a significant amount of local N data (soil nitrate, manure analyses, etc.), can be undermined by overly optimistic yield estimates, and traditionally does not directly address economic issues, although economic adjustment factors can be added.

The grouped economic optimum is the most direct and easy to use approach and avoids the problems with estimating yields. However, it has limited ability to predict precise fertilizer N needs for a specific site because it is based on response functions aggregated over large geographic areas. It is also subject to misjudgments from grouping of nonsimilar soils into similarly responding classes and to the subjective selection of an economic response model. This approach relies heavily on soil–plant N resiliency and requires a continual commitment to measuring crop fertilizer N responses for the current varieties of crops and the common agronomic practices. In practice, the traditional economic approach is usually combined with mass-balance N credits to improve recommendations for specific fields or cropping systems.

The mass-balance approach and the grouped economic approach, however, do share some common elements. Both require an estimate of crop N response, the mass-balance derived from the difference between crop-N requirement and soil-N supply, and the grouped economic approach from the yield versus fertilizer N-response equation. Both methods also lack a direct estimate of the environmental-loss component. The mass-balance method, however, can provide a long-term estimate of total unrecovered N by employing the whole-crop approach and calculating the percentage of N not recovered in the crop and soil. The grouped economic approach does not currently consider the cost to society for N lost to water or greenhouse gases; these losses could be added to the economic models (Teague et al., 1995; Ribaudo et al., 1999; Daberkow et al., 2008, see Chapter 22), but to date they remain difficult to quantify and have been excluded. The environmental and economic consequences of nonrecovered N will become increasingly important in the future, as society places more value on the environmental issues and as energy becomes more expensive.

The past 10 to 15 yr has seen the rapid development of many remote-sensing and georeferenced tools that offer the prospect for improving the traditional preplant N mass-balance and the grouped economic approaches. The manual within-season techniques, such as the PSNT and LCM, have proven useful for small acreages or areas requiring careful N management but are too laborious for large areas. Real-time midseason crop sensors coupled with variable-rate applicators have distinct advantages over traditional approaches because they can utilize submeter

Table 14–4. **Advantages and disadvantages of several N recommendation approaches commonly used for cereals in the USA.**

Approach	Advantages	Disadvantages
Preplant N mass-balance or budgeting approaches	Site specific at the spatial level of the soil sampling, e.g., soil series within a field, N management zones of field, directly accounts for varying N sources such as residual NO_3, manure N, or irrigation N	Requires detailed site information, e.g., soil nitrate N, soil organic N, previous yield/crop, average yield, manure N, irrigation water N input; expected yield can be difficult to estimate
	Excellent tool for teaching producers the soil N cycle	High information requirement for large farms, calculations needed
	Fertilizer N can be estimated before planting on a crop by crop basis, useful for multiple crops or short-season crops	Cannot adjust to within-season weather
	Future price and cost estimates not needed	No economic factors considered in traditional mass-balance approach
	Can be augmented with an economic adjustment factor	Requires a commitment to N-response studies for N credits, crop N requirements, fertilizer N efficiencies
Preplant grouped economic approaches	Easily calculated	Uses general values averaged over a range of weather conditions and selected agronomic practices
	Economic factors considered heavily	End-of-season prices and future response functions difficult to forecast, assumes unlimited capital in maximizing return to N
	Minimal site information needed, e.g., no soil tests	Site factors affecting N response not considered in traditional approach, e.g., residual nitrate, manure, forage legume N
	Avoids use of yield goal or expected yields with their associated estimation problems	Considers yields averaged over large soil-resource areas or cropping systems, heavy reliance on soil–plant N resiliency
	Can be combined with N mass-balance credits	Requires long-term commitment to yield vs. N-response studies on representative soil–crop systems
		Crop N-response function for existing data difficult to select, economic estimates dependent on the model selected
		Cannot adjust to within-season weather or small-scale spatial variability

Table cont.

Table 14–4. cont.

Approach	Advantages	Disadvantages
Within-season monitoring or real-time sensing	Highly site specific, can adjust for spatial variability and site weather up to the time of sensing	Requires investment in sensors and high-clearance equipment, access to fields, higher technical knowledge than traditional approaches
	Can provide data for local within field database development through yield monitors, visual evaluation of N stress from variable-rate N applications	Requires development of crop-specific N algorithms for local conditions and field evaluation and validation of the algorithms
	Uses plant as an indicator of need as compared to local non-N-limiting area	Risk of yield loss if N deficiency is not corrected in timely manner
	Small spatial resolution, allows for small-scale (submeter) management, potential for managing the spatial variability of the soil N cycle	Narrow in-season application window for cereals, requires ample time frames for sensing large areas within the window to correct crop deficiencies

resolution to monitor actual plant growth at midseason and estimate N response. These approaches are conducive to variable-rate N application strategies using active sensors that are commercially available; however, these approaches will require algorithms to interpret the crop N status and estimate subsequent fertilizer N needs. Reliable algorithms have been developed for wheat, and algorithms for other crops are being developed, but challenges remain such as the narrow window for N application, depending on equipment clearance, and the risk of reduced yields if deficiencies are not corrected early in the crop life cycle. Research over the coming years will investigate these challenges as algorithm development and real-time sensors continue to be evaluated. The development of georeferenced field equipment for yield and fertilizer application, georeferenced databases of soil resources, and real-time crop N sensors offer significant opportunities for improving N recommendations.

It is our opinion that N recommendation strategies would benefit from a factual reexamination of the underlying principles, the methods used to estimate various parameters, and the intended application of the recommendations to the soil–crop–livestock systems of a particular state. It is likely that the common ground of incorporating economic estimates of crop N need into the mass-balance approaches, or adding the appropriate site-specific N mass-balance credits into the economic approaches will produce improved preplant N recommendations. It is also likely that the N management needs of a state will require multiple approaches or a hybrid combination of approaches. For example, the economic approach could be used for large-area resolution on grain farms growing simple grain-crop rotations with minimal use of manure and minimal site information. The mass-balance approach could be used for field-scale resolution in livestock systems employing various forage-crop rotations with high use of manures. Areas requiring the most careful N management could employ within-season monitoring or real-time sensing of N management zones. Areas requiring careful N management might be sensitive groundwater recharge zones, areas affecting nearby N-sensitive ecosystems, or management areas receiving P-based quantities of manure that require variable rates of supplemental N.

The future could also see the wide-spread use of real-time sensors on a meter-square resolution throughout agriculture, if suitable algorithms can be developed to interpret crop N stress and forecast remaining N needs. Although some may view this statement as overly optimistic, we have suggested it to encourage scientists to study new approaches, because we can attain only what we are willing to envision. Whatever N recommendation method is chosen for the desired level of resolution, improving N recommendations should lead to increased N use efficiencies, improved profitability, and reduced N losses to the environment.

Acknowledgments

The authors wish to acknowledge and thank Dr. Larry Bundy for his significant inputs into this chapter. His initial drafts describing the economic approaches, constructive critiques of several versions of the manuscript, and thoughtful suggestions and editing provided major contributions to the final manuscript. We also thank Dr. John Sawyer for providing the data for Fig. 14–4 and for editorial suggestions on the maximum return to N approach. Finally, we thank the three anonymous reviewers of this chapter, their constructive suggestions and thoughtful interactions that provided valuable improvements to this chapter.

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