Nitrogen management in irrigated spring wheat

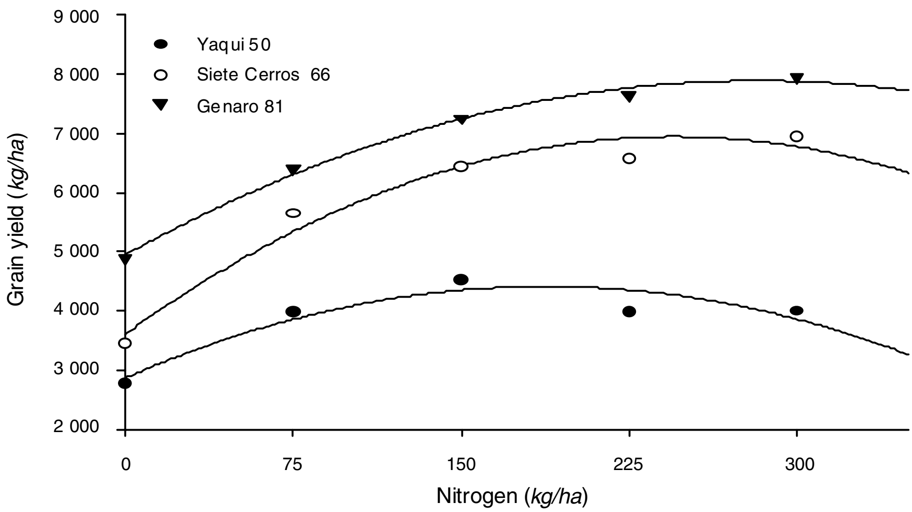
J.I. Ortiz-Monasterio R.

Globally, fertilizer nitrogen (N) applications are approximately 80 million tonnes, with half being applied in developing countries and the other half in developed countries (FAO, 1990). It has been estimated that by the year 2025 the consumption of nitrogen fertilizer will increase 60 to 90 percent, with two-thirds of this being applied in the developing world (Galloway *et al*., 1995). This trend in fertilizer use is mostly driven by the need of developing countries to keep food supply up with population growth. It has been projected that by the year 2020 world population will be more than 8 billion people, with more than 90 percent of this additional growth concentrated in developing countries (Sadik, 1992). Most of the irrigated spring wheat in the world is located in developing countries. These areas have high yield potential and high levels of input use compared to other wheat-producing regions in the developing world. The International Maize and Wheat Improvement Center (CIMMYT) has defined the wheat irrigated areas as mega-environment one (ME1) (for a description of mega-environments, see chapter "CIMMYT international wheat breeding), which includes the Indo-Gangetic plains in India and Pakistan, the Nile River Valley in Egypt and the Yaqui Valley in Mexico among others (Rajaram *et al*., 1993). These areas already produce 42 percent of the wheat in developing countries, and it is likely that further intensification will take place in order to keep up with food demand. However, the efficiency of N fertilizer use tends to be low in these systems (Byerlee and Siddiq, 1994), and further intensification with current agronomic practices will likely lead to higher inefficiencies and therefore higher N losses. The nitrogen that is lost, in addition to being an expense to the farmers, also has an environmental cost. It has been documented that land conversion and intensification alter the biotic interaction and patterns of resource availability in ecosystems and can have serious local, regional and global environmental consequences (Matson *et al*., 1997). Therefore, it is important to identify nitrogen management practices that will allow meeting the increasing demand for food and fibre while minimizing environmental impact and being economically attractive to farmers.

APPROACHES TO IMPROVING NITROGEN-USE EFFICIENCY IN IRRIGATED WHEAT

Wheat production in many areas of ME1 is particularly dependent on synthetic nitrogen fertilizer due to: (i) the use of animal manure is very limited because (a) other higher value crops have priority over wheat, (b) the increasing demand of this product for use as fuel and (c) a declining number of animals that are being replaced by tractors (Hobbs *et al*., 1998; Fujisaka *et al*., 1994); (ii) many of the soils of ME1 are naturally low in levels of soil organic matter, and there is evidence that this continues to decrease due to increased tillage, burning and/or removal of crop residues for animals (Meisner *et al*., 1992; Hobbs and Morris, 1996); and (iii) there are few legumes present in the main wheat rotations in ME1 (rice-wheat, cotton-wheat, maize-wheat, soybean-wheat and sorghum-wheat) that could supply symbiotically fixed nitrogen. There are two main approaches for increasing nitrogen-use efficiency, plant breeding and crop management.

FIGURE 26.1
Response of tall (Yaqui 50) and semidwarf (Siete Cerros 66 and Genaro 81) spring wheat cultivars to increasing levels of nitrogen fertilizer



NITROGEN-USE EFFICIENCY THROUGH PLANT BREEDING

CIMMYT semidwarf spring wheat cultivars were first adopted in the irrigated wheat areas of the developing world (Byerlee and Moya, 1993; Byerlee, 1996). During the process of adoption, it was often claimed that modern wheat cultivars could not perform well in the absence of nitrogen fertilizer (Simmonds, 1979), asserting that farmers would be better off growing their old tall cultivars if no fertilizer was available. It has been shown that CIMMYT's semidwarf spring wheat cultivars can outperform old tall cultivars under high or low N fertility conditions in Mexico (Ortiz-Monasterio *et al*., 1997). These results are in agreement with those of other researchers in other countries where it has been shown that semidwarf wheat cultivars either yield the same or more than old tall cultivars under low nitrogen fertility conditions (Jain *et al*., 1975; Wall *et al*., 1984; Entz and Fowler, 1989; Austin *et al*., 1993). Semidwarf wheat cultivars do not require more nitrogen; in fact they often need less N to produce the same yield per unit of available N than old tall cultivars. Perhaps this misconception has evolved because semidwarfs have a better response to nitrogen and, therefore, they have a higher optimum economic rate (Figure 26.1).

According to Moll *et al*. (1982), nitrogen-use efficiency (grain yield/N supplied) in cultivar development can be divided in two components: (i) uptake efficiency (plant total N/N supplied), which is the ability of the crop to extract nitrogen from the soil; and (ii) utilization efficiency (grain yield/plant total N), which measures the capacity of the plant to convert the already absorbed nitrogen in the plant into grain yield. One of the conditions for breeding nitrogen-use efficient wheat cultivars is the presence of genetic diversity for that trait. Genetic variability for nitrogen-use efficiency in wheat has been reported (Dhugga and Waines, 1989; van Sanford and

MacKown, 1986; Ortiz-Monasterio *et al.*, 1997). Furthermore, it has been shown that by breeding under medium to high N fertility conditions, the performance of CIMMYT's spring wheat cultivars from 1950 to 1985 has been improved when these are grown under high or low N fertility. In the semidwarfs, this increase in grain yield has been associated with gains in both components: uptake and utilization efficiency at the medium to high levels of N fertility and only with uptake efficiency under low N fertility (Ortiz-Monasterio *et al.*, 1997). This suggests that the level of nitrogen in the soil plays a very important role in the genetic expression of uptake and utilization efficiency in wheat. At the low N levels, there is a better expression of uptake, while at high N levels in the soil, utilization is better expressed. This means that in theory the nitrogen level in the soil could be manipulated together with the genetic diversity of the crop as a breeding tool for the development of wheat cultivars with improved uptake and/or utilization efficiency (Ortiz-Monasterio *et al.*, 1997). In the past, breeding for high yield potential in favourable environments (N not limiting) has produced germplasm with improved nitrogen-use efficiency when this is grown under low or high N fertility conditions in irrigated areas. It needs to be answered if other breeding strategies considering low N, or alternating low- and high-N environments during the selection of segregating populations and grain yield evaluations could result in germplasm with higher N-use efficiency.

Improvement in lodging tolerance was one of the main characteristics of the early semi-dwarf wheat cultivars. However, in some irrigated areas grain yield levels have been improved to the point where lodging may be keeping the levels of N fertilizer use below the agronomic optimum (Hobbs *et al.*, 1998). Thus, further progress in lodging tolerance will be fundamental in the development of new cultivars with higher nitrogen-use efficiency under high fertility conditions.

NITROGEN-USE EFFICIENCY THROUGH CROP MANAGEMENT

Nitrogen deficiency is the most widespread nutritional problem in irrigated wheat production. In addition, nitrogen fertilizer recovery tends to be low; in Pakistan N recovery was estimated at about 30 percent (Byerlee and Siddiq, 1994), while in Mexico the estimates for the Yaqui Valley are less than 50 percent with similar N management to that of farmers (Ortiz-Monasterio *et al.*, 1994). Crop management practices to improve nitrogen-use efficiency have been reviewed by many authors (Stanford and Legg, 1984; Bock, 1984; Bock and Hergert, 1991; Schepers and Mosier, 1991; Doerge *et al.*, 1991; Strong, 1995). The main practices suggested by these authors are discussed together with CIMMYT's experience in the context of irrigated systems. Four main crop management strategies are often mentioned for improving N-use efficiency.

Rate/yield goal

Only apply what is needed to meet crop demand

Several authors have suggested different types of N budgets to approximate the rate of N application (Bock, 1984; Halvorson *et al.*, 1987; Sims, 1995; Fageria *et al.*, 1997). Often the information required in these budgets is not available, particularly in developing countries. The typical information needed is: nitrogen requirement for a given yield goal, efficiency of fertilizer use, residual soil nitrate test, N mineralization from organic matter test, N credits from manure or other organic wastes, N credits from rotations with legume crops and N credits from nitrates in irrigation water.

In these budgets, the first step is to identify the N rate needed by the crop to obtain the N requirement. The N requirement is defined as the minimum amount of N in the above-ground portions of crops associated with maximum production. This information can be generated from experiments with different

TABLE 26.1
Nitrogen in the above-ground wheat biomass at maturity for different harvest index values and different yield levels

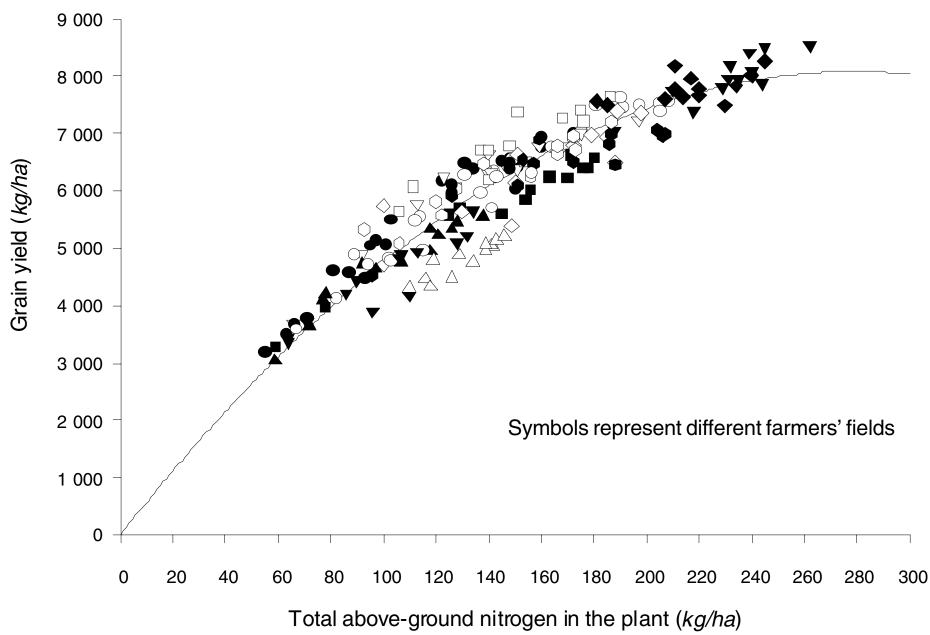
Yield (*kg/ha*)	Nitrogen (*kg*) Harvest index			Grain-N[a] (%)	Straw-N[a] (%)
	0. 3	0. 4	0. 5		
1 000	19	17	16	1.45	0.18
2 000	41	37	35	1.53	0.22
3 000	69	62	58	1.68	0.26
4 000	95	86	81	1.75	0.27
5 000	147	132	123	2.10	0.36
6 000	197	174	160	2.19	0.47
7 000	235	207	190	2.22	0.49
8 000	283	246	224	2.25	0.55

[a]Data from grain-N and straw-N are taken from CIMMYT trials in Obregon, Mexico, except for data for the 1 000 and 8 000 kg/ha yield levels, which are estimated based on the data trends (Hobbs *et al*., 1998).

N rates in which the total above-ground N content is known. Two such sets of data are presented here for irrigated spring wheat, that of Hobbs *et al.* (1998) in Table 26.1, which was derived from a number of experiments at a research station in the Yaqui Valley, and that in Figure 26.2. The information in Figure 26.2 was derived from an N rate experiment in farmers' fields with different rotations, soil types and management practices, also in the Yaqui Valley (Ortiz-Monasterio and Naylor, unpublished data, 1997). Both sets of information show that the N requirement per tonne of grain yield increases at the higher yield levels. For instance, at the lower yield levels it takes approximately 20 kg N in the above-ground biomass to produce 1 tonne of grain yield, while at the higher yield levels it is approximately 30 kg N per tonne of grain yield. These values tend to be lower, even at the high yield levels, when compared to those reported for irrigated spring wheat areas in high-latitude environments such as Washington (40 kg N/tonne) and Montana (37 kg N/tonne) in the United States (Sanmaneechai *et al*., 1984; Christensen and Killorn, 1981). Some authors recommend estimating the N requirement based only on the N removal by the grain, given that in some situations most of the non-grain biomass will be returned to the soil. It has been discussed that in most areas of ME1 the straw is either removed or burned, therefore, both grain and straw are being considered. Farmers in the Yaqui Valley and other areas of ME1 tend to keep good grain yield records. The average grain yield from the last five wheat crops for a given field could be a reasonable yield goal to expect for the coming wheat cycle. The N requirement can then be estimated by using Table 26.1 and Figure 26.2 together with the yield goal.

The second step is to estimate the N contribution from the soil. Residual nitrate from the previous crop and the mineralization potential of the organic matter, with the use of soil tests, could provide a reasonable estimate of this value as has been recommended by some authors. On the other hand, it has been suggested by Meisinger (1984) that determining the N uptake of a field crop receiving no fertilizer is the most satisfactory method of estimating the soil N supply in a given soil-crop-climate system because it integrates the factors of crop growth and soil N dynamics under natural conditions. The disadvantage of this method is that the

FIGURE 26.2
Relationship between wheat grain yield and total above-ground nitrogen at maturity in farmers' fields, Yaqui Valley, Mexico



information is not available until the end of the crop cycle. However, if a reasonable estimate of grain yield without any fertilizer can be obtained, this could be used in conjunction with Table 26.1 and Figure 26.2 to estimate the soil N contribution.

The third step quantifies credits for manure, legume crops and irrigation nitrogen contributions.

The fourth step is to subtract the soil nitrogen, manure, legume and irrigation nitrogen contributions from the nitrogen requirement.

The fifth step is to select the expected N fertilizer recovery and divide the N requirement by the efficiency after having subtracted the different nitrogen contributions. This will result in the amount of fertilizer N needed to achieve the yield goal. Table 26.2 shows an example of these calculations.

Soil diagnostics

Problems with soil nitrate tests, particularly in high-rainfall environments, have for a long time been recognized. Nitrate is a very mobile and dynamic nutrient, which is greatly affected by soil properties, climate of the area, irrigation management, fertilizer source, application method and tillage practice among other factors. On the other hand, Aldrich (1980) and Hergert (1987) reported that soil nitrate-nitrogen tests can be used effectively for improving N fertilizer recommendations and are heavily used in irrigated areas of the United States to estimate carry-over nitrate-N that may not have been used by the previous crop. Others have tried to further improve the usefulness of nitrogen tests by also measuring ammonium-N in the soil (Keeney, 1982; Stanford, 1982). However, irrigated systems in the developing world tend to have

TABLE 26.2
Example of nitrogen budget

$$\text{N Rate} = \frac{\text{N requirement} - \text{N contributions}}{\text{N fertilizer efficiency}}$$

Calculation	Example
Realistic yield goal (5.5 tonnes/ha)	120 kg N (from Figure 26.2, nitrogen requirement)[b]
Soil N contribution (2.5 tonnes/ha)[a]	- 50 kg N (from Figure 26.2, nitrogen requirement)[b]
Contribution from manure	0
Contribution from legume rotation	0
Contribution from irrigation water	0
N requirement after N contributions	70 kg N
Efficiency of fertilizer use:	N to be supplied as fertilizer in kg N/ha
70 kg N/ 35% efficiency	200
70 kg N/ 45% efficiency	156
70 kg N/ 65% efficiency	108

[a]Yield expected without N fertilizer is used as an estimation of the N supplying capacity of the soil.
[b]This value is the kg N/ha in the above-ground biomass for the given grain yield level.

favourable soil temperature and moisture levels for nitrification, which can quickly convert ammonium into nitrate. Matson *et al*. (1998), working in the Yaqui Valley in an irrigated spring wheat crop, found that urea was rapidly hydrolysed to ammonium within three to four days after an irrigation, and within 15 days most of the ammonium was converted to nitrate. Ammonium values remained very low through the crop cycle unless additional ammonium-forming fertilizers were applied, which again were rapidly converted to nitrate. This showed that the nitrogen nutrition of wheat in this environment was dominantly in the form of nitrate. Another approach towards improving the assessment of N coming from the soil has been to try to measure not only the currently available mineral soil N but also the potentially mineralizable N (Groot and Houba, 1995). Preliminary results have shown that nitrate values after aerobic incubations correlate better with wheat grain yield than pre-incubation nitrate values in the Yaqui Valley (Ortiz-Monasterio *et al*., unpublished data, 1998). Nitrate soil tests in irrigated wheat systems in developing countries are rarely used, and although they have their limitations, nitrate soil tests can clearly be a step forward towards improving nitrogen-use efficiency in these systems.

Plant and other diagnostics

It has been suggested that periodic plant tissue nitrogen tests are particularly helpful in fine-tuning nitrogen applications under irrigated conditions. Knowles *et al*. (1991) concluded that the use of mid-season basal stem nitrate values in conjunction with a pre-plant soil test can successfully be used for intensive N management of irrigated spring wheat. They identified deficiency, sufficiency and excessive values for basal stem nitrate at different stages of development to aid in identifying N rates of application. On the other hand, they suggest that exact N application rates at each of the defined stem nitrate-N ranges require local calibration. Similar strategies using basal stem nitrate have been used by other researchers (Gardner and Jackson, 1976; Papastylianou *et al*., 1982). Other methodologies that also use the plant as the indicator of N needs are being proposed. This is the case of the chlorophyll SPAD meters, which have also been proposed as a diagnostic tool to manage nitrogen in irrigated crops, particularly in maize (Schepers *et al*., 1992).

A new level of precision in targetting N applications is evolving under the name of 'precision farming'. This technology, which uses sophisticated computer equipment together with global positions systems (GPS), geographic information systems (GIS), grain yield monitors and variable rate application equipment for fertilizer applications, promises to make significant improvement in nutrient management. Particularly interesting are the use of sensors measuring the normalized difference vegetative index (NDVI), which have been applied successfully to treat N deficiency in the field at a scale of 1 m^2 in winter wheat (Stone *et al*., 1996). Others have looked at crop models as a tool to diagnose and better understand N requirements in crops including wheat. With simulation models, it is possible to calculate, on a daily basis, the availability of N to the crop and the nitrogen uptake and growth of the crop using average or actual weather data and soil, crop and field parameters as inputs. Unlike the other diagnostic methods, simulation models can estimate the environmental side effects of nitrogen fertilizer applications. On the other hand, these models aim primarily at obtaining a better understanding of processes in soil-crop systems (Neeteson, 1995). It would require a great deal of simplification of these models before they could be used by extension agents or farmers as diagnostic tools in developing countries.

One of the most important contributions that agronomic research can make towards improving the nitrogen-use efficiency in irrigated wheat is the development of appropriate diagnostic tests that could help the farmer identify the correct N rate.

Timing

Should be done to coincide with the periods of highest nitrogen demand

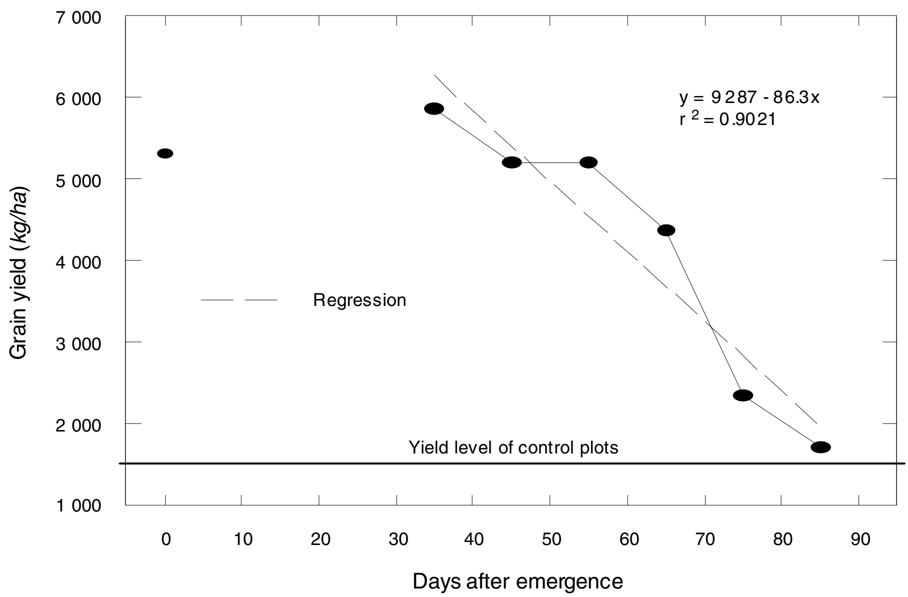
To be able to match supply with demand, it is important to identify the periods of high N requirement. This has been documented by Doerge *et al*. (1991) where they show that N uptake in irrigated spring wheat proceeds very slowly until tillering begins, and in addition, the N flux (kg N/ha/day) increases to a maximum during the jointing stage. This points at Zadoks 31 (Zadoks *et al*., 1974) or Feekes 6 (Large, 1954), beginning of stem elongation, as the start of rapid N uptake by the wheat crop. On the other hand, nitrogen management in irrigated agriculture should not only consider crop demand but also the specific irrigation schedule that is followed.

In order to match the time of high N demand with N availability (which occurs several weeks after planting), several strategies could be tested: the use of nitrification inhibitors, urease inhibitors, slow release fertilizer, split applications or delayed application.

Delayed nitrogen applications

Delayed N applications (where all the N is applied close to Z31) have produced very interesting results compared to N applications at planting. It has been found that even when the wheat crop has been severely nitrogen stressed early in the crop cycle, breaking the stress with a delayed N application by Z31 results in higher N recoveries; these often translate into higher yields and consistently produce higher protein concentration in the grain (Fischer *et al*., 1993; Ortiz-Monasterio *et al*., 1994), less lodging (Hobbs *et al*., 1998) and lower incidence of the disease Karnal bunt, *Tilletia indica* (syn. *Neovossia indica*) (Ortiz-Monasterio *et al*., 1993). A recent worldwide study (including ten countries) lead by the International Atomic Energy Agency (IAEA) in collaboration with CIMMYT and the International Fertilizer Development Center (IFDC) evaluated the effect of N timing application in a five-year study using ^{15}N techniques (IAEA, 2000). This study compared Z31 nitrogen applications in irrigated wheat systems with applications at planting. They concluded that

FIGURE 26.3
Effect on wheat yield of delaying a single dose of 150 kg N/ha from planting to 85 days after emergence, in a plot with low residual soil nitrogen after a crop of unfertilized maize



in nine of the ten countries where the study took place N recoveries were higher at Z31 stage than at planting.

Split nitrogen applications

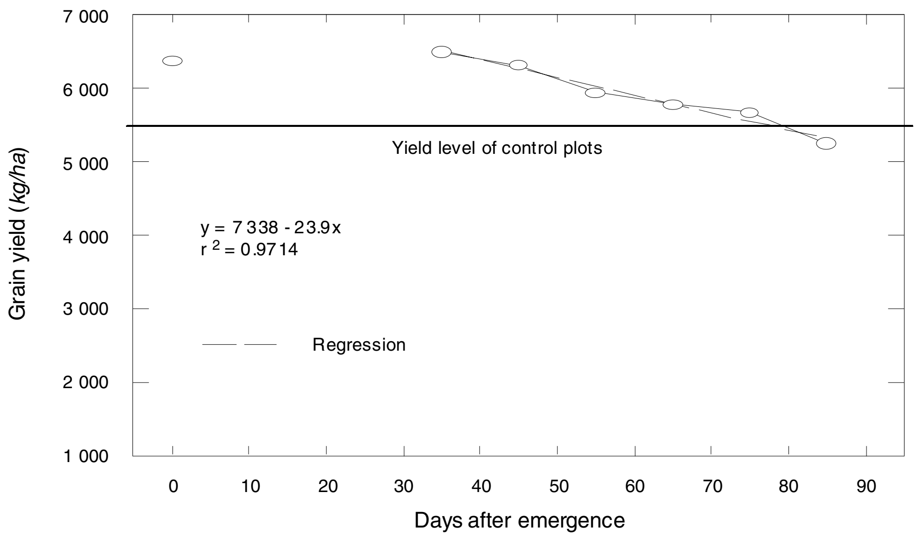
Split applications with some of the N applied at planting and most of the N applied at Z31 has generally resulted in higher yields than applications of all nitrogen at planting or Z31. Although N applications are more efficient at Z31 than at planting, it appears that some nitrogen needs to be supplied early in the crop cycle, particularly when the soil is highly N deficient.

In a study over four environments comparing N applications at planting, delayed applications at Z31 (where all nitrogen was applied at that stage) and split applications (where one-third of the total rate was applied at planting and the other two-thirds at Z31), it was shown that the split application resulted in higher grain yield and higher apparent N recovery than the Z31 delayed or the planting application. Furthermore, it was found that a three-way split with one-third at planting, one-third at Z31 and one-third at Z37 resulted in the same grain yield as the one-third at planting and two-thirds at Z31 when the last application in the three-way split was given at stage of development Z37 (flag leaf just visible) or 54 days after emergence under Yaqui Valley conditions (Ortiz-Monasterio *et al.*, 1994). These experiments were carried out in heavy clay soils. It is expected that in lighter textured soils, with potentially higher leaching problems, the three- or four-way split could be more efficient than the two-way split.

Critical times of nitrogen application for grain yield and protein

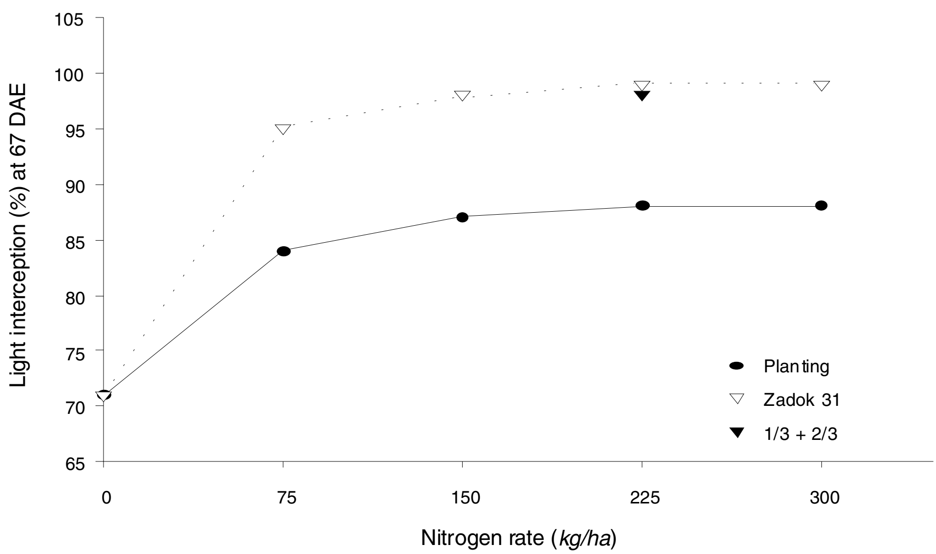
In another study also over four environments, it was shown that in a three-way split N

FIGURE 26.4
Effect on wheat yield of delaying a single dose of 150 kg N/ha from planting to 85 days after emergence, in a plot with high residual soil nitrogen after a crop of Sesbania *spp. green manure*



application, one-third at planting, one-third at Z31 and one-third at Z47 where the last N split was given at stage Z47 (flag leaf sheath opening) or 64 days after emergence under Yaqui Valley conditions, grain yield and N recovery declined compared to the one-third at planting and two-thirds at Z31 application (Ortiz-Monasterio *et al*., unpublished data, 1995). These data suggest that N applications given closer to anthesis (about 85 days after emergence in the Yaqui Valley) than to Z31 may not be as efficient at increasing grain yield. This was confirmed in another study that showed a linear reduction in grain yield when single N applications were given after stage Z31 at ten-day intervals. This was observed under low as well as high residual soil N conditions (Ortiz-Monasterio *et al*., unpublished data, 1995). Figure 26.3 and Figure 26.4 show a linear reduction in the response to grain yield to a single application of 150 kg N/ha at ten-day intervals between 35 and 85 days after emergence. The horizontal line in both Figures represents the yield level of the control plots that did not receive N fertilizer. In these studies, as well as others in the Yaqui Valley, there has been a limited or no grain yield response to N applications around the time of anthesis. Other experiments also in irrigated spring wheat have found a great deal of variability in grain yield response to N applications at anthesis. Wuest and Cassman (1992) reported the results of four experiments in irrigated spring wheat where N was applied at planting and at anthesis. In two of the experiments, there was no grain yield response to N application at anthesis, while in all four experiments there was an increase in protein concentration in the grain. They concluded that early-season N applications should be managed to optimize grain yield, but that excess N applications at this time reduce the N partitioning efficiency to the grain, whereas

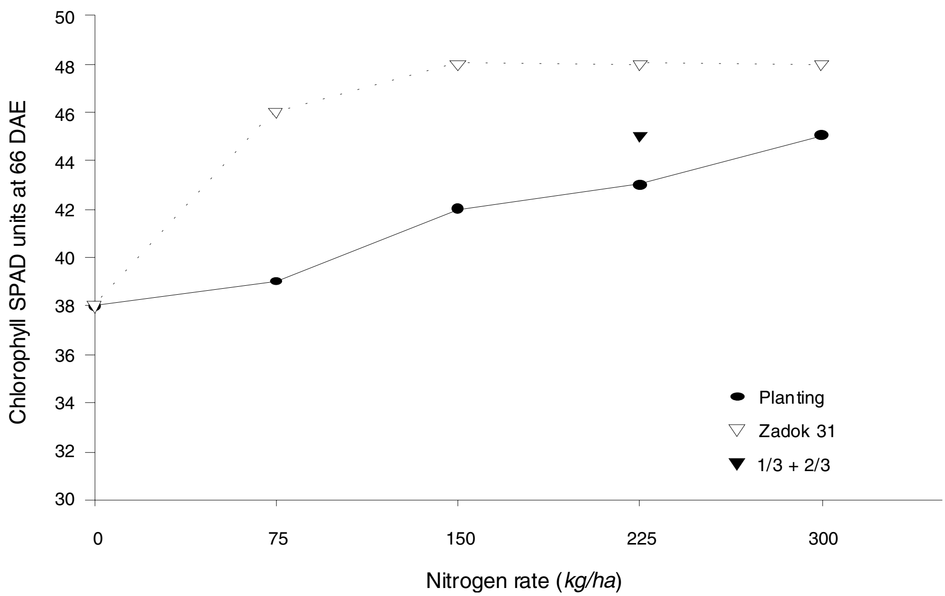
FIGURE 26.5
Percent light interception in a wheat canopy at 67 days after emergence (DAE) with different timings and rates of nitrogen application



the anthesis N applications can be adjusted to increase grain protein levels without reducing the N partitioning efficiency to the grain. Tindall *et al*. (1995) evaluated N top dress applications at the beginning of heading in irrigated hard red spring wheat in a three-year study. A grain yield response occurred only in one of the three years. In contrast, there was an increase in protein concentration in all three years. These studies show an inconsistent response to grain yield with N applications at heading, but a consistent response to grain protein. This suggests that N applications close to or at heading should be avoided as a way to increase grain yield and instead these should be used as a way to increase grain protein. On the other hand, most of the nitrogen should be applied around Z31 as a way to maximize grain yield and should not be delayed beyond Z37, except perhaps in sandy soils.

Timing of nitrogen applications should also consider the planting method, equipment available to the farmer and irrigation management. Nitrogen applications should be scheduled to coincide with the irrigation events to ensure incorporation (in the case of urea that has not been incorporated mechanically) and availability of N to the plant. When wheat is planted in the bed systems (described in chapter "Management of irrigated wheat"), there is easy access to the field around stage of development Z31, allowing nitrogen applications at this time. In this bed-planting system, nitrogen applications at Z31 and cultivation for weed control can be done simultaneously to reduce the number of field operations. In small farms, such as some of the irrigated areas of the Indian subcontinent, farmers can walk into the field and make broadcast fertilizer applications by hand at the critical stages.

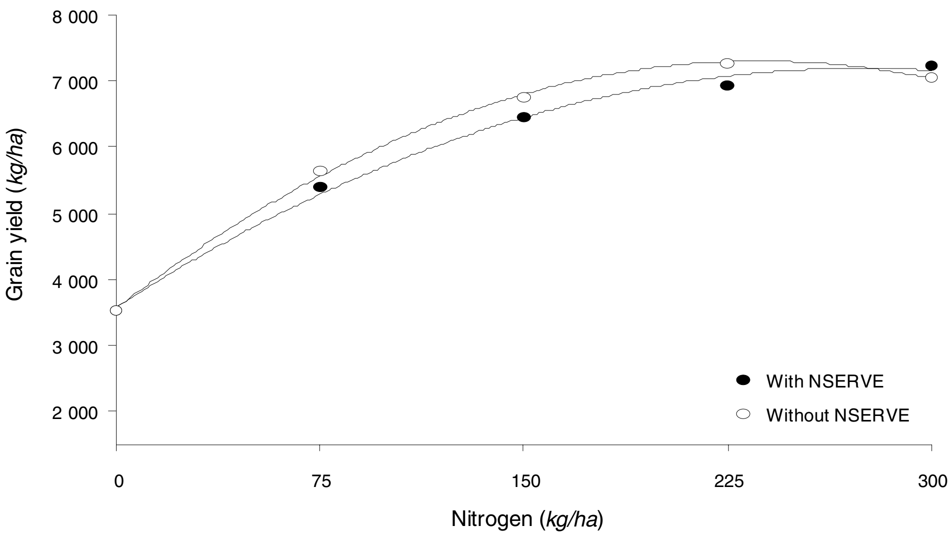
FIGURE 26.6
Chlorophyll SPAD units in a wheat crop at 66 days after emergence (DAE) with different timings and rates of nitrogen application



Physiological aspect of timing of nitrogen application for grain yield
Nitrogen deficiency in the wheat crop mainly affects: (i) leaf expansion (leaf area = light interception); and (ii) nitrogen concentration (chlorophyll concentration = radiation-use efficiency). It is interesting to point out that under conditions of low initial soil nitrogen, the treatments of a delayed single nitrogen application at Z31 did not reach full light interception before the onset of rapid spike growth, thought to be critical for attaining maximum grain yield in irrigated conditions (Figure 26.5). On the other hand, the chlorophyll content of the leaves in the delayed single application at Z31 was significantly higher. This suggests a higher radiation-use efficiency that not only compensated for the lack of light interception, but was sufficiently high to result in a higher grain yield than the treatments where all the nitrogen was applied at planting, which reached close to full light interception by the onset of rapid spike growth (Figure 26.6). The treatment of one-third at planting and two-thirds at Z31 was able to reach close to full light interception by the onset of rapid spike growth, thanks to the nitrogen applied at planting. In addition, this treatment was able to accumulate higher levels of chlorophyll in the leaves compared to the treatment of all nitrogen applied at planting, presumably increasing the radiation-use efficiency. The challenge seems to be to identify the optimum rate of N to be applied at planting and later at Z31 that will result in the ideal combination of light interception (LAI) and chlorophyll content in the leaves.

Nitrification inhibitors
Nelson and Huber (1988) reviewed the

FIGURE 26.7
Response of spring wheat to increasing levels of nitrogen fertilizer with and without NSERVE 24



literature on the use of nitrification inhibitors; he found great variability in the effectiveness of these products. He concluded that the greatest potential for benefits are with soils that are poorly to moderately or imperfectly drained. However, he suggested that even more likely to benefit are coarse-textured soils (sands) than fine-textured soils, since the nitrification inhibitor will reduce the potential for leaching that exists with such soils. Studies with the use of NSERVE 24 (a.i., nitrapyrin) mixed with urea and anhydrous ammonia (AA) have not shown any improvement in nitrogen-use efficiency in wheat in clay soils of the Yaqui Valley (Figure 26.7) (Ortiz-Monasterio *et al.*, unpublished data, 1996). The author speculates that the relatively high-maximum soil temperatures (0 to 5 cm) at the time of planting (late November, 29° to 33°C and early December, 24° to 30°C) may have resulted in high volatilization of the product.

Sources

Should correspond to the time and method of application that will result in the lowest possible losses

A three-year study coordinated by the International Atomic Energy Agency evaluated several solid sources of N fertilizer (sodium nitrate, ammonium nitrate and urea) in wheat in 12 different countries. They concluded that the effectiveness of the three sources was remarkably similar except for a few cases (IAEA, 1974). Studies in the Yaqui Valley that evaluated ammonium sulphate, potassium nitrate and urea use for several seasons in heavy clay soils showed no difference in wheat grain yield associated with the source of nitrogen (Ortiz-Monasterio, unpublished data, 1993). Similarly, in light-textured soils Knowles *et al.* (1991) did not find grain yield differences between ammonium nitrate, urea and calcium nitrate. However, the studies showed the importance of selecting immobile ammonium forms of N fertilizer early in the season to reduce leaching due to the mobility of urea and nitrate fertilizers in irrigated wheat systems. Halvorson *et al.* (1987) reported that in the humid wheat-producing areas of the United States urea, AA, urea-ammonium nitrate (UAN) solutions or ammonium sulphate were generally rated as being equal.

Urea

Urea is the most widely used nitrogen fertilizer in developing countries. However, when surface applied it should be incorporated as soon after application as possible to reduce losses by volatilization and/or runoff. Meisinger and Randal (1991) have listed the conditions that favour volatilization, which should be avoided whenever possible. These are: surface applications, soil pH above 7, little or no rain within seven days, low cation exchange capacity (CEC) soils (less than 10 meq/10 g), more than 50 percent surface residue cover (zero-tillage, etc.) and weather conditions favouring drying.

Anhydrous ammonia

Anhydrous ammonia is the main source of nitrogen in the wheat irrigated systems of the Yaqui Valley, mainly because of its lower cost compared to all other N sources. Typically, there are two ways in which AA is applied in wheat in the Yaqui Valley. One way is to inject the AA into the soil before planting and the other is to apply it with the irrigation water approximately 40 to 50 days after planting.

Parr and Papendik (1966) suggest the following guidelines to minimize losses of AA application to the soil:

- Select proper depth of application. This is especially important in sandy soils when losses can be markedly decreased by increased depth of application. The recommended depths of application vary between 12 to 24 cm below the soil surface.
- Select proper soil moisture and soil physical conditions to ensure rapid and complete closure of the injection channel. Properly designed equipment and use of moderate speeds also help to ensure channel closure.
- Space applicator knives properly to ensure a maximum efficiency of retention (i.e. sorption and reaction) of ammonia by soil.

Other technologies have been considered toward further improving the efficiency of injecting AA into the soil. One of these is the use of cold AA (-32° to -34°C) during applications to maintain the liquid state for prolonged periods and potentially reduce losses. The benefits of this system compared with conventional equipment are still being debated (Achorn and Broder, 1984).

In this chapter, the application of AA in irrigation water will focus on furrow-irrigated systems given that trickle or sprinkler irrigation are rarely used in spring wheat systems in developing countries. Warnock (1966) and Denmead *et al.* (1982) suggest the following guidelines to minimize losses of AA application during irrigation:

- Irrigate on cool, humid, quiet days (no wind) or at night when volatilization losses tend to be 50 percent of those observed during the day.
- Maintain a concentration of not over 110 ppm of ammonia.
- Keep the exposed surface of flowing water to a minimum by reducing the turbulence of the water and by using narrow, deep ditches.

During the application of AA, the pH of the water can increase to high levels. High pH in the water during application may result in two problems:

- Nitrogen losses from ammonia volatilization can exceed 50 percent when AA is applied in alkaline irrigation water.
- Precipitation of some of the calcium (Ca) and magnesium (Mg) in irrigation water with high bicarbonate content (HCO_3) can occur. The precipitation of Ca and Mg can result in water with a higher sodium absorption ratio (SAR) and the hazard of increased exchangeable sodium percentage (ESP).

In addition, volatilization losses may result in very uneven applications of N. Denmead *et al*. (1982) reported that the N content of the irrigation water decreased by 84 percent over a distance of 400 m along the furrow. Furthermore, the mineral N content in the top 10 cm of soil one week after application was significantly less at the end of the 400 m run compared with the head of the furrows.

To reduce this and other water quality problems, sulphuric acid can be added to the irrigation water to neutralize bicarbonate and/or counteract the alkalinity produced by ammonia additions. Moreover, the sulphuric acid changes sodium bicarbonate to less harmful sodium sulphate (Doerge *et al*., 1991; Brady and Weil, 1996).

The Yaqui Valley seems to be the only spring wheat irrigated area in the developing world where there is extensive use of AA. Although AA tends to be less expensive than urea, its use in developing countries is limited by the lack of pressurized equipment and the safety risks associated with its management.

Placement

Use a method that will place nitrogen in the zone of maximum uptake

Three main types of fertilizer application methods used in irrigated systems are: (i) broadcast; (ii) band; and (iii) in the irrigation water. Nitrogen fertilizer application is usually avoided during planting because of the need to separate the placement of the seed and the N fertilizer (Strong, 1995). A number of studies have shown a delay in germination or a stand reduction when the seed and N fertilizer are placed together (Brage *et al*., 1960; Radford *et al*., 1989). Therefore, it is suggested that only low rates of N be applied together with the seed to avoid risk of seedling damage from ammonia toxicity. A study by the IAEA (1974) evaluated the use of 20 kg N/ha as ammonium nitrate together with the seed versus side-banding the fertilizer below the seed. They found no differences between both methods in N uptake or yield. Doerge *et al*. (1991) recommend no more than 34 kg N/ha acre as urea of diamonium phosphate for irrigated wheat in Arizona, United States. Anhydrous or aqua ammonia should be injected 15 to 23 m below the soil surface prior to planting and should never be placed near the seed zone. In the bed-planting systems, there is the possibility of either broadcasting or banding an N top dress in the furrows. CIMMYT experiments have compared both methods, and no difference was found in grain yield when an irrigation is applied the same day of the N application. Also in the bed-planting systems, it was possible to apply up to 180 kg N/ha as AA to the soil in the furrows at the mid-tillering period without any toxic effect on the wheat crop (Ortiz-Monasterio *et al*., 1996a).

ENVIRONMENTAL ASPECTS OF NITROGEN USE IN IRRIGATED WHEAT

Globally, agricultural activities have had a major impact on the nitrogen cycle. Nitrogen fertilizer production and planting of leguminous crops fix more N globally than do all natural ecosystems (Vitousek and Matson, 1993). The environmental consequences of nitrogen fertilizer use in irrigated cropping systems has mostly focused on the issue of nitrate leaching and water quality (CAST, 1985; Keeney, 1982). High nitrate concentrations in drinking water represent a human health concern, causing methamoglobinemia (Aldrich, 1980). Nitrate also influences the health of natural systems. Eutrophication of estuaries and other coastal marine environments can cause low or no oxygen conditions in stratified waters, leading to loss of fish and shellfish resources and to blooms of nuisance algae and organisms that are toxic to fish (Howarth *et al*., 1996).

Nitrogen fertilizer use also results in the emission of N gases to the atmosphere, nitrous oxide (N_2O), nitric oxide (NO), ammonia (NH_3) and dinitrogen (N_2). The first three have a negative impact on the environment. Nitrous oxide, which has an effect at a global level, absorbs infrared radiation and thus contributes to greenhouse warming. In addition, it also participates in the depletion of the stratospheric ozone layer (Granli and Bockman, 1994). Nitric oxide plays a role more at a regional scale, where it reacts to form tropospheric ozone, a major atmospheric pollutant that affects human health as well as the health of agricultural crops and natural ecosystems. Chameides *et al*. (1994) suggest that as much as 35 percent of cereal crops worldwide may be exposed to damaging levels of ozone. Moreover, nitric oxide is a precursor to nitric acid, a principal component of acid deposition, and together with ammonia, also emitted from agricultural systems, may be transported and deposited in gaseous or solution forms to downwind terrestrial and aquatic ecosystems (Matson *et al*., 1997). This deposition constitutes, in effect, inadvertent fertilization and can lead to acidification, eutrophication, shifts in species diversity and effects on predator and parasite systems (Vitousek *et al*., 1997). Recent research has shown that intensively managed wheat irrigated systems in the Yaqui Valley have lead to extremely high fluxes of nitrous oxide and nitric oxide following the typical farmer's practice compared to other agricultural areas. On the other hand, it was shown that by using alternative practices, which changed rate and timing of N application, the emissions of these two gases could be reduced by more than 50 percent without a reduction in grain yield or quality (Matson *et al*. 1998; Ortiz-Monasterio *et al*., 1996b). In the future, it is projected that most of the N fertilizer will be used in the developing world. There is very little information available about the consequences of N use in these countries. While ways to increase productivity and efficiency of N use are being developed, the environmental consequences of the resulting practices need to be considered. This will allow reconciliation between increased world food production and greater protection of the environment (Matson *et al*., 1997).

CONCLUDING REMARKS

There is currently information available on practices that can potentially improve the efficiency of N fertilizer use in irrigated wheat areas in developing countries. Some of this information could be transferred readily to different regions of the world, such as better synchronization of nitrogen supply and demand. This was demonstrated with the IAEA project, which showed better efficiency of time of N applications at Z31 compared to applications at planting in nine out of ten countries where the study took place. Other information will require local calibration to include soil and plant tissue tests. The fact that blanket fertilizer N applications are customarily used in these areas suggests that there are good opportunities for improving N-use efficiency by the identification of the proper N rate at the individual field level. A refinement over blanket recommendations could take into account previous management and soil types. Thus, instead of having one recommendation for one region, there could be three or five that could take into account soil type and/or rotation. A further level of refinement could be achieved with the use of appropriate soil and plant tissue test diagnostics that are taken during the critical stages of development. This would allow the identification of N recommendations for site- and season-specific conditions that together with the information available on timing, sources and placement would result in significant improvements in N-use efficiency. Given that most of the ME1 wheat systems have a high dependency on inorganic fertilizers, the feasibility of a more integrated approach to nutrient management should be explored. In India, for instance, the intensive rice-wheat systems of the Punjab are beginning to show signs of serious decline associated with loss of soil quality and increased plant health problems (Nambiar, 1994). Improvements in

N use should result in higher yields with the same rate of N fertilizer use or the same yield with less N applied, therefore increasing farm income. This in turn translates into less N lost to the environment, resulting in a win-win situation that will improve the efficiency of N use and minimize the environmental consequences.

REFERENCES

Achorn, F.P. & Broder, M.F. 1984. Mechanics of applying nitrogen fertilizer. *In* R.D. Hauch, ed. *Nitrogen in crop production*, p. 475-491. Madison, WI, USA, ASA, CSSA, SSSA.

Aldrich, S.R. 1980. *Nitrogen in relation to food, environment and energy*. Special Publication 61. Illinois Agricultural Experiment Station.

Austin, R.B., Ford, M.A., Morgan, C.L. & Yeoman, D. 1993. Old and modern wheat cultivars compared to broadbalk wheat experiment. *Eur. J. Agron.*, 2(2): 141-147.

Brady, N.C. & Weil, R.R. 1996. *The nature and properties of soils*, 11th ed., p. 740. Upper Saddle River, NJ, USA, Prentice.

Brage, B.L., Zich, W.R. & Fine, L.O. 1960. The germination of small grain and corn as influenced by urea and other nitrogenous fertilizers. *Soil Sci. Soc. Am. Proc.*, 24: 294-296.

Bock, B.R. 1984. Efficient use of nitrogen in cropping systems. *In* R.D. Hauch, ed. *Nitrogen in crop production*, p. 273-293. Madison, WI, USA, ASA, CSSA, SSSA.

Bock, B.R. & Hergert, W. 1991. Fertilizer nitrogen management. *In* H. Follet *et al.*, eds. *Managing nitrogen for groundwater quality and farm profitability*, p. 140-164. Madison, WI, USA, SSSA.

Byerlee, D. 1996. Modern varieties, productivity, and sustainability: recent experience and emerging challenges. *World Devel.*, 24-4: 697-718.

Byerlee, D. & Moya, P. 1993. *Impacts of international wheat breeding research in the developing world, 1966-90*. Mexico, DF, CIMMYT.

Byerlee, D. & Siddiq, A. 1994. Has the green revolution been sustained? The quantitative impact of the seed-fertilizer revolution in Pakistan revisited. *World Devel.*, 22(9): 1345-1361.

CAST (Council for Agricultural Science and Technology). 1985. *Agricultural and ground-water quality*. Report No. 103. Ames, IA, Council for Agricultural Science and Technology.

Chameides, W.L., Kasibhatla, P.S., Yienger, J. & Levy, H. 1994. Growth of continental-scale metro-agro-plexes, regional ozone pollution, and world food production. *Science*, 264: 74-77.

Christensen, N.W. & Killorn, R.J. 1981. Wheat and barley growth and N fertilizer utilization under sprinkler irrigation. *Agron. J.*, 73: 307-312.

Denmead, O.T., Freney, J.R. & Simpson, J.R. 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. *Soil Sci. Soc. Am. J.*, 46: 149-155.

Dhugga, K.S. & Waines, J.G. 1989. Analysis of nitrogen accumulation and use in bread and durum wheat. *Crop Sci.*, 29: 1232-1239.

Doerge, T.A., Roth, R.L. & Gardner, B.R. 1991. *Nitrogen fertilizer management in Arizona*. Tucson, AZ, USA, Collage of Agriculture, The University of Arizona.

Entz, M.H. & Fowler, D.B. 1989. Response of winter wheat to N and water: growth, water use, yield and grain protein. *Plant Sci.*, 69: 1135-1147.

Fageria, N.K., Baligar, V.C. & Jones, C.A. 1997. *Growth and mineral nutrition of field crops*, 2nd ed., p. 624. New York, NY, USA, Marcel Dekker.

FAO. 1990. *Fertilizer yearbook 1990*. Rome.

Fischer, R.A., Howe, G.N. & Ibrahim, Z. 1993. Irrigated spring wheat and timing and amount of nitrogen fertilizer. I. Grain

Yield and protein content. *Field Crops Res.*, 33: 37-56.

Fujisaka, S., Harrington, L.W. & Hobbs, P.R. 1994. Rice-wheat in South Asia: System and long-term priorities established through diagnostic research. *Agric. Sys.*, 46: 169-187.

Galloway, J.N., Schlesinger, W.H., Levy, H., Michaels, A. & Schnoor, J.L. 1995. Nitrogen fixation - anthropogenic enhancement-environmental response. *Glob. Biogeochem. Cycl.*, 9: 235-252.

Gardner, B.R. & Jackson, E.B. 1976. Fertilization, nutrient composition and yield relationships in irrigated spring wheat. *Agron. J.*, 68: 75-78.

Granli, T. & Bockman, O.C. 1994. Nitrous oxide from agriculture. *Norw. J. Agric. Sci., Suppl. 12*.

Groot, J.J.R. & Houba, V.R.G. 1995. A comparison of different indices for nitrogen mineralization. *Biol. Fertil. Soils*, 19: 1-9.

Halvorson, A.D., Alley, M.M. & Murphy, L.S. 1987. Nutrient requirements and fertilizer use. *In* E.G. Heyne, ed. *Wheat and wheat improvement*, 2nd ed., *Agron. Monograph No. 13*, p. 347-383. Madison, WI, USA, ASA, CSSA, SSSA.

Hergert, W.G. 1987. Status of residual nitrate-nitrogen soil tests in the United States of America. *In* J.R. Brown, ed. *Soil testing: sampling, correlation, calibration, and interpretation. SSSA Special Publication Number 21*, p. 73-88. Madison, WI, USA.

Hobbs, P.R. & Morris, M. 1996. *Meeting south Asia's future food requirements from rice-wheat cropping systems: priority issues facing researchers in the post-green revolution era*. NRG Paper 96-01. Mexico, DF, CIMMYT.

Hobbs, P.R., Sayre, K.D. & Ortiz-Monasterio, J.I. 1998. *Increasing wheat yield sustainably through agronomic means*. NRG Paper 98-01. Mexico, DF, CIMMYT.

Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren, R., Caraco, N., Jordan, T., Berendse, D., Freney, J., Kudeyarov, V., Murdoch, P. & Zhu, Z.L. 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. *Biogeochemistry*, 35(1): 75-139.

IAEA (International Atomic Energy Agency). 1974. *Isotope studies on wheat fertilization*. Technical Report Series No. 157. Vienna. 99 pp.

IAEA. 2000. *Optimizing nitrogen fertilizer application to irrigated wheat*. Results of a co-ordinated research project organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture 1994-1998. IAEA-TECDOC-1164. Vienna. 245 pp.

Jain, N.K., Krantz, B.A., Bains, K.B., Bhardwaj, R.B.L., Bhattacharya, S., Gill, G.S., Gupta, K.P., Moolani, M.K., Morabad, I.R., Patel, U.J., Reddy, M.K., Sandhu, K.S., Sharma, A.K., Sharma, K.C., Shekhawat, G.S., Singh, M., Singh, R.R., Srivastava, M.M.P. & Wright, B.C. 1975. Response of dwarf wheat varieties to nitrogen. *In* A.M. Wadhwani & R. Singh, eds. *Agronomy of Dwarf Wheats - Summary of Investigations of the All-India Co-ordinated Wheat Improvement Project*, p. 11-23. New Delhi, Indian Council of Agricultural Research.

Keeney, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution.. *In* F.J. Stevenson, ed. *Nitrogen in agricultural soils. Agron. Monograph No. 22*, p. 605-649. Madison, WI, USA, ASA, CSSA, SSSA.

Knowles, T.C., Doerge, T.A. & Ottman, M.J. 1991. Improved nitrogen management in irrigated durum wheat using steam nitrate analysis. I. Nitrate uptake dynamics. *Agron. J.*, 83: 346-352.

Large, E.C. 1954. Growth scales in cereals. Illustrations of the Feekes Scale. *Plant Pathol.*, 3: 128-129.

Matson, P.A., Parton, W.J., Power, A.G. & Swift, M. 1997. Agricultural intensification and ecosystem properties. *Science*, 277: 504-509.

Matson, P.A., Naylor, R. & Ortiz-Monasterio, I. 1998. Integration of environmental, agronomic and economic aspects of fertilizer management. *Science*, 280: 112-115.

Meisinger, J.J. 1984. Plant available N in soil-crop systems. *In* R.H. Hauck, ed. *Nitrogen in crop production*, p. 391-416. Madison, WI, USA, ASA, CSSA, SSSA.

Meisinger, J.J. & Randal, G.W. 1991. Estimating nitrogen budgets for soil-crop systems. *In* H. Follet *et al.*, eds. *Managing nitrogen for groundwater quality and farm profitability*, p. 85-124. Madison, WI, USA, SSSA.

Meisner, C.A., Acevedo, E., Flores, D., Sayre, K.D., Ortiz-Monasterio, I. & Byerlee, D. 1992. *Wheat production and growers practices in the Yaqui Valley, Sonora, Mexico*. Special Wheat Report No. 6. Mexico DF, CIMMYT.

Moll, R.H., Kamprath, E.J. & Jackson, W.A. 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agron. J.*, 74: 562-564.

Nambiar, K.K.M. 1994. Yield sustainability of rice-rice and rice-wheat systems under long-term fertilizer use. In *Resource management for sustained crop productivity*, p. 266-269. New Delhi, Indian Society of Agronomy.

Neeteson, J.J. 1995. Nitrogen management for intensively grown arable crops and field vegetables. *In* P.E. Bacon, ed. *Nitrogen fertilization in the environment*, p. 295-325. New York, NY, USA, Marcel Dekker.

Nelson, D.W. & Huber, D.H. 1988. Nitrification inhibitors for corn production. In *National corn handbook, crop fertilization NCH-55*. Urbana-Champaign, IL, USA, Cooperative Extension Service, University of Illinois.

Ortiz-Monasterio, R., J.I., Sayre, K.D., Fuentes Davila, G., Camacho, M. & Moreno, O. 1993. Algunas practicas agronomicas relacionadas con la incidencia de carbon parcial (*Neovossia indica*). In *Taller sobre las estrategias para el control del carbon parcial del trigo (*Neovossia indica*) en el estado de Sonora*, p. 47-58. Ciudad Obregon, Sonora, Mexico, CIRNO-Campo Experimental Valle del Yaqui.

Ortiz-Monasterio, R., J.I., Sayre, K.D., Pena, J. & Fischer, R.A. 1994. Improving the nitrogen use efficiency of irrigated spring wheat in the Yaqui Valley of Mexico. *15th World Cong. Soil Science*, vol. 5b: 348-349.

Ortiz-Monasterio, R., J.I., Huber, D. & Castellarin, J. 1996a. Metodos y dosis de inyeccion de NH_3 al suelo en un cultivo de trigo (*Triticum turgidum* L. var. *durum*) establecido. *In* V. Ordaz Chaparro, G. Alcantar Gonzalez & C. Castro Barrales, eds. *La Investigacion Edafologica en Mexico 1995-1996. Memorias del XXVII Congreso Nacional de la Ciencia del Suelo*, Ciudad Obregon, Sonora, Mexico. Ciudad Obregon, Sonora, Mexico, Sociedad Mexicana de la Ciencia del Suelo. 195 pp.

Ortiz-Monasterio, R., J.I., Matson, P.A., Panek, J. & Naylor, R.L. 1996b. Nitrogen fertilizer management: consequences for N_2O and NO emissions in Mexican irrigated wheat. In *Transactions 9th Nitrogen Workshop*, p. 531-534. Braunschweig, Germany, Technische Universitat Braunschweig.

Ortiz-Monasterio, R., J.I., Sayre, K.D., Rajaram, S. & McMahon, M. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four N rates. *Crop. Sci.*, 37(3): 898-904.

Papastylianou, I., Graham, R.D. & Puckridge, D.W. 1982. The diagnosis of nitrogen deficiency in wheat by means of a critical nitrate concentration in stem bases. *Commun. Soil Sci. Plant Anal.*, 13: 473-485.

Parr, J.F. & Papendick, R.I. 1966. Retention of ammonia in soils. *In* M.H. McVickar *et al.*, eds. *Agricultural anhydrous ammonia technology and use*, p. 213-236. Memphis, TE, USA, Madison, WI, USA, AAI, ASA, SSSA.

Radford, B.J., Strong, W.M. & Wildermuth, B.G. 1989. The effects of urea, and flutriafol on germination, coleoptile length and establishment of wheat and barley. *Aust. J. Exp. Agric.*, 29: 551-557.

Rajaram, S., van Ginkel, M. & Fischer, R.A. 1993. CIMMYT's wheat breeding mega-environments (ME). *In* Z.S. Li & Z.Y. Xin, eds. *Proc. 8th International Wheat Genetic Symp.*, 29-24 Jul. 1993. Beijing, China Agricultural Scientech.

Sadik, N. 1992. *The state of world population*. New York, NY, USA, United Nations Population Fund.

Sanmaneechai, M., Koehler, F.E. & Roberts, S. 1984. Nitrogen fertilization practices for sequential cropping of wheat, turnips, and sweet corn. *Soil Sci. Soc. Am. J.*, 48: 81-86.

Schepers, J.S. & Mosier, A.R. 1991. Accounting for nitrogen in nonequilibrium soil-crop-systems. *In* H. Follet *et al.*, eds. *Managing nitrogen for groundwater quality and farm profitability*, p. 85-124. Madison, WI, USA, SSSA.

Schepers, J.S., Blackmer, T.M. & Francis, D.D. 1992. Predicting N fertilizer needs for corn in humid regions: using chlorophyll meters. *In* B.R. Bock & K.R. Kelley, eds. *Predicting N fertilizer needs for corn in humid regions. Bull. Y-226*, p. 105-114. Muscle Shoals, AL, USA, National Fertilizer and Environmental Research Center.

Simmonds, N.W. 1979. *Principles of crop improvement*. New York, NY, USA, Longman. 361 pp.

Sims, J.T. 1995. Organic wastes as alternative nitrogen sources. *In* P.E. Bacon, ed. *Nitrogen fertilization in the environment*, p. 487-535. New York, NY, USA, Marcel Dekker.

Stanford, G. 1982. Assessment of soil nitrogen availability. *In* F.J. Stevenson, ed. *Nitrogen in agricultural soils. Agron. Monograph No. 22*, p. 651-649. Madison, WI, USA, ASA, CSSA, SSSA.

Stanford, G. & Legg, **J.O.** 1984. Nitrogen and yield potential. *In* R.H. Hauck, ed. *Nitrogen in crop production*, p. 263-272. Madison, WI, USA, ASA, CSSA, SSSA.

Stone, M.L., Solie, J.B., Raun, W.R., Whitney, R.W., Taylor, S.L. & Ringer, J.D. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Trans. ASAE*, 39: 1623-1631.

Strong, W.M. 1995. Nitrogen fertilization in upland crops and pastures. *In* P.E. Bacon, ed. *Nitrogen fertilization in the environment*, p. 129-170. New York, NY, USA, Marcel Dekker.

Tindall, T.A., Jeffrey, J.C. & Brooks, R.H. 1995. Irrigated spring wheat response to topdressed nitrogen as predicted by flag leaf nitrogen concentration. *J. Prod. Agric.*, 8: 46-52.

van Sanford, D.A. & MacKown, C.T. 1986. Variation in nitrogen use efficiency among soft red winter wheat genotypes. *Theor. Appl. Genet.*, 72: 158-163.

Vitousek, P.M. & Matson, P.A. 1993. Agriculture, the global nitrogen cycle, and trace gas flux. *In* R.S. Oremland, ed. *The biogeochemistry of global change: radiatively active trace gases*. New York, NY, USA, Chapman and Hall.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H. & Tilman, D.G. 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Appl.*, 7(3): 737-750.

Wall, P.C., McMahon, M.A. & Ransom, J.K. 1984. Do semidwarf wheats require more nitrogen than traditional tall varieties? In *Agronomy abstracts*, p. 45. Madison, WI, USA, ASA.

Warnock, R.E. 1966. Ammonia application in irrigation water. *In* M.H. McVickar *et al.*, eds. *Agricultural anhydrous ammonia technology and use*, p. 115-124. Memphis, TE, USA, Madison, WI, USA, AAI, ASA, SSSA.

Wuest, S.B. & Cassman, K.G.. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application. *Agron. J.*, 84(4): 682-688.

Zadoks, J.C., Chang ,T.T. & Konzak, C.F. 1974. A decimal code for growth stages of cereals. *Weed Res.*, 14: 415-421.