A Classification System for Factors Affecting Crop Response to Nitrogen Fertilization

John A. Lory,* Michael P. Russelle, and Gyles W. Randall

ABSTRACT

Crop response to N fertilizer (Nf) is influenced by factors such as Nf management, soil type, crop sequence, and supply of residual and mineralized N, but there is no framework to define the best strategy to account for a given factor in an Nf recommendation. This paper describes a three-component classification system for evaluating the effect of any factor on yield response to Nf. This system provides (i) a vocabulary to describe clearly the effect of a factor on Nf recommendations, and (ii) insight on how to adjust Nf recommendations for the effect. Factors that affect yield response to Nf but not to N supply (Ns) were classified as shift effects (i.e., movement of a response curve in the x and/or y direction, with no change in coefficients of curvature). Factors that interact with Nf and Ns response were classified as interaction effects. Nitrogen supply was defined as the sum of aboveground plant N content of the control (0 N applied) plot, postharvest fall NO3 in the surface 1.5 m of the control plot, and Nf applied. Two 2-yr experiments were conducted at Rosemount and Waseca, MN, to compare Nf response of continuous corn (Zea mays L.) with that of first- and then second-year corn following alfalfa (Medicago sativa L.). We used the classification system to evaluate effects of crop sequence, year, and location on corn yield response to Nf. Year and crop sequence effects at Rosemount were primarily shift effects, implying that quantifying the effect on Nf would be sufficient to account for these effects on Nf recommendations. In contrast, the interaction model predominated at Waseca. Consequently, at this location simple adjustments of Nf were not sufficient to account for the complexity of crop sequence effects on Nf recommendations. This classification system facilitates the organization, evaluation, and communication of the many factors that influence crop yield.

Concern about the sustainability of agriculture has encouraged the use of more diverse cropping systems with a wider range of cultural practices, each having the potential to impact crop yield response to fertilizer N (Nf). At the same time, more accurate Nf recommendations are required to minimize the negative environmental consequences of N losses to ground water and the atmosphere. The integration of additional variables into Nf recommendations should result in improved Nf management. Current recommendations already account directly for some variables. For example, University of Minnesota N recommendations for corn have adjustments for soil organic matter content, residual nitrate, location, yield goal, and previous crop (Rehm et al., 1993).

Given the lack of a standard vocabulary or process to describe and evaluate the impact of a variable on an Nf recommendation, our primary objective was to develop and demonstrate a three-component classification system to characterize the effect of different factors on yield response to Nf. Information from field studies that contrasted Nf response of continuous corn with that of first- and second-year corn following alfalfa was used to characterize the effect of crop sequence, year, and location on Nf response. We also used the proposed classification system to evaluate the impact of crop sequence on two components of N supply use efficiency (NUEs): (i) N uptake efficiency (plant N uptake per unit Nf) and (ii) N utilization efficiency (grain yield per unit aboveground assimilated N).

THEORETICAL FRAMEWORK

The effect of a factor on Nf response of a crop can be classified using regression analysis into three response characteristics: (i) y-shift effects, (ii) x-shift effects, and (iii) interaction effects. Each characteristic is classified by yield response to Nf within the larger context of yield response to Nf (Fig. 1). The Nf is the sum of all sources of potentially available N, including Nf. A y-shift effect alters yield independently of Nf and Ns (Fig. 1a; Table 1); i.e., it changes intercept coefficients but not slope coefficients. An x-shift effect causes an apparent difference in yield response to Nf but not to Ns, between treatments (Fig. 1b; Table 1). This difference occurs because two parts of the same Nf response curve are compared. Shifting Nf response along the x-axis to account for differences in Nf will bring the curves into unison. Compensating for treatment effects with shifts along both axes has been labeled the double-shift technique (Black, 1993). Interaction effects, the third potential characteristic, are those that cannot be accounted for with shift methods. An interaction effect causes a unique relationship between yield and Nf for each factor (Fig. 1c; Table 1).

Adjustment of an Nf recommendation for a specific management practice depends on which components are involved. A y-shift effect has no impact on Nf response, so the Nf recommendation does not need adjustment. Adjustment for an x-shift effect requires quantification of the factor's effect on Nf. Examples include efforts to adjust Nf recommendations for factors such as residual soil nitrate and previous legume crops (Onken et al., 1985; Fox and Piekielek, 1988). Adjustments for interaction effects require that we either understand the underlying causes of the interaction or develop empirical relationships to describe the interaction. Interaction effects may require that unique Nf recommendations be developed, as is done for different geographic regions. Computer modeling has the potential to account for the complexity of interaction effects.

Crop response typically is modeled using variations of the quadratic equation or the Mitscherlich equation (Black, 1993). A y-shift affects only the intercept of the quadratic equation and the maximum yield coefficient of the Mitscherlich equation. An x-shift requires changing the x-axis from Nf to Ns to produce a congruent Nf response in both equations. An interaction effect changes the slope co-

Abbreviations: Gw, grain dry matter yield; Nf, fertilizer N; Ns, N supply; NUEs, N use efficiency; Nf, aboveground plant N.
by Shrader et al. (1966). They modeled the effect of alfalfa used to describe the effects of alfalfa on corn N_f response of yield with N_f, rather than N_s. A shift method was first previous crop effects on N_f response, because published re-
search has focused almost exclusively on the interaction of yield with N_t, rather than N_s. A shift method was first used to describe the effects of alfalfa on corn N_f response by Shrader et al. (1966). They modeled the effect of alfalfa on N_f response of continuous corn as an x-shift effect within each year of the experiment. Year effects were modeled as double-shifts. A modified Mitscherlich equation was used to model crop response to N. The magnitude of x- and y-shifts were determined empirically to bring them in line with the common response function.

Since the seminal work of Shrader et al. (1966), three other reports have used the shift model to describe the effects of alfalfa on corn response to N_t. The effects of alfalfa in sequence with corn were modeled as an x-shift (Baldock and Musgrave, 1980) and as a double-shift (Baldock et al., 1981). Both approaches were variations of Shrader et al. (1966). Black (1993) discussed subsequent research from the same experimental site as used by Shrader et al. (1966), reporting that corn was more responsive to N_t in the follow-up study than in the earlier work. In addition, yield effects of soybean [Glycine max (L.) Merr.] in a crop rotation could not be accounted for with the shift models.

Fertilizer N recommendations for corn following alfalfa typically are reduced by a set quantity of N, referred to as the legume N credit, legume fertilizer N equivalent, or legume fertilizer N replacement value. We will use the term N credit. The objective of the N credit is to adjust N_t recommendations for the effect of crop rotation on N_t to the nonlegume crop. Methodology for determining N credits has evolved over the past decade. The traditional method determines an N credit by solving for x in the continuous corn N_t response curve [G_w as y vs. N_t application rate as x], with y equal to G_w of nonfertilized corn following alfalfa (Shrader et al., 1966; Hesterman, 1988). The underlying assumption of the traditional approach is that the previous crop effect on N_t response is an x-shift (Shrader et al., 1966). This model was expanded by Baldock et al. (1981) to adjust for y-shifts caused by crop sequence effects that were confounding N credit measurements in that study.

Smith et al. (1987) recognized that accurate determination of an N credit could be assured only by comparing N_t response of continuous corn with N_t response of corn following the legume. This difference N credit is measured as the difference in N_t required for maximum yield in continuous corn and in corn following a legume, such as alfalfa. This is the only method that will determine the N credit accurately in the presence of y-shift and interaction effects on N_t response due to a previous crop (Lory et al., 1995b).

**LITERATURE REVIEW**

Limited information is available on classification of previous crop effects on N_t response, because published research has focused almost exclusively on the interaction of yield with N_t, rather than N_s. A shift method was first used to describe the effects of alfalfa on corn N_t response by Shrader et al. (1966). They modeled the effect of alfalfa on N_t response of continuous corn as an x-shift effect within each year of the experiment. Year effects were modeled as double-shifts. A modified Mitscherlich equation was used to model crop response to N. The magnitude of x- and y-shifts were determined empirically to bring them in line with the common response function.

Since the seminal work of Shrader et al. (1966), three other reports have used the shift model to describe the effects of alfalfa on corn response to N_t. The effects of alfalfa in sequence with corn were modeled as an x-shift (Baldock and Musgrave, 1980) and as a double-shift (Baldock et al., 1981). Both approaches were variations of Shrader et al. (1966). Black (1993) discussed subsequent research from the same experimental site as used by Shrader et al. (1966), reporting that corn was more responsive to N_t in the follow-up study than in the earlier work. In addition, yield effects of soybean [Glycine max (L.) Merr.] in a crop rotation could not be accounted for with the shift models.

**MATERIALS AND METHODS**

We conducted two 2-yr experiments on a Webster clay loam (fine-loamy, mixed, mesic Typic Hapludolls) at the Southern Experiment Station, Waseca, MN, and on a Tallula silt loam (coarse-silty, mixed, mesic Typic Hapludolls) at the Rosemount Agricultural Experiment Station, Rosemount, MN. The first year of each experiment compared N_t response of first-year corn following alfalfa vs. continuous corn; the second year compared N_t response of second-year corn following alfalfa vs. continuous corn. The experimental design, treatments, sample acquisition and analysis, weather data, and an evaluation of N_t and manure N response of G_w, grain N, stover N, and soil inorganic N have been described in detail by Lory et al. (1995a). The N_t response data from that investigation were used in this analysis. The following abbreviated summary includes the information most pertinent to this paper.

**Table 1.** Classification system describing the effect of a factor on crop response to N_t. The classification contrasts G_w response to N_t and N_s, with and without the factor of interest.†

<table>
<thead>
<tr>
<th>Classification</th>
<th>G_w vs. N_t</th>
<th>G_w vs. N_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>different intercepts, same slope coefficients</td>
<td>different intercepts, same slope coefficients</td>
<td>y-shift</td>
</tr>
<tr>
<td>different slope coefficients</td>
<td>different intercepts, same slope coefficients</td>
<td>x-shift</td>
</tr>
<tr>
<td>different slope coefficients</td>
<td>different slope coefficients</td>
<td>double-shift</td>
</tr>
<tr>
<td>same intercept and slope coefficients</td>
<td>same intercept and slope coefficients</td>
<td>interaction</td>
</tr>
<tr>
<td>no effect</td>
<td>no effect</td>
<td>no effect</td>
</tr>
</tbody>
</table>

† G_w, grain dry matter yield; N_t, fertilizer N; N_s, N supply.
Plot History

In Exp. 1, 'Blazer' alfalfa was seeded in April 1984 at Waseca and Pioneer® '532' alfalfa was seeded after oat (Avena sativa L.) in fall 1985 at Rosemount throughout the entire plot area. Both stands were managed for hay production. Randomly allocated portions of the alfalfa stands were moldboard plowed in spring 1988 and planted to corn, creating a randomized complete block design with four replicate blocks at Waseca and three blocks at Rosemount. Corn was managed for grain production and received no Nf in 1988, and 112 and 34 kg N ha⁻¹ as urea preplant incorporated 1989 at Waseca and Rosemount, respectively. Alfalfa was managed for hay production in a three-cut system.

In Exp. 2, corn and alfalfa treatments were established in spring 1988 in a randomized complete block design with four blocks at Waseca and three blocks at Rosemount to establish previous crop treatment effects. Alfalfa was harvested once in 1988 and then managed on a three-cut management system in 1989 and 1990. Corn was managed for grain production. Corn received 170, 135, and 110 kg N ha⁻¹ as urea in 1988, 1989, and 1990, respectively at Rosemount, and 170, 170, and 135 kg N ha⁻¹ as NH₄NO₃ in 1988, 1989, and 1990, respectively, at Waseca.

Fertilizer Rate Treatments

Fertilizer N treatments were initiated in 1990 in Exp. 1 and in 1991 in Exp. 2. Fertilizer N treatments were applied preplant as urea, disk incorporated, and the entire plot area was planted to corn (Pioneer hybrid 3751). Subplots within each previous crop main plot in both experiments received 0, 67, 112, 157, and 202 kg N ha⁻¹ in continuous corn and 0, 34, 67, 112, and 157 kg N ha⁻¹ in first-year corn following alfalfa. The remaining subplots in all experiments received 112 kg N ha⁻¹ if the previous crop was corn or no Nf if previous crop was alfalfa. This ensured that all Nt treatments within a crop sequence had the same fertilization history in the second year of the experiments.

In the second year of treatments in both experiments, five Nf rate treatments were randomly applied as urea to the plot area that received the uniform N treatment in the first year of the experiment. In Exp. 1, both cropping sequences received 0, 67, 112, 157, and 202 kg N ha⁻¹. In Exp. 2, second-year treatments in continuous corn were 0, 67, 112, 157, and 202 kg N ha⁻¹, and in second-year corn following alfalfa were 0, 34, 67, 112, and 157 kg N ha⁻¹.

Data Analysis

The following definitions were used to estimate Nf and Nt.

\[ N_f (\text{kg ha}^{-1}) = \text{aboveground plant N in grain and stover at physiological maturity} \]
\[ N_t (\text{kg ha}^{-1}) = N_f \text{ applied} + N_i \text{ of control (0 N applied) plot + postharvest fall soil NO}_3^- \text{ in the surface 1.5 m of the control plot} \]

Huggins and Pan (1993) suggested using this estimation of Nt, which assumes that the amount of N supplied from the soil does not interact with Nf. This approach contrasts with Shrader et al. (1966), who determined Nf empirically.

Classification of Crop Sequence Effects

Regression techniques (SAS, 1987) were used to model the yield relationships, Gw vs. Ni (see Lory et al., 1995a) and Gw vs. Nt, and the NUE relationships, Gw vs. Nf and Nf vs. Nt. The experiment was modeled first by location and as quadratic responses. Regression analysis techniques were used to test hypotheses that regression lines from different cropping sequences or different experiments (years) had the same slope (Weisberg, 1985; Weisberg and Cook, 1990). A general model (i.e., each rotation phase in each experiment had a unique intercept and slope coefficients) was compared to more restrictive models (i.e., some or all rotation phases and experiments had the same slope coefficients but unique intercepts). Restrictions to the model were rejected if they significantly increased error sums of squares (α = 0.05) (Weisberg and Cook, 1990). Regression lines of the location models were compared across locations using the same restriction test. Nonsignificant quadratic and linear coefficients were removed step-wise from the overall model (α = 0.05). Finally, restrictions were applied to test for effects of crop sequence, year, and location on intercept coefficients.

The overall models developed for yield and NUE, relationships were used to classify the following effects: (i) crop sequence effects (first-year corn following alfalfa vs. continuous corn in 1990 and 1991, and second-year corn following alfalfa vs. continuous corn in 1991 and 1992); (ii) year effects for continuous corn (contrast 1990, 1991, and 1992), first-year corn following alfalfa (1990 vs. 1991), and second-year corn following alfalfa (1991 vs. 1992); and (iii) location effects (Rosemount vs. Waseca).

Classification of each effect on Gw response to Nf was determined by contrasting Gw response to Nf and Nf (Table 1). Components of NUE were also evaluated. Factors that caused unique slope coefficients for a particular component of NUE, were defined as having an interaction effect; factors that had the same slope coefficients but different intercepts were defined as having y-shift effects; and factors that had no effect on intercept and slope coefficients had no effect on that component of NUE.

Calculation of Nitrogen Credits

Alfalfa N credits were calculated by both the traditional and difference methods. If Gw response to Nf exhibited no plateau (dx/dy = 0), then the recommended Nf rate for the location was substituted in both methods (based on Rehm et al., 1993). If neither crop sequence attained maximum Gw, but the response curves of Gw vs. Ni had the same slope, then the difference N credit was 0. The difference method estimate of the N credit was used as the standard to judge the accuracy of the traditional method (Lory et al., 1995b).

RESULTS AND DISCUSSION

Location Effects on Nf Response

Location influenced Gw vs. Ni (data not shown) and Gw vs. Nf (Fig. 2) in all cropping sequences. Location was classified as an interaction effect, because the double-shift method failed to account for differences in Nf response between Rosemount and Waseca. The interaction of Gw vs. Ni with location is consistent with results in Iowa (Shrader et al., 1966). Diverse locations include uncontrollable differences in soil type, environment, and crop management that may influence yield response to Nf. For example, Rosemount was spring plowed whereas Waseca was fall plowed (consistent with local cultural practices) in all but one year.

Crop Sequence and Year Effects on Nf Response

Shift models were able to account for most crop sequence (Table 2) and year (Table 3) effects on Nf response at Rosemount. There was a uniform response of Gw to Nf,
differing only in intercept values, except for first-year corn following alfalfa in 1990 (Fig. 2). The relationship of $G_w$ to $N_r$ in first-year corn following alfalfa was difficult to establish at Rosemount because of the limited response of $G_w$ to $N_r$ in both years. Our interpretation of year and crop sequence effects at Rosemount is in agreement with results of a long term study on a Kenyon silt loam soil (fine-loamy, mixed, mesic Typic Hapludolls) in northeastern Iowa (Shrader et al., 1966), although the Iowa study did not evince $y$-shifts in crop sequence effects.

The success of the shift model on these two silt loam soils suggests that $N_r$ recommendations may be adjusted reliably for the effects of year and crop sequence based on changes in $N_r$. Future attempts to predict year effects on $N_r$ recommendations at Rosemount and similar sites may be simplified, because year effects did not change the slope of the $G_w$ vs. $N_r$ curve. Thus, one need only predict the unique $x_0$ point ($N_r$ with no $N_f$ applied) each year to adjust for year effects. The use of residual nitrate tests to adjust $N_r$ for year effects falls within the conceptual framework of this double-shift approach.

Simple $x$- and $y$-shifts did not account for crop sequence effects at Waseca (Fig. 2; Table 2). This contrasts with results at Rosemount, and with results of Shrader et al. (1966) on a similar clay loam soil in north-central Iowa. Shift models accounted for crop sequence effects in only one of four comparisons at Waseca. Shift models also were inconsistent in accounting for year effects at Waseca (Table 3). This may have been due to the highly anomalous year of 1992, when summer air temperatures averaged $2.3^\circ C$ below average.

The relationship between $G_w$ and $N_r$ was different for the two locations in Minnesota. All comparisons were made to continuous corn.†

### Table 2. Classification of crop sequence effects on $G_w$ response to $N_r$ rates at two locations in Minnesota. All comparisons were made to continuous corn.†

<table>
<thead>
<tr>
<th>Location</th>
<th>Crop sequence</th>
<th>Year</th>
<th>$G_w$ vs. $N_r$</th>
<th>$G_w$ vs. $N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slope effect</td>
<td>Intercept effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slope effect</td>
<td>Intercept effect</td>
</tr>
<tr>
<td>Rosemount</td>
<td>-A-C</td>
<td>1990</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>-A-C</td>
<td>1991</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>-A-C-C</td>
<td>1991</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>-A-C-C</td>
<td>1992</td>
<td>NS</td>
<td>*</td>
</tr>
<tr>
<td>Waseca</td>
<td>-A-C</td>
<td>1990</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>-A-C</td>
<td>1991</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>-A-C</td>
<td>1991</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>-A-C-C</td>
<td>1992</td>
<td>*</td>
<td>NS</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
† $G_w$, grain dry matter yield; $N_r$, fertilizer $N$; $N_f$, $N$ supply.
‡ A, alfalfa; C, corn. Underlining indicates the crop measured in the given year.
§ Blank (-): Not necessary to evaluate for classification.
Table 3. Classification of year effects on Gw response to Nt rates at two locations in Minnesota.†

<table>
<thead>
<tr>
<th>Crop sequence‡</th>
<th>Location</th>
<th>Year</th>
<th>Slope effect</th>
<th>Intercept effect</th>
<th>Slope effect</th>
<th>Intercept effect</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>-C-C-C</td>
<td>Rosemount</td>
<td>1990 vs. 1991</td>
<td>NS</td>
<td>*</td>
<td>NS</td>
<td>*</td>
<td>y-shift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1990 vs. 1992</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>double-shift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1991 vs. 1992</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>double-shift</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waseca</td>
<td>1990 vs. 1991</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>double-shift</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1990 vs. 1991</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>double-shift</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1991 vs. 1992</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>double-shift</td>
<td></td>
</tr>
<tr>
<td>-A-C</td>
<td>Rosemount</td>
<td>1990 vs. 1991</td>
<td>NS</td>
<td>*</td>
<td>NS</td>
<td>*</td>
<td>x-shift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1990 vs. 1991</td>
<td>NS</td>
<td>*</td>
<td>NS</td>
<td>*</td>
<td>y-shift</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
† Gw, grain dry matter yield; Nt, fertilizer N; Ns, N supply.
‡ A, alfalfa; C, corn. Underlining indicates the crop measured in the given year.
§ Blank (-): Not necessary to evaluate for classification.

Crop following alfalfa and for continuous corn, and the nature of that interaction changed from year to year at Waseca. This result implies that simple adjustments for Ns (such as universal N credits) may not consistently account for crop sequence effects for the glacial till soil at Waseca.

Crop Sequence Effects on Components of NUE

Crop sequence effects on N utilization efficiency (Gw vs. Ns) were limited to y-shifts; i.e., crop sequence did not interact with N utilization efficiency (Fig. 3). Consequently, N utilization efficiency was not the source of the crop sequence interaction of Gw vs. Ns (Table 4). When crop sequence effects on N utilization efficiency were evident, corn following alfalfa typically had higher N utilization efficiency than continuous corn, although a negative effect of first-year corn following alfalfa was observed in 1990 at Waseca.

Interaction of crop sequence with Gw vs. Ns was due to changes in N uptake efficiency (Nt vs. Ns, Table 4). The universal aspect of these interactions was that corn following alfalfa had lower Ns requirements to attain maximum Nt (Fig. 4). At Waseca, maximum Nt was attained with 330 kg Ns ha⁻¹ in first-year corn following alfalfa, but required 410 kg Ns ha⁻¹ in second-year corn following alfalfa. Continuous corn attained maximum Nt with Ns greater than 410 kg ha⁻¹ (predicted with the quadratic equation to be 570 kg Ns ha⁻¹) in 1990 and 1991. Nitro-

![Fig. 3](image-url)
Table 4. Classification of crop sequence effects on components of NUE \(_\text{a}\) at two locations in Minnesota. All comparisons were made to continuous corn. The table summarizes information in Fig. 2 (\(G_w\) vs. \(N_s\)), Fig. 3 (\(G_w\) vs. \(N_t\)), and Fig. 4 (\(N_t\) vs. \(N_s\)).

<table>
<thead>
<tr>
<th>Location</th>
<th>Crop sequence</th>
<th>Year</th>
<th>(G_w) vs. (N_s)</th>
<th>(G_w) vs. (N_t)</th>
<th>(N_t) vs. (N_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosemount</td>
<td>A-C</td>
<td>1990</td>
<td>shift (+)§</td>
<td>NS¶</td>
<td>y-shift (+)</td>
</tr>
<tr>
<td></td>
<td>A-C</td>
<td>1991</td>
<td>interaction (+)</td>
<td>shift (+)</td>
<td>interaction (+)</td>
</tr>
<tr>
<td></td>
<td>A-C-C</td>
<td>1991</td>
<td>shift (+)</td>
<td>shift (+)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>A-C-C</td>
<td>1992</td>
<td>interaction</td>
<td>shift (-)</td>
<td>interaction (+)</td>
</tr>
<tr>
<td></td>
<td>A-C-C</td>
<td>1991</td>
<td>interaction</td>
<td>shift (+)</td>
<td>interaction (-)</td>
</tr>
<tr>
<td></td>
<td>A-C-C</td>
<td>1992</td>
<td>shift</td>
<td>shift (+)</td>
<td>interaction (-)</td>
</tr>
</tbody>
</table>

\(G_w\), grain dry matter yield; \(N_s\), N supply; \(N_t\), aboveground plant N.

\(\pm\), A, alfalfa; C, corn. Underlining indicates the crop measured in the given year.

§ A sign in parentheses indicates the direction of the y-shift associated with corn following alfalfa. It was not always possible to determine the sign.

¶ NS, not significant at the 0.05 probability level.

![Fig. 4](image_url)

Fig. 4. The relationship between aboveground plant N \((N_t)\) and N supply \((N_s)\) for corn \((C)\) grown with (solid symbols) or without (open symbols) alfalfa \((A)\) in the crop sequence. The crop measured in the indicated year is underlined within the crop sequence. Data plotted with all intercepts set to 0; the actual intercept is reported in the symbol legend (e.g., \(N_t\) following alfalfa at Rosemount in 1990 was 46 kg ha\(^{-1}\) greater than shown in the figure). Plotted are data from individual replicates in two 2-yr experiments at two locations in Minnesota. The minimum number of fitted curves required to describe the data are shown.

The benefits of rotation historically have been divided into two categories: (i) N rotation effects, which are differences in yield due to rotation that can be overcome in the continuous crop with an application of N, and (ii) non-N rotation effects, which are differences in yield due to rotation that persist even under conditions of unlimited N (after Baldock et al., 1981). Efforts to quantify the magnitude of rotation effects (as opposed to N rotation effects) are aided by the observation that rotation effects are crop sequence factors that affect NUE\(_a\).
Differentiation of rotation effects based on $N_t$ response is difficult even when the maximum yield of both crop sequences is well defined (Fox and Piekielek, 1988). Regression methods are most sensitive in quantifying rotation effects when there is no interaction between the yield term and the indicator of N status due to crop sequence. Under these conditions, rotation effects are estimated as the magnitude of the y-shift. Expanding the analysis of rotation effects to the components of NUE, eliminates some interaction effects due to crop sequence, thereby providing additional sensitivity for identifying some rotation effects.

It was not possible to quantify rotation effects based on $G_w$ response to $N_t$ in many cases in this study, because maximum yield was not attained at the highest $N_t$ rate and there was an interaction of crop sequence with $G_w$ vs. $N_t$. However, quantifiable rotation effects (y-shifts) were common in the N utilization efficiency component of NUE (Table 4). There were additional effects of previous crop that could not be partitioned into N rotation and rotation effects, particularly at Waseca, because of the interaction of $N_t$ vs. $N_f$ (Table 4) and because maximum $N_t$ was not attained in continuous corn (Fig. 4).

**Accurate Determination of Nitrogen Credits**

Classification of crop sequence effects (Table 2) demonstrates that y-shifts can be a component of crop sequence effects at Rosemount, and that interaction effects due to crop sequence are common at Waseca. The prevalence of interaction effects associated with corn following alfalfa at Waseca violates the underlying assumptions of the traditional N credit method. Consequently, on a theoretical basis, the increased accuracy of the difference N credit method is required to assess N credits at Waseca accurately. The presence of occasional positive y-shifts at Rosemount means that the traditional method will tend to overestimate the N credit.

Table 5 summarizes N credit estimates by the difference and traditional methods. Current N credit recommendations for a good stand of alfalfa at both locations are 170 kg N ha$^{-1}$ for first-year corn following alfalfa and 85 kg N ha$^{-1}$ for second-year corn following alfalfa (Rehm et al., 1993). At Waseca, it appears the traditional method tended to overestimate N credits. The variability of the N credit estimates at Waseca reflects the complexity of the crop sequence effects measured there. These results confirm our hypothesis that traditional N credit methodology provided inaccurate N credit estimates at Waseca. At Rosemount, the two methods were in agreement except in second-year corn following alfalfa in 1992, where the traditional method erroneously assigned an N credit for a y-shift effect. Our data suggest that the difference method provides increased accuracy in some cases at Rosemount, and one should question assigning a second-year N credit for corn following alfalfa on this soil.

**INTERPRETIVE SUMMARY**

We have introduced a classification system to evaluate any factor’s influence on fertilizer N response. When a factor interacts with grain dry matter yield response to fertilizer N rates because of an x-shift, differences are due to the factor’s effect on N supply. Year and crop sequence effects seem to fit this model on a moderately well-drained, medium-organic-matter loess soil at Rosemount, MN. Interaction effects imply a unique crop response to fertilizer N and N supply for each factor. Consequently, information derived from crop response to fertilizer N rates under one condition may not provide reliable information on crop response under the alternative condition. Interaction effects due to year and crop sequence were prevalent on a poorly drained, high-organic-matter glacial till soil at Waseca, MN.

The classification of a factor’s effects on crop response to fertilizer N determines the approach to adjusting fertilizer N recommendations for a factor’s influence. Research on crop sequence and year effects should focus on their effect on N supply on the loess soil in Minnesota. Examples of this type of research are the development of N credits for corn following alfalfa and residual nitrate tests to characterize year effects. In contrast, research must focus on grain dry matter yield response to fertilizer N rates in each crop sequence on the glacial till soil, in an effort to elucidate any consistent relationship between the two over time. Fertilizer N recommendations that attempt to account for year and crop sequence effects based only on their influence on N supply are likely to be insufficient at this location.

**REFERENCES**


