Agronomy Journal

Volume 91 May–June 1999 Number 3

REVIEW & INTERPRETATION

Improving Nitrogen Use Efficiency for Cereal Production

William R. Raun* and Gordon V. Johnson

ABSTRACT

Worldwide, nitrogen use efficiency (NUE) for cereal production (wheat, *Triticum aestivum* L.; corn, *Zea mays* L.; rice, *Oryza sativa* L. and *O. glaberrima* Steud.; barley, *Hordeum vulgare* L.; sorghum, *Sorghum bicolor* (L.) Moench; millet, *Pennisetum glaucum* (L.) R. Br.; oat, *Avena sativa* L.; and rye, *Secale cereale* L.) is approximately 33%. The unaccounted 67% represents a $15.9 billion annual loss of N fertilizer (assuming fertilizer–soil equilibrium). Loss of fertilizer N results from gaseous plant emission, soil denitrification, surface runoff, volatilization, and leaching. Increased cereal NUE is unlikely, unless a systems approach is implemented that uses varieties with high harvest index, incorporated NH_4–N fertilizer, application of prescribed rates consistent with in-field variability using sensor-based systems within production fields, low N rates applied at flowering, and forage production systems. Furthermore, increased cereal NUE must accompany increased yields needed to feed a growing world population that has yet to benefit from the promise of N_2–fixing cereal crops. The Consultative Group on International Agricultural Research (CGIAR) linked with advanced research programs at universities and research institutes is uniquely positioned to refine fertilizer N use in the world via the extension of improved NUE hybrids and cultivars and management practices in both the developed and developing world.

In 1996, a total of 82 906 340 Mg of fertilizer N was applied in the world, of which 11 184 400 was applied in the United States (FAO, 1996). Cereal production accounted for approximately 49 743 804 Mg of N fertilizer world-wide (60% of the total; Table 1) (Alexandratos, 1995, p. 190). Of that, only an estimated 16 572 232 Mg was removed in the grain (Dale, 1997; Tkachuk, 1977; Keeney, 1982) (Table 1). The world cereal grain NUE would therefore be estimated at 33% {NUE = [(total cereal N removed) − (N coming from the soil + N deposited in the rainfall)]/(fertilizer N applied to cereals)}, far less than the 50% generally reported (Hardy and Havelka, 1975). Similar results in NUE for West German agriculture would have been found, had they considered N derived from the soil (Keeney, 1982; van der Ploeg et al., 1997). Using the same references and assumptions in Table 1, cereal NUEs are 42 and 29% in developed and developing nations, respectively. Based on present fertilizer use, a 1% increase in the efficiency of N use for cereal production worldwide would lead to a $234 658 462 savings in N fertilizer costs (Table 1). An increase in NUE of 20% would result in a savings in excess of $4.7 billion per year.

Why Are Nitrogen Use Efficiencies So Low?

Not until recently have scientists documented that cereal plants release N from plant tissue, predominantly as NH_3 following anthesis (Harper et al., 1987; Francis et al., 1993). Plant N losses have accounted for 52 to 73% of the unaccounted N using ^{15}N in corn research (Francis et al., 1993), and between 21% (Harper et al., 1987) and 41% (Daigger et al., 1976) in winter wheat. Gaseous plant N loss in excess of 45 kg N ha^{-1} yr^{-1} has also been documented in soybean [*Glycine max* (L.) Merr.] (Stutte et al., 1979).

Reported gaseous N losses due to denitrification from applied fertilizer N include 9.5% in winter wheat (Aulakh et al., 1982), 10% in lowland rice (De Datta et al., 1991), and 10% (conventional tillage) to 22% (no-till) in corn (Hilton et al., 1994). Incorporation of straw and/or application of straw on the surface of zero-till plots can double denitrification losses (Aulakh et al., 1984).

Fertilizer N losses in surface runoff range between 1% (Blevins et al., 1996) and 13% (Chichester and Richardson, 1992) of the total N applied, and are generally lower under no-tillage. When urea fertilizers are applied to the surface without incorporation, losses of fertilizer N as NH_3 can exceed 40% (Fowler and Brydon, 1989; Hargrove et al., 1977), and generally greater with increasing temperature, soil pH, and surface residue.

When fertilizer N is applied at rates in excess of that needed for maximum yield in cereal crops, NO_3 leaching

---

Dep. of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078. Contribution from the Okla. Agric. Exp. Stn. Received 30 Sept. 1998. *Corresponding author (wrr@soilwater.agr.okstate.edu).

Published in Agron. J. 91:357–363 (1999).

Abbreviations: ATP, adenosine-5′-triphosphate; NUE, nitrogen use efficiency.

Table 1. World consumption of N fertilizers for cereal production, N removal in cereal grain, and estimated N use efficiency.

Commodities and computations	Amount	Variable
	Mg	
World fertilizer N consumption, 1996		
Total (FAO, 1996)	82 906 340	*A*
Cereal† (Alexandratos, 1995)	49 743 804	*B*
World cereal production, 1996 (FAO, 1996)		
Wheat	586 960 900	
Corn	590 417 900	
Rice	569 683 000	
Barley	156 148 100	
Sorghum	70 667 040	
Millet	28 857 320	
Oat	30 881 440	
Rye	23 022 100	
Total	2 056 637 800	*C*
World cereal grain N removal, 1996 (Dale, 1977; Tkachuk, 1977)‡§¶		
Wheat (N_{tot} = 21.3 g kg^{-1})	12 502 267	
Corn (N_{tot} = 12.6 g kg^{-1})	7 439 266	
Rice (N_{tot} = 12.3 g kg^{-1})	7 007 101	
Barley (N_{tot} = 20.2 g kg^{-1})	3 154 192	
Sorghum (N_{tot} = 19.2 g kg^{-1})	1 356 807	
Millet (N_{tot} = 20.1 g kg^{-1})	580 032	
Oats (N_{tot} = 19.3 g kg^{-1})	596 012	
Rye (N_{tot} = 22.1 g kg^{-1})	508 788	
Total	33 144 465	*D*
N removed in cereals coming from the soil and that deposited in rainfall, 1996 (Keeney, 1982)#	16 572 232	*E*
Nitrogen use efficiency		
Estimated NUE = $[(D - E)/B] \times 100$ = 33%		
N fertilizer savings per year for each 1% increase in NUE under constant yield = 489 892 Mg		
Value of fertilizer savings (assuming \$479 Mg^{-1} actual N) = \$234 658 462		

† World fertilizer N consumption for cereals is 60% of the total N consumed ($A \times 0.6$).

‡ World cereal grain N removal = total cereal production × %N = $C \times \%N$.

§ Cereal grain N values obtained from Dale (1977). Wheat: average of hard and soft wheat grain; corn: yellow grain; rice: rough grain; barley: grain; sorghum: sorghum, milo, grain; millet: grain; oat: grain; rye: grain.

¶ Total N values in g kg^{-1}: $N_{tot} = \%N \times 10$. Tkachuk's (1977) calculations of %N: crude protein was divided by 5.7 for wheat, barley, sorghum, millet, oat, and rye; by 6.25 for corn; and by 5.95 for rice.

N removed in cereals coming from the soil + N deposited in rainfall = 50% of total cereal grain N removed = $D \times 0.5$.

can be significant (Olson and Swallow, 1984; Raun and Johnson, 1995). In cooler temperate climates, NO_3 losses through tile drainage have approached 26 kg N ha^{-1} yr^{-1} under conventional tillage corn when only 115 kg N ha^{-1} was applied (Drury et al., 1996). Note, however, that because past N-balance work has failed to account for plant N losses, leaching losses attributed to unaccounted N have probably been overestimated (Francis et al., 1993; Kanampiu et al., 1997).

Many ^{15}N recovery experiments have reported losses of fertilizer N in cereal production from 20 to 50%. These losses have been attributed to the combined effects of denitrification, volatilization, and/or leaching (Francis et al., 1993; Olson and Swallow, 1984; Karlen et al., 1996; Wienhold et al., 1995; Sanchez and Blackmer, 1988) when these factors were not measured separately.

Using today's management practices, low NUEs in the world are compounded by both complacency and economics. Depending on the source of fertilizer, N costs approximately \$0.49 kg^{-1}. Applying an added 40 kg N ha^{-1} at planting when average cereal N rates are greater than 100 kg N ha^{-1} will cost less than \$20 ha^{-1}. This affordability combined with the convenience of not having to apply N again during the growing season is attractive to farmers. In this regard, excess N is applied as insurance, and because farmers often are overly optimistic concerning expected yields and yield goals (Schepers et al., 1991). Because of this, the affordability of N in the developed world has led to its misuse and overapplication. The same does not always hold true in the developing world, where access to fertilizer is limited (Hubbell, 1995), especially for subsistence farmers in remote areas. Their immediate goal is economic survival, not preservation of the environment (Campbell et al., 1995).

How Can Nitrogen Use Efficiencies Be Increased?

Production practices that have resulted in increased NUE relative to conventional or standard practices are those that will counter conditions, or environments, known to contribute to N loss from soil–plant systems.

Rotations

In irrigated or high-rainfall production regions, soybean–corn rotations have high NUE and can reduce the amount of residual N available for leaching when compared with continuous corn (Huang et al., 1996). Also, precipitation use efficiency is greater for corn grown in rotation than for continuous corn (Varvel, 1994). Unfortunately, rotations are not easily adopted by farmers who have become accustomed to monoculture production systems, since a new crop often requires purchase of additional equipment and learning to integrate new cultural practices. In irrigated agriculture, the use of high N rates as a substitute for more N-use-efficient rotation systems (such as corn–soybean) must be weighed against the increased potential for NO_3–N loss (Anderson et al., 1997).

Nitrogen use efficiency for wheat following legumes is greater than that for wheat following fallow or continuous wheat (Badaruddin and Meyer, 1994). Wheat–corn–fallow production systems are now promoted instead of the popular wheat–fallow where only 420 mm precipitation is received per year (Kolberg et al., 1996). The more intensive systems (growing more crops in a given period of time), require greater fertilizer N inputs but are higher in total yield and thus can be economically advantageous (Kolberg et al., 1996). More intensive dryland cropping systems lead to increased water use efficiency, and also better maintain soil quality (Halvorson and Reule, 1994). Alternative dryland systems proposed include spring barley, corn, and winter wheat grown in rotation with adequate N fertilization instead of continuous winter wheat–fallow (Halvorson and Reule, 1994).

Forage Production Systems

Forage-only production systems have lower plant gaseous N loss and improved NUE because the plant is never allowed to approach flowering where N losses have been found to be greater (Altom et al., 1996).

Averaged over 3 yr and two locations, forage-only NUEs for winter wheat were 77%, compared with 31% for grain-only when 90 kg N ha^{-1} yr^{-1} was applied preplant (Thomason, 1998). Total N removed in the forage-only production system was nearly double that found in grain, averaging 104 and 59 kg N ha^{-1}, respectively (Thomason, 1998). Similarly, calculated NUEs for forage (silage) production in corn exceeded 70% and were greater than that reported for grain (O'Leary and Rehm, 1990). Note, however, that substitution of forage for grain will ultimately place greater dependency on animal protein and decrease the supply of starch for human diets.

Improved NUE due to Hybrid or Cultivar

The early study of NUE was facilitated by identifying individual components that explained both uptake and utilization efficiency (Moll et al., 1982). Differences among corn hybrids for NUE are largely due to variation in the utilization of accumulated N before anthesis, especially under low N supply (Moll et al., 1982). Eghball and Maranville (1991) noted that NUE generally parallels water use efficiency (WUE) in corn.

Wheat varieties with a high harvest index (grain produced divided by the total dry biomass) and low forage yield have low plant N loss and increased NUE (Kanampiu et al., 1997). Higher NUE has also been observed in rice varieties with high harvest index (Bufogle et al., 1997). Other work by Karrou and Maranville (1993) suggests that wheat varieties that produce more seedling dry matter with greater N accumulation are not necessarily the ones that use N more efficiently. Furthermore, N assimilation after anthesis is needed to achieve high wheat yields (Cox et al., 1985) and high NUE.

Genetic selection is often conducted with high fertilizer N input in order to eliminate N as a variable; however, this can mask efficiency differences among genotypes in accumulating and utilizing N to produce grain (Kamprath et al., 1982). This is consistent with Earl and Ausubel (1983), noting that high-yielding varieties of corn, wheat, and rice released during the Green Revolution were selected to respond to high N inputs. Consequently, continued efforts are needed to include plant selection under low N—something not often considered a priority by plant breeders, and uncharacteristic of agricultural experiment stations.

Conservation Tillage

Conservation tillage systems have not been found to increase productivity of high-yielding corn genotypes, but neither have they resulted in yield reductions relative to conventional tillage (Al-Darby and Lowery, 1986). The use of conservation tillage is based more on erosion control, the environment and operation costs than on yield potential (Al-Darby and Lowery, 1986), which is where potential advantages in NUE would be seen.

Under a no-tillage production system, grain yield was improved 32% when 60 kg N ha^{-1} was banded 8 to 10 cm below the seed row, and 15% when banded between the rows, compared with surface broadcast urea (Rao and Dao, 1996). Adaptation of subsurface placement of N fertilizer for no-till winter wheat has the potential to significantly improve N availability to plants and thereby improve NUE and reduce environmental and economic risks (Rao and Dao, 1996).

NH_4–N Source

Because NH_4–N is less subject to leaching or denitrification losses, N maintained as NH_4 in the soil should be available for late-season uptake (Tsai et al., 1992). Increased N uptake during grain-fill, for N-responsive hybrids, indicates a potential advantage of NH_4 nutrition for grain production (Tsai et al., 1992).

Wheat N uptake was increased by 35% when one-quarter of the N was supplied as NH_4^+, compared with all N as NO_3^- (Wang and Below, 1992). High-yielding corn genotypes were unable to absorb NO_3^- during ear development, which limited yields otherwise increased by supplies of NH_4^+ (Pan et al., 1984). Assimilation of NO_3^- requires the energy equivalent of 20 ATP mol^{-1} NO_3^-, whereas NH_4^+ assimilation requires only 5 ATP mol^{-1} NH_4^+ (Salsac et al., 1987). This energy savings may lead to greater dry weight production for plants supplied solely with NH_4^+ (Huffman, 1989). However, this has not been consistently observed, nor is it easy to carry out given N-cycle dynamics.

In-Season and Foliar-Applied N

Increasing protein content by applying higher rates of fertilizer is relatively inefficient, as NUE decreases with increasing N level, especially under dry soil conditions (Gauer et al., 1992). In-season applied N resulted in more efficient fertilizer use in 4 of 5 yr, compared with N incorporated prior to planting winter wheat (Olson and Swallow, 1984). Preplant N must be carefully managed to optimize grain yield, but adding excess N at that time reduces NUE, whereas the late-season supplied N can be adjusted to increase grain protein and NUE (Wuest and Cassman, 1992b). In-season N applied with point injection or topdressing can maintain or increase NUE compared with preplant N in wheat (Sowers et al., 1994).

Nitrogen fertilization should take place early in the season to maximize winter wheat forage production (Boman et al., 1995a). If grain production is the only goal, however, N fertilization can be delayed until much later in the season without significantly affecting wheat grain yields. Injection of anhydrous NH_3 into established winter wheat has produced significant stand damage; however, it has proven to be equally effective when compared with broadcast urea–NH_4NO_3 in grain production (Boman et al., 1995b). In general, placement of fertilizer N below the surface soil layer can decrease immobilization and increase plant uptake of N (Sharpe et al., 1988).

As early as 1957, foliar application of urea solutions at rates from 11 to 56 kg N ha^{-1} at flowering was shown to increase wheat grain protein by as much as 4.4% (Finney et al., 1957). Recovery of N applied at planting ranged from 30 to 55% while that applied at anthesis ranged from 55 to 80% (Wuest and Cassman, 1992a).

Foliar-applied urea (50 kg N ha^{-1} at 6–10 d after awn emergence, applied in three sprayings to minimize leaf damage) increased grain protein in barley more effectively than broadcast NH_4NO_3 (Bulman and Smith, 1993).

Irrigation

Work in corn has shown that maximum fertilizer use efficiency can be obtained with low N rates applied in-season and with light, frequent irrigation (Russelle et al., 1981). Randall et al. (1997) reported that split N applications do not always result in increased NUE for corn production in cooler, wetter climates. Freney (1997) indicated that supplying fertilizer in the irrigation water, applying fertilizer to the plant rather than the soil and use of slow-release fertilizers were useful for controlling losses of fertilizer N. This work also suggested that urease and nitrification inhibitors have the capacity to prevent loss of N and increase yield of crops. Wienhold et al. (1995) reported that supplemental irrigation appears to be a viable technology for growing corn in the northern Great Plains if care is taken to ensure that irrigation inputs are optimized to prevent nutrient leaching from the root zone. On sandy soils, N fertilizer placement and timing and effective irrigation management are both important considerations in promoting efficient N use, which will also maintain groundwater quality (Oberle and Keeney, 1990). In this work, the principles of production related to increased NUE are considered to be similar under dryland and irrigated conditions, since NUE decreases in relation to the amount of excess fertilizer N applied in both systems.

Precision Agriculture and Application Resolution

Conventional application of N to cultivated fields is made at a single rate based upon perceived average needs of the field as a whole (usually >10 ha). Natural and acquired variability in production capacity or potential within a field cause the average rate to be excessive in some parts and inadequate in others. Precision agriculture practices allow timely and precise application of N fertilizer to meet plant needs as they vary across the landscape.

To capitalize on any potential N fertilizer savings and increased NUE, management decisions need to be made at the appropriate field element size (Solie et al., 1996). Field element size is defined as that area or resolution which provides the most precise measure of the available nutrient where the level of that nutrient changes with distance (Solie et al., 1996). Random field variability in soil test and plant biomass has been documented at resolutions less than or equal to 1 m^2 (Solie et al., 1996). When N management decisions are made on areas of 1 m^2, the variability present at that resolution can be detected using sensors (normalized difference vegetative index or NDVI) and treated accordingly with foliar N (Solie et al., 1996; Stone et al., 1996), thus increasing NUE (Stone et al., 1996).

Note that soil testing (NO_3–N), irrespective of within-field variability, is a first approximation to refine field N rates. A combination of soil testing, fertilizer N experiences of the producer, and projected N requirement (expected yield or yield goal) are the best management tools available for farmers to determine fertilizer N rates (Westfall et al., 1996).

Discussion

The best hope for reducing fertilizer N needs lies in finding more efficient ways to fertilize crops (Smil, 1997). After 5 yr of annually applied N (56–112 kg N ha^{-1}) in winter wheat produced under conventional tillage, only 27 to 33% of the fertilizer N had been recovered in the grain (Olson and Swallow, 1984). Results like these are common, consistent with worldwide NUE data and are a cause for initiating a collaborative global effort to increase NUE.

Organic farming methods that include legume cultivation and crop rotation are highly efficient. Nonetheless, if all farmers adopted these methods, they could not feed today's population (Smil, 1997). Also, the promise of N_2–fixing cereal crops (specifically, corn and wheat) by the turn of the century (Hardy, 1988) has not materialized, compelling the present need for increased adoption of high-NUE practices using commercial fertilizers. Alternative N application strategies—specifically, split preplant and in-season applications of N, which are known to increase NUE—have not been widely adopted, largely because of the ease and affordability of applying more N than needed at or before planting. Agriculture's focus in developed countries has been on maximizing yields per unit area, and not until recently have we considered the environmental consequences of over-application of nutrients (Schlegel et al., 1996). Improving NUE will decrease the risk of NO_3–N contamination of inland surface and groundwater supplies (Stone et al., 1996), as well as the hypoxia in specific oceanic zones believed to be caused by excess N fertilizer (Malakoff, 1998).

Unfortunately, some benefits are associated with practices that have low NUEs. Increasing the N rate where lower rates are applied will increase crop production, especially in the developing world (Hardy and Havelka, 1975); however, if not combined with recommended management practices, this will decrease NUE. Also, when N fertilizer is applied at rates greater than required for maximum yield, plant biomass and long-term soil organic C increase (Raun et al., 1998), but NUE decreases. Increasing soil organic C when high N rates are used could assist in removing the excess atmospheric CO_2 widely believed to be responsible for global warming (Smit et al., 1988), but are likely to increase N losses via denitrification (Aulakh et al., 1984).

Similar to what took place in the auto industry when confronted with demands for increased fuel efficiency, approaches to increasing NUE should integrate many known components of grain crop production into one system. Foliar-applied N at 10 to 25 kg N ha^{-1} is highly efficient, but it alone will not meet N demands for maximum yields. Slow-release NH_4–N sources, forage production, improved NUE hybrids and varieties, and in-season applied N combined with an application resolution consistent with in-field variability is expected to lead to NUEs in excess of 85%. Unfortunately, there is as yet no published research wherein scientists have designed a package of practices specifically for high NUE. Some combinations of practices that optimize NUE may at present be unaffordable; nonetheless, agronomic scientists need to accumulate the knowledge of systems that will achieve an NUE for grain crop production in excess of 85%, always bearing in mind that what makes sense for increased NUE may adversely affect our ability to maintain production and satisfy human needs.

The overall impact of adopting increased NUE production practices in cereal production suggests that the environment would be less at risk. However, economic risk should increase substantially, since short-term adoption would likely come with a cost. Nonetheless, the incidence of hunger and related human suffering should decrease, in that these practices as a whole should increase production, reflecting the value of better stewardship.

Research and extension of production practices that would lead to a worldwide increase in NUE should be implemented by a reorganized and formal association of the CGIAR centers with other research institutes and universities that have advanced plant and soil science research programs. Although the principal focus of the CGIAR centers has been on developing improved varieties, they are uniquely equipped to extend management and fertilization practices, along with new seed, that are easily adopted by farmers. In addition, the CGIAR network of regional programs, directly interfaced with the national programs of virtually every developing nation in the world, provide needed access and credibility for both short- and long-term adoption of new production practices. Advanced research programs at universities and research institutes can provide the basic and strategic research underpinning to backstop NUE. A 1% increase in NUE for cereal production world-wide would cover three-quarters of the entire annual budget ($333 million in 1997; CGIAR, 1998) for the 16 international centers in the CGIAR.

So who would pay for such an effort? The international community should expand support to the CGIAR to enable the CGIAR centers to engage in and coordinate a worldwide effort on NUE. Likewise, developed countries should provide funding for research to increase NUE. The benefit–cost ratio to the U.S. government for contributions to the International Maize and Wheat Improvement Center (CIMMYT) in Mexico were estimated at 190:1, and at 17:1 for the International Rice Research Institute (IRRI) in the Philippines (Pardey et al., 1996). Both of these CGIAR centers focus on improved higher-yielding genetic materials and have outreach programs in place to extend both new varieties and production practices to wheat, maize, and rice growing regions throughout the world. With this kind of success and benefit to the U.S. economy from U.S. government support of CGIAR research centers, their involvement seems obvious. Excess N flowing down the Mississippi River each year is estimated to be worth $750 000 000 (Malakoff, 1998). At an average value of $490 Mg^{-1} of actual N, the $750 000 000 would comprise more than 13.6% of the total value ($5 480 356 000) of N fertilizer applied in 1996 in the entire United States. In light of this excessive waste, adoption of known practices to improve NUE should be encouraged, and increased NUE should be a first priority.

REFERENCES

Al-Darby, A.M., and B. Lowery. 1986. Evaluation of corn growth and productivity with three conservation tillage systems. Agron. J. 78:901–907.

Alexandratos, N. (ed.). 1995. World agriculture: Towards 2010: An FAO study. FAO, Rome, and John Wiley & Sons, New York.

Altom, W., J.L. Rogers, W.R. Raun, G.V. Johnson, and S.L. Taylor. 1996. Long-term rye–wheat–ryegrass forage yields as affected by rate and date of N application. J. Prod. Agric. 9:510–516.

Anderson, I.C., D.R. Buxton, D.L. Karlen, and C. Cambardella. 1997. Cropping system effects on nitrogen removal, soil nitrogen, aggregate stability, and subsequent corn grain yield. Agron. J. 89: 881–886.

Aulakh, M.S., D.A. Rennie, and E.A. Paul. 1982. Gaseous nitrogen losses from cropped and summer fallowed soils. Can. J. Soil Sci. 62:187–195.

Aulakh, M.S., D.A. Rennie, and E.A. Paul. 1984. The influence of plant residues on denitrification rates in conventional and zero tilled soils. Soil Sci. Soc. Am. J. 48:790–794.

Badaruddin, M., and D.W. Meyer. 1994. Grain legume effects on soil nitrogen, grain yield, and nitrogen nutrition of wheat. Crop Sci. 34:1304–1309.

Blevins, D.W., D.H. Wilkison, B.P. Kelly, and S.R. Silva. 1996. Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. J. Environ. Qual. 25:584–593.

Boman, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995a. Time of nitrogen application: Effects on winter wheat and residual soil nitrate. Soil Sci. Soc. Am. J. 59:1364–1369.

Boman, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995b. Spring-applied nitrogen fertilizer influence on winter wheat and residual soil nitrate. J. Prod. Agric. 8:584–589.

Bufogle, A., Jr., P.K. Bollich, J.L. Kovar, R.E. Macchiavelli, and C.W. Lindau. 1997. Rice variety differences in dry matter and nitrogen accumulation as related to plant stature and maturity group. J. Plant Nutr. 20:1203–1224.

Bulman, P., and D.L. Smith. 1993. Grain protein response of spring barley to high rates and post-anthesis application of fertilizer nitrogen. Agron. J. 85:1109–1113.

Campbell, C.A., R.J.K. Myers, and D. Curtin. 1995. Managing nitrogen for sustainable crop production. Fert. Res. 42:277–296.

Chichester, F.W., and C.W. Richardson. 1992. Sediment and nutrient loss from clay soils as affected by tillage. J. Environ. Qual. 21: 587–590.

CGIAR. 1998. CGIAR funding. [Online.] Available at http://www.cgiar.org/funding.html (Nov. 1998; verified 3 May 1999).

Cox, M.C., C.O. Qualset, and D.W. Rains. 1985. Genetic variation for nitrogen assimilation and translocation in wheat: II. Nitrogen assimilation in relation to grain yield and protein. Crop Sci. 25: 435–440.

Daigger, L.A., D.H. Sander, and G.A. Peterson. 1976. Nitrogen content of winter wheat during growth and maturation. Agron. J. 68: 815–818.

Dale, N. 1997. Ingredient analysis table. 1997 ed. Feedstuffs. 69(30): 24–31.

De Datta, S.K., R.J. Buresh, M.I. Samsom, W.N. Obcemea, and J.G. Real. 1991. Direct measurement of ammonia and denitrification fluxes from urea applied to rice. Soil Sci. Soc. Am. J. 55:543–548.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya, and T.W. Welacky. 1996. Influence of controlled drainage–subirrigation on surface and tile drainage nitrate loss. J. Environ. Qual. 25:317–324.

Earl, C.D., and F.M. Ausubel. 1983. The genetic engineering of nitrogen fixation. Nutrition Reviews 41:1–6.

Eghball, B., and J.W. Maranville. 1991. Interactive effects of water and nitrogen stresses on nitrogen utilization efficiency, leaf water status and yield of corn genotypes. Commun. Soil Sci. Plant Anal. 22:1367–1382.

FAO. 1996. FAOSTAT: Statistics database. [Online.] [Subset Fertilizer within Agriculture database.] Available at http://apps.fao.org (verified 3 May 1999).

Finney, K.F., J.W. Meyer, F.W. Smith, and H.C. Fryer. 1957. Effect of foliar spraying of Pawnee wheat with urea solutions on yield, protein content, and protein quality. Agron. J. 49:341–347.

Fowler, D.B., and J. Brydon. 1989. No-till winter wheat production on the Canadian prairies: Placement of urea and ammonium nitrate fertilizers. Agron. J. 81:518–524.

Francis, D.D., J.S. Schepers, and M.F. Vigil. 1993. Post-anthesis nitrogen loss from corn. Agron. J. 85:659–663.

Freney, J.R. 1997. Strategies to reduce gaseous emissions of nitrogen from irrigated agriculture. Nutr. Cycling Agroecosyst. 48:155–160.

Gauer, L.E., C.A. Grant, D.T. Gehl, and L.D. Bailey. 1992. Effects of nitrogen fertilization on grain protein content, nitrogen uptake, and nitrogen use efficiency of six spring wheat (*Triticum aestivum* L.) cultivars, in relation to estimated moisture supply. Can. J. Plant Sci. 72:235–241.

Halvorson, A.D., and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. Agron. J. 86:315–318.

Hardy, R.W.F. 1988. Biotechnology for agriculture and food in the future. Am. Chem. Soc. Symp. Ser. 362:312–319.

Hardy, R.W.F., and U.D. Havelka. 1975. Nitrogen fixation research: A key to world food? Science (Washington, DC) 188:633–643.

Hargrove, W.L., D.E. Kissel, and L.B. Fenn. 1977. Field measurements of ammonia volatilization from surface applications of ammonium salts to a calcareous soil. Agron. J. 69:473–476.

Harper, L.A., R.R. Sharpe, G.W. Langdale, and J.E. Giddens. 1987. Nitrogen cycling in a wheat crop: Soil, plant, and aerial nitrogen transport. Agron. J. 79:965–973.

Hilton, B.R., P.E. Fixen, and H.J. Woodward. 1994. Effects of tillage, nitrogen placement, and wheel compaction on denitrification rates in the corn cycle of a corn–oats rotation. J. Plant Nutr. 17: 1341–1357.

Huang, W.-Y., D. Shank, and T.I. Hewitt. 1996. On-farm costs of reducing residual nitrogen on cropland vulnerable to nitrate leaching. Rev. Agric. Econ. 18:325–339.

Hubbell, D.H. 1995. Extension of symbiotic biological nitrogen fixation technology in developing countries. Fert. Res. 42:231–239.

Huffman, J.R. 1989. Effects of enhanced ammonium nitrogen availability for corn. J. Agron. Educ. 18:93–97.

Kamprath, E.J., R.H. Moll, and N. Rodriguez. 1982. Effects of nitrogen fertilization and recurrent selection on performance of hybrid populations of corn. Agron. J. 74:955–958.

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20:389–404.

Karlen, D.L., P.G. Hunt, and T.A. Matheny. 1996. Fertilizer 15nitrogen recovery by corn, wheat, and cotton grown with and without pre-plant tillage on Norfolk loamy sand. Crop Sci. 36:975–981.

Karrou, M., and J.W. Maranville. 1993. Seedling vigor and nitrogen use efficiency of Moroccan wheat as influenced by level of soil nitrogen. Commun. Soil Sci. Plant Anal. 24:1153–1163.

Keeney, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution. p. 605–649. *In* F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA, CSSA, and SSSA, Madison, WI.

Kolberg, R.L., N.R. Kitchen, D.G. Westfall, and G.A. Peterson. 1996. Cropping intensity and nitrogen management impact of dryland no-till rotations in the semi-arid western great plains. J. Prod. Agric. 9:517–522.

Malakoff, D. 1998. Death by suffocation in the Gulf of Mexico. Science (Washington, DC) 281:190–192.

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

Oberle, S.L., and D.R. Keeney. 1990. Factors influencing corn fertilizer N requirements in the northern U.S. Corn Belt. J. Prod. Agric. 3:527–534.

O'Leary, M.J., and G.W. Rehm. 1990. Nitrogen and sulfur effects on the yield and quality of corn grown for grain and silage. J. Prod. Agric. 3:135–140.

Olson, R.V., and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 48:583–586.

Pan, W.L., E.J. Kamprath, R.H. Moll, and W.A. Jackson. 1984. Prolificacy in corn: Its effects on nitrate and ammonium uptake and utilization. Soil Sci. Soc. Am. J. 48:1101–1106.

Pardey, P.G., J.M. Alston, J.E. Christian, and S. Fan. 1996. Hidden harvest: U.S. benefits from international research aid. Int. Food Policy Res. Inst., Washington, DC.

Randall, G.W., T.K. Iragavarapu, and B.R. Bock. 1997. Nitrogen application methods and timing for corn after soybean in a ridge-tillage system. J. Prod. Agric. 10:300–307.

Rao, S.C., and T.H. Dao. 1996. Nitrogen placement and tillage effects on dry matter and nitrogen accumulation and redistribution in winter wheat. Agron. J. 88:365–371.

Raun, W.R., and G.V. Johnson. 1995. Soil–plant buffering of inorganic nitrogen in continuous winter wheat. Agron. J. 87:827–834.

Raun, W.R., G.V. Johnson, S.B. Phillips, and R.L. Westerman. 1998. Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma. Soil Tillage Res. 47:323–330.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M. Stevanovic, and R.A. Olson. 1981. Effects of water and nitrogen management on yield and ^{15}N-depleted fertilizer use efficiency of irrigated corn. Soil Sci. Soc. Am. J. 45:553–558.

Salsac, L., S. Chaillou, J.F. Morot-Gaudry, C. Lesaint, and E. Jolivoe. 1987. Nitrate and ammonium nutrition in plants. Plant Physiol. Biochem. 25:805–812.

Sanchez, C.A., and A.M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. Agron. J. 80:102–108.

Schepers, J.S., M.G. Moravek, E.E. Alberts, and K.D. Frank. 1991. Maize production impacts on groundwater quality. J. Environ. Qual. 20:12–16.

Schlegel, A.J., K.C. Dhuyvetter, and J.L. Havlin. 1996. Economic and environmental impacts of long-term nitrogen and phosphorus fertilization. J. Prod. Agric. 9:114–118.

Sharpe, R.R., L.A. Harper, J.E. Giddens, and G.W. Langdale. 1988. Nitrogen use efficiency and nitrogen budget for conservation tilled wheat. Soil Sci. Soc. Am. J. 52:1394–1398.

Smil, V. 1997. Global population and the nitrogen cycle. Sci. Am. 277(1):76–81.

Smit, B., L. Ludlow, and M. Brklacich. 1988. Implications of a global climatic warming for agriculture: A review and appraisal. J. Environ. Qual. 17:519–527.

Solie, J.B., W.R. Raun, R.W. Whitney, M.L. Stone, and J.D. Ringer. 1996. Optical sensor based field element size and sensing strategy for nitrogen application. Trans. ASAE 39(6):1983–1992.

Sowers, K.E., W.L. Pan, B.C. Miller, and J.L. Smith. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. Agron. J. 86:942–948.

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

Stutte, C.A., R.T. Weiland, and A.R. Blem. 1979. Gaseous nitrogen loss from soybean foliage. Agron. J. 71:95–97.

Tkachuk, R. 1977. Calculation of the nitrogen-to-protein conversion factor. p. 78–82. *In* J.H. Hulse et al. (ed.) Nutritional standards and methods of evaluation for food legume breeders. Int. Dev. Res. Ctr., Ottawa, ON.

Thomason, W.E., 1998. Winter wheat nitrogen use efficiency in grain and forage production systems. M.S. thesis. Oklahoma State Univ., Stillwater.

Tsai, C.Y., I. Dweikat, D.M. Huber, and H.L. Warren. 1992. Interrelationship of nitrogen nutrition with maize (*Zea mays*) grain yield, nitrogen use efficiency and grain quality. J. Sci. Food Agric. 58:1–8.

van der Ploeg, R.R., H. Ringe, G. Machulla, and D. Hermsmeyer. 1997. Postwar nitrogen use efficiency in West German agriculture and groundwater quality. J. Environ. Qual. 26:1203–1212.

Varvel, G.E. 1994. Monoculture and rotation system effects on precipitation use efficiency in corn. Agron. J. 86:204–208.

Wang, X., and F.E. Below. 1992. Root growth, nitrogen uptake, and tillering of wheat induced by mixed-nitrogen source. Crop Sci. 32:997–1002.

Westfall, D.G., J.L. Havlin, G.W. Hergert, and W.R. Raun. 1996. Nitrogen management in dryland cropping systems. J. Prod. Agric. 9:192–199.

Wienhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the northern great plains. Agron. J. 87:842–846.

Wuest, S.B., and K.G. Cassman. 1992a. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application. Agron. J. 84:682–688.

Wuest, S.B., and K.G. Cassman. 1992b. Fertilizer-nitrogen use efficiency of irrigated wheat: II. Partitioning efficiency of preplant versus late-season application. Agron. J. 84:689–694.

TILLAGE

Crop Sequence and Surface Residue Effects on the Performance of No-Till Corn Grown on a Poorly Drained Soil

Alice M. Wolfe and Donald J. Eckert*

ABSTRACT

On noncrusting, poorly drained soils, yield differences between corn (*Zea mays* L.) grown following corn and following soybean [*Glycine max* (L.) Merr.] can be much greater when no-till rather than moldboard plowing practices are used. We conducted this experiment to determine whether differences in previous crop, surface residue cover, or a combination of both contribute to yield differences when no-till corn follows corn or soybean. Corn was grown without tillage in 1991 and 1992 on a tile-drained Kokomo silty clay loam (fine, mixed, mesic Typic Argiaquolls), following either corn or soybean. On half of the plots, residues were switched, so that the previous crop was corn but surface residue was soybean, and vice versa. On other plots, residue was left undisturbed. Plots with corn residue cover showed slightly lower spring soil temperatures in both years, and in 1992 showed slower early development of corn plants, than did plots covered with soybean residue. In both years, however, final plant height, grain yield, and stalk mass were greater where corn followed soybean, regardless of residue cover ($P < 0.05$). These differences appeared greater in 1991, a dry year, than in 1992, a more favorable year for corn production. Corn following corn showed more barren stalks and fewer kernels per ear than corn following soybean in the dry year, 1991 ($P < 0.05$). Nutrient concentrations in ear leaves of corn plants were all above sufficiency levels, were unaffected by surface residue, and were inconsistently affected by previous crop. Results indicate that lower yields of no-till corn following corn rather than soybean are due more to previous crop than surface residue influences.

On noncrusting, poorly drained soils, crop rotation can be a significant factor determining the performance of no-till corn production systems. Though corn following corn often produces lower yields than corn following soybean on such soils, the difference can be intensified greatly when no-tillage rather than moldboard plowing practices are used (Griffith et al., 1988; Van Doren et al., 1976). The effect is also such that corn produces nearly equivalent yields under different tillage conditions when it follows soybean but much lower yields under no-till than moldboard plow conditions when it is grown continuously. Such yield differences can occur even when drainage improvements are provided. The differences may persist for many years, though some investigators have seen them moderate over time (Dick et al., 1991; Griffith et al., 1988).

A number of effects, often related to the presence of heavy surface residue cover, have been proposed to explain the rather severe yield depressions often seen in continuous no-till corn on poorly drained soils. Crop residue on the soil surface may insulate the soil and retard early season soil warming, leading to lower plant densities and slower early development than occurs on bare soils (Fausey, 1984; Griffith et al., 1973; Mock and Erbach, 1977; Willis et al., 1957). Van Doren et al. (1976), however, noted that heavy residue did not affect corn yield when corn followed alfalfa (*Medicago sativa* L.) hay on a poorly drained soil. An autotoxic effect may also occur when corn shoot residues are placed near the seed, retarding early development (Yakle and Cruse, 1983). Increased root-disease pressure in the cooler, wetter, no-till soil environment has also been proposed (Van Doren et al., 1976). Although such effects should be less evident if surface residue is removed from the vicinity of the seed row. However, removing or excluding residues from near the seed row has had mixed effects on corn performance: either improving it, on plots where corn followed fallowing (Kaspar et al., 1990), or having inconsistent effects in different seasons on crusting soils (Swan et al., 1994), or having no effect (Janovicek et al., 1997; Stewart et al., 1994). Also, deleterious effects of corn residue are not normally seen on well-drained soils, where yields in the presence of surface residue often exceed those without residue. Therefore, although residue-related factors may lead to yield reduction in some situations, it is not clear that these residue effects are the major cause of the reductions.

The yield differences seen on poorly drained soils

A.M. Wolfe, 212 Church St., Mt. Orab, OH 45154; D.J. Eckert, School of Natural Resources, The Ohio State Univ., Columbus, OH 43210-1085. Salaries and research support provided by state and federal funds appropriated to the Ohio Agric. Res. & Dev. Ctr., The Ohio State Univ., Wooster, OH 44691. Received 7 May 1998. *Corresponding author (eckert.1@osu.edu).

Published in Agron. J. 91:363–367 (1999).