CONCLUSIONS

Each crop presents unique challenges in applying DRIS to the diagnosis of its nutrition. Current standard DRIS methodology is fairly straightforward for well-researched annual crops such as corn and soybeans (*Glycine max* [L.] Merr.), where large data sets are available for establishing norms. The use of DRIS on unconventional crops with small data sets poses special problems that may require modifications to standard DRIS methodology in order to maximize the usefulness of this system. In the case of this tree crop, D_{adj} was used as a response variable in the place of traditionally used biomass yield. Symmetrical index equations allow the use of the NBI for interpreting overall nutrient balance. Index equations are symmetrical when all nutrient ratios used in the analysis are discriminatory for plant response. When a nutrient element discriminated in one or more ratios, but not in all nutrient combinations, symmetry was achieved by setting their standardization functions equal to zero. Fraser fir perform well across a broad range of micronutrient concentrations; therefore, broad norm ranges for certain ratios, as opposed to discrete norms, were incorporated into the system. This combination of modifications to the traditional use of the system is an example of how DRIS can be successfully applied to nonconventional crops.

REFERENCES

Beaufils, E.R. 1971. Physiological diagnosis—a guide for improving maize production based on principles developed for rubber trees. FSSA J. 1:1–31.

Beaufils, E.R., and M.E. Sumner. 1976. Application of the DRIS approach for calibrating soil and plant factors in their effects on yield of sugarcane. Proc. S. Afr. Sugar Technol. Assoc. 50:118–124.

Beverly, R.B. 1987. Modified DRIS method for simplified nutrient diagnosis of "Valencia" oranges. J. Plant Nutr. 10:1401–1408.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—total. p. 595–622. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Elwali, A.M.O., and G.J. Gascho. 1984. Soil testing, foliar analysis, and DRIS as guides for sugarcane fertilization. Agron. J 76:466–470.

Hockman, J.N. 1986. Evaluating the nutritional status of Fraser fir (*Abies fraseri* [Pursh] Poir.) Christmas trees using foliar analysis and DRIS application. M.S. Thesis. Virginia Polytechnic Inst. and State Univ., Blacksburg.

Hockman, J.N., J.A. Burger, and D.W. Smith. 1989a. A DRIS application to Fraser fir Christmas trees. Commun. Soil Sci. Plant Anal. 20:305–318.

Hockman, J.N., J.A. Burger, and D.W. Smith. 1989b. Spatial and temporal variability of foliar nutrient levels in Fraser fir Christmas trees. For. Sci. 35:632–639.

Hockman, J.N., J.A. Burger, and D.W. Smith. 1990. Classification model to predict Fraser fir Christmas tree grade. For. Sci. 36:45–53.

Jones, C.A. 1981. Proposed modifications of diagnosis and recommendation integrated system (DRIS) for interpreting plant analyses. Commun. Soil Sci. Plant Anal. 12:785–794.

Kim, Y.T., and R.H. Leech. 1981. The potential use of DRIS in fertilizing hybrid poplar. Commun. Soil Sci. Plant Anal. 17:429–438.

Kopp, V.A., and J.A. Burger. 1990. Applying DRIS to Fraser fir Christmas trees. Soil Sci. Soc. Am. J. 54:453–456.

Letzsch, W.S., and M.E. Sumner. 1984. Effect of population size and yield level in selection of Diagnosis and Recommendation Integrated System (DRIS) norms. Commun. Soil Sci. Plant Anal. 15:997–1006.

Mead, D.J. 1984. Diagnosis of nutrient deficiencies in plantations. p. 259–291. *In* G.D. Bowen and E.K.S. Nambiar (ed.) Nutrition of plantation forests. Academic Press, London.

Pritchett, W.L., and R.F. Fisher. 1987. Properties and management of forest soils. 2nd ed. John Wiley & Sons, New York.

Rathfon, R.A. 1990. Developing DRIS norms for Fraser fir Christmas trees. M.S. Thesis. Virginia Polytechnic Inst. and State Univ., Blacksburg.

Righetti, T.L., O. Alkoshab, and K. Wilder. 1988. Diagnostic biases in DRIS evaluations on sweet cherry and hazelnut. Commun. Soil Sci. Plant Anal. 19:1429–1447.

Sumner, M.E. 1977. Use of the DRIS system in foliar diagnosis of crops at high yield levels. Commun. Soil Sci. Plant Anal. 8:251–268.

Technicon Industrial Systems. 1978. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Industrial Method no. 329-74W. Technicon Ind. Syst., Tarrytown, NY.

Timmer, V.R., and L.D. Morrow. 1984. Predicting fertilizer growth response and nutrient status of jack pine by foliar analysis. p. 335–351. *In* E.L. Stone (ed.) Forest soils and treatment impacts. Proc. N. Am. For. Soils Conf. 6th, Knoxville, TN. June 1983. Dep. of Forestry, Wildlife, and Fisheries, Univ. of Tennessee, Knoxville.

Walworth, J.L., and M.E. Sumner. 1987. The diagnosis and recommendation system (DRIS). Adv. Soil Sci. 6:149–188.

Field Crop Recovery and Modeling of Nitrogen Mineralized from Labeled Sorghum Residues

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ABSTRACT

Efficient use of fertilizer N requires an assessment of the N contribution from decomposing crop residues. The objectives of this study were to quantify and model the amount of mineralized N recovered by a growing crop from ¹⁵N-labeled sorghum (*Sorghum bicolor* [L.] Moench) residues of variable N concentration and composition. The residues were incorporated into the surface soil of field microplots. The microplots were double-cropped with sorghum and wheat (*Triticum aestivum* L.) for a 3-yr period. The ¹⁵N tag in the crop residue was used to distinguish between residue-derived N and that from soil organic matter. Between 4.5 and 25% of the residue N applied (36–83 kg N ha⁻¹ was applied as crop residue N) was recovered by a sorghum crop 110 d after incorporation. This constituted 56 to 77% of the total N recovered during a 3-yr period. Accumulated N recovered over time was described by modified first-order models. Regression analysis indicated that 93% of the variability in N recovered by 110 d could be explained using the C/N ratio and acid-detergent fiber contents of the residues. Measurements of N mineralized, using the method described above, were compared with predicted N mineralized, using MINIMO (a subroutine of the CERES-Maize model). After adjusting MINIMO parameters using data collected 110 d after residue incorporation, the slope and intercept of a linear fit between measured and MINIMO-predicted N mineralized 1097 d after residue incorporation were not different from one and zero, respectively.

THE DEVELOPMENT of fertilizer recommendations that maintain sustainable crop yields without contaminating the environment is a major problem.

Part of the solution is in quantifying the amount of mineralized N recovered from decomposing crop residues by a growing crop. The C/N ratio of a crop residue is used to qualitatively predict whether net mineralization or immobilization of N will occur during residue decomposition (Harmsen and Van Schreven, 1955; Bartholomew, 1965; Alexander, 1977). Recently, Frankenberger and Abdelmagid (1985), Fu et al. (1987), and Yadvinder-Singh et al. (1988) reported on lab investigations designed to quantify the effect of residue C/N ratio on N mineralization. However, only a few field investigations included the use of several crop residues of variable N content. Wagger et al. (1985a) used ^{15}N-labeled wheat and sorghum residues and found that N from sorghum residues with C/N ratios of 27, 35, 37, and 38 mineralized 33, 19, 15, and 12% of the applied residue N within 1 yr. For wheat residues with C/N ratios from 93 to 117, they reported a net mineralization of 12 to 15% of the N contained in the residue within 1 yr. Ladd et al. (1981, 1983, 1985), and Ladd and Amato (1986), in a series of studies with Coast medic (*Medicago littoralis* Rohde ex Lois.), found that up to 17% of the N applied in the legume residue was recovered by a subsequent wheat crop. In all of the ^{15}N-labeled experiments mentioned above, an association between residue C/N ratio and the amount of N recovered was reported; however, none of the studies were specifically designed to investigate this effect.

This experiment was conducted to estimate the amount of N mineralized from decomposing sorghum residues of variable N content under field conditions by measuring N uptake in a growing crop. A second objective was to describe, with mathematical models, the relationship between the chemical properties of a crop residue and the amount of N mineralized over time. Our final objective was to compare the measured amounts of N mineralized with those predicted by an existing simulation model, MINIMO, a subroutine of the CERES-maize model (Jones and Kiniry, 1986) taken from the mineralization-immobilization portion of the PAPRAN model (Seligman and Van Keulan, 1981).

MATERIALS AND METHODS

Crop Residue Collection and Labeling

On 2 July 1984, sorghum was planted 8 cm apart, in rows spaced 76 cm apart, at the Ashland and North Agronomy Farm Research Centers in Manhattan, KS, on a Haynie fine sandy loam (coarse-silty, mixed (calcareous), mesic Mollic Udifluvent) and a Smolan silt loam (fine, montmorillonitic, mesic Pachic Argiustoll), respectively. The planted sorghum was separated from the surrounding field area by inserting a plywood barrier 0.6 m deep around 6 rows 3.3 m long. Two weeks after seedling emergence, K^{15}NO$_3$ mixed with unenriched NH$_4$NO$_3$ was applied at N rates of 200 or 20 kg ha^{-1} (2.1 and 10.6 atom % ^{15}N, respectively). The fertilizer was injected as a solution with a syringe 5 cm deep and 5 cm away from individual plants. Sorghum was harvested on 13, 20, and 27 Aug., 6 and 17 Sept., and 3 Oct. 1984 at both sites in an effort to obtain sorghum tissues of variable N concentration. Sorghum tissues were oven dried at 50 °C for 5 d. Mature plants of the 6 and 17 Sept. and 3 Oct. harvests were separated into leaves, stems, and heads. Leaves were chopped into particles no longer than 3 cm. Stem materials were cut into 6-cm lengths. Head materials that had grain

were not used. Plants of earlier harvests on 13, 20, and 27 Aug. were chopped as whole plants. Crop residues were stored at room temperature in a cool, dry, air-conditioned storeroom. Total N was determined using the method of Bremner (1982), and samples for isotope-ratio analysis were prepared using the method of Wagger et al. (1985b). Isotope ratios of the residues were determined with a Perkin-Elmer RMS-4 mass spectrometer (Perkin-Elmer, Norwalk, CT), using the method of Smith et al. (1963). Total C was determined on a Leco C analyzer (Leco Corp., St. Joseph, MI) and the contents of permanganate lignin, cellulose, hemicellulose, acid-detergent fiber (ADF), and neutral-detergent fiber (NDF) were determined using the methods of Goering and Van Soest (1970).

In the following spring of 1985, a 6 by 11 m area of Smolan silt loam on a southern slope (3–5% slope) at the North Agronomy Farm, Manhattan, KS, was raked clear of the previous year's sorghum residues. Twelve field microplots consisting of open-ended steel boxes (0.61 by 0.61 by 0.61 m) were then installed 1 m apart in two rows 2.28 meters apart, six microplots to a row, using the device described by Swallow et al. (1987). The Smolan silt loam has a 1:1 soil/water pH of 6.4, a total organic N of 1.2 g N kg^{-1} soil, a total C content of 14.1 g C kg^{-1} soil, and an average surface (0–10 cm) bulk density of 1.0 g cm^{-3}. Following installation on 29 May 1985, the soil in each microplot was excavated to a depth of 12 cm, combined in one lot, and carefully mixed; then a known weight of soil was repacked into individual microplots to a bulk density of 1.1 g/cm^3. The soil in each microplot was sampled just before residue incorporation by taking eight, 25-mm-diameter cores from the 0- to 10-cm depth and three cores from the 10- to 25-, 25- to 45-, and 45- to 65-cm depths. These samples were used for moisture analysis by drying a subsample of each in a forced-air oven at 105 °C. The remainder of the sampled soil was dried at 45 to 50 °C and later used for inorganic-N, and total-N determination. Total N was determined in the 0- to 10-cm depth for each microplot by digesting 0.5-g samples in salicylic–sulfuric acid (Bremner and Mulvaney, 1982) and analyzing the NH$_4^+$-N in the digest with a Technicon Autoanalyzer (Technicon Industrial Systems, 1977a,b). Ammonium N and NO$_3^-$-N were determined in all soil samples for each microplot using 2 M KCl as the extractant and the Technicon Autoanalyzer for analysis.

On 30 May 1985, the crop residues listed in Table 1 were mixed into the top 10 cm of soil of individual microplots at a rate of 3947 kg residue ha^{-1}. Duplicate microplots were prepared for residues containing C/N ratios of 20, 25, 30, and 44. Single microplots were prepared for residues with C/N ratios of 27 and 37. Two additional microplots received no residue and were used as checks. Soil temperatures at 5 and 15 cm were recorded daily using Datapod temperature recorders (Omnidata Int., Logan, UT) from mid-May until the end of October in two microplots. The recorders were set to record the maximum, minimum, and average soil temperatures on a daily basis. During the winter and early spring months, soil temperatures were not measured daily. Missing soil temperatures at these times were estimated from soil temperatures measured daily at a weather station located approximately 500 m from the microplots.

Sorghum was planted on 1 June 1985 in a single row down the center of each microplot. Three weeks after seedling emergence, the plots were thinned to seven plants per microplot. Sorghum was also planted in the area surrounding the microplots in rows 76 cm apart and thinned to a plant population of 150 000 plants ha^{-1}. On 19 Sept. 1985, the plants in each microplot were pulled up by hand. Soil clinging to roots was shaken off into the microplot. The heads, leaves, stems, and crowns plus large roots were separated and dried at 50 °C for 3 d. The heads were threshed, the chaff combined with the stover, and the grain and stover dry weights were recorded. The plant tissues were ground to pass

Table 1. Selected chemical properties of the sorghum crop residues added to field microplots.

Residue description†	C/N	¹⁵N	Total N	Total C	Lignin	ADF‡	NDF‡	Cellulose	Hemicellulose
		atom %				g kg⁻¹			
Stage 2 sorghum plants	20	1.51	21.0	411	51	332	568	244	234
Stage 3 sorghum plants	25	1.10	17.1	419	51	299	572	239	273
Postharvest sorghum leaves	30	1.70	13.3	404	71	409	656	290	247
Postharvest sorghum leaves	37	2.44	11.0	407	57	343	596	263	253
Stage 4 sorghum stems	27	1.30	15.3	411	57	274	523	224	249
Postharvest sorghum stems	44	2.29	9.2	408	74	328	594	261	266

† Sorghum residue maturity indicated is as described by Vanderlip (1979).
‡ ADF = acid-detergent fiber; NDF = neutral-detergent fiber.

a 1-mm sieve, and total N and atom % ¹⁵N was determined using the methods described previously. On the day when plants were harvested, soil samples for inorganic N analysis, gravimetric moisture, and bulk-density measurements to a depth of 65 cm were taken at the same depth increments used prior to sowing. Bulk-density measurements were used for water-balance determinations. Gravimetric moisture contents were also determined in the plot area around the microplots by taking four cores to a depth of 65 cm, also at the same depth increments.

Wheat was planted on 18 Oct. 1985, in two rows spaced 15 cm apart down through the center of each microplot. As with sorghum, the area between and around the microplots was planted with wheat at the same row spacing. Just prior to planting the wheat and all subsequent crops, 30 kg P ha⁻¹ as superphosphate (0–20–0) and 5 kg Zn ha⁻¹ as ZnSO₄ were mixed into the soil of each microplot, since a soil test indicated medium to low P and Zn levels. On 9 June 1986, wheat was harvested and soil and plant samples were taken as described for sorghum. On 26 June 1986, sorghum was planted again in each microplot using the same procedures as in 1985. Since severe N deficiency appeared to threaten the viability of the experiment, 20 kg N ha⁻¹ as NH₄NO₃ was applied to each microplot 4 wk after emergence of the 1985 sorghum crop. The microplots were then planted with wheat on 18 Oct. 1986. The double-cropped sorghum–wheat rotation was continued for a 3rd yr, giving a total of six crops. The soil was sampled and analyzed for NH₄⁺–N and NO₃⁻–N down to the 65-cm depth at harvest for each of the four crops grown in 1986 and 1987, using the same methods as in 1985.

The accumulated amount of residue N recovered in the harvested plants during the 3-yr period was summed and expressed as a ratio of the mineralized N recovered over the initial amount of N applied in the residue.

Modeling and Curve Fitting

For modeling purposes, we assumed the net amount of N mineralized from the crop residues could be estimated from the mineralized N recovered by the growing crops. We assumed that leaching and denitrification losses were small, and that crop uptake was the major sink for the mineralized N. These assumptions are based on the following:

1. The restriction of the crop roots to the microplot area would prevent them from using N from the surrounding soil. The presence of the growing crop (to which no fertilizer N was added) in the immediate vicinity of the decomposing labeled residues provided an active sink for any mineralized N that might be produced. The active sink of N-deficient plants would limit the buildup of NO₃⁻–N.
2. Most of the N in the labeled crop residues was organic N that would be slowly released through mineralization. This slow release would limit the size of the NO₃⁻–N pool for potential leaching and denitrification losses.
3. The Smolan silt loam has a thick argillic horizon and

a very low leaching potential (Kissel et al., 1982) and is categorized as having insignificant amounts of leaching on an annual basis.
4. The placement of the microplots on the side of a hill with a gentle slope would prevent them from being flooded for extended periods of time.

Regression analysis was performed on the mineralized N recovered 110 d after incorporation, using the chemical properties of the crop residues as independent variables. Regression equations were fit using two independent variables at a time for all of the residue chemical properties measured. The model fitted was:

$$Nmin_{(110)} = \beta_0 + \beta_1(X_1) + \beta_2(X_2) \qquad [1]$$

where $Nmin_{(110)}$ is the amount of N mineralized recovered by Day 110 and X_1 and X_2 are two chemical properties of the residue that can be best used to predict the amount of mineralized N recovered by the growing crop. All possible two-parameter models were determined.

The relative mineralized N recovered (relative to the amount recovered by Day 110) from each of the incorporated residues was also calculated by dividing the amount of mineralized N recovered at 110, 476, 840, and 1097 d by the amount recovered at 110 d and then subtracting one from the relative values. This set the amount of mineralized N recovered by Day 110 equal to zero. A modified form of the first-order model used to describe N mineralization of native soil organic matter (Stanford and Smith, 1972) was fit to the relative N mineralized between 110 and 1097 d. The modified first-order model used was:

$$RNmin = N_{or}[1 - e^{-k(t - 110)}] + 1 \qquad [2]$$

where RNmin is the cumulative amount of mineralized N recovered on any day after Day 110 relative to the amount of mineralized N recovered at Day 110, N_{or} is the organic N remaining in the crop residue or soil at 110 d that is potentially mineralizable after 110 d, k is the fitted rate constant in day⁻¹, and t is time in days.

The long-term mineralization for any of the residues could be predicted by combining Eq. [1] and [2]. This was accomplished for a specific crop residue by first using Eq. [1] to determine the amount of N mineralized by Day 110 from the chemical properties (X_1 and X_2) of the residue. This amount was then multiplied by the predicted relative N mineralized for any day (after 110) using Eq. [2]

$$Nmin_{(110+t)} = Nmin_{(110)} \times RNmin_{(t)} \qquad [3]$$

where $Nmin_{(110+t)}$ is the amount of N mineralized at any time after 110 d, $Nmin_{(110)}$ is the amount of N mineralized by 110 d determined from Eq. [1], and $RNmin_{(t)}$ is the N mineralized relative to the amount mineralized by Day 110 determined from Eq. [2].

The MINIMO model, a subroutine of the CERES-Maize model, was also used to simulate the amounts of mineralized N recovered by 110 through 1097 d. In this simulation, the simulated amount of N mineralized from the labeled residues was assumed to be the amount that would be recovered
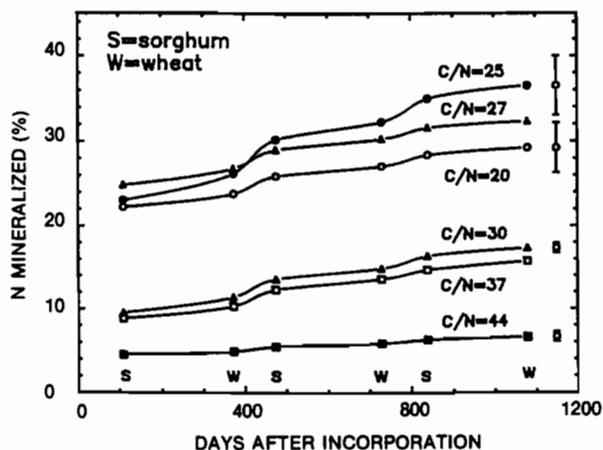
Fig. 1. Accumulated mineralized N recovered from ^{15}N-labeled sorghum residues by double-cropped sorghum and wheat during a 3-yr period. The error bars are the largest standard errors of the mean for a C/N ratio treatment calculated at any harvest.
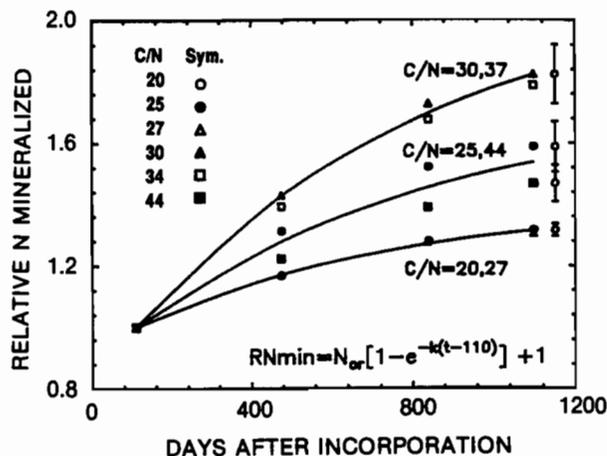

Fig. 2. Accumulated mineralized N recovered relative to the amount recovered by Day 110. The symbols are measured values and the solid lines are predicted by the fitted equations.

by a growing crop. To run this simulation, daily soil temperatures and soil water contents were read from an external data file. Soil parameters used to simulate mineralization in the Smolan silt loam were a surface soil layer depth of 10 cm, a bulk density of 1.0 g cm^{-3}, an initial inorganic N of 12.1 mg kg^{-1}, an organic C content of 14.1 g C kg^{-1} soil, a residue loading rate of 3947 kg ha^{-1}, and several soil moisture parameters expressed on a percent-water basis by volume. Soil-moisture parameters were a soil moisture lower limit (LL) for crop uptake of 0.06, an air-dry soil water content (AD) of 0.05, a saturation water content (SAT) of 0.40, and a drained upper limit (DUL) of 0.32. Soil water content read into the MINIMO model was simulated using the soil water balance model described by Ritchie et al. (1986). The soil water contents measured on 20 different days during the summer of 1988 were used to determine the LL, DUL, AD, and SAT parameters of the water balance model to fit the soil and location of the field study. A weather station approximately 500 m away from the site was used to obtain climatic data for the soil water balance model. MINIMO parameters were adjusted to force an agreement between measured N mineralized and N mineralized as predicted by the MINIMO model.

RESULTS AND DISCUSSION

Generally, as the C/N ratio increased, the percent recovery of mineralized residue N decreased (Fig. 1). The N recovered by the first sorghum crop constituted 56 to 77% of the total N recovered during the 3-yr period. We observed a greater recovery of mineralized N by sorghum plants harvested each fall than by winter wheat plants harvested each spring (Fig. 1), no doubt

due to higher temperatures and more precipitation from April through August (Table 2).

All five crops after the initial sorghum crop harvested in 1985 showed severe N deficiency. Soil NO$_3$-N concentrations were low, whereas soil NH$_4^+$-N did not decrease significantly from year to year (Table 3). The unchanging NH$_4^+$-N concentrations before and after subsequent crops suggests that most of the 2 M KCl-extracted NH$_4^+$-N was not available for crop uptake. In previous unpublished work from our laboratory, we found that a portion of the extracted NH$_4^+$-N was released upon drying the soil at 45 °C or during the extraction process and was not available for crop uptake. Since only small amounts of NO$_3$-N were extracted after each of the six harvests (Table 3), and because of the low leaching potential of Smolan soil (Kissel et al., 1982), the amount of residue mineralized N recovered was assumed to be nearly equal to the net N mineralized.

The first-order models describe the relative N mineralized vs. time accurately (Fig. 2 and Table 4). It is not apparent why the data separates into three curves. The residues with C/N ratios of 30 and 37 are mature sorghum leaves with generally higher ADF, NDF, and

Table 2. Rainfall by month for the years of the study.

Month	1985	1986	1987	1988
			mm	
Jan.	34	0	14	8
Feb.	41	43	31	13
March	44	44	121	13
April	147	85	56	81
May	83	170	194	58
June	113	171	79	91
July	51	119	34	97
Aug.	161	147	134	61
Sept.	154	157	36	47
Oct.	106	141	69	4
Nov.	36	22	69	27
Dec.	14	24	27	1

Table 3. Soil inorganic N extracted with 2 M KCl at each harvest, for sorghum and wheat.

	Sorghum		Wheat	
Soil depth	NH$_4^+$	NO$_3$	NH$_4^+$	NO$_3$
cm		mg kg^{-1}		
	1985		1986	
0–10	7.47	0.75	10.45	2.08
10–25	7.60	0.45	7.90	0.72
25–45	7.43	0.32	6.58	0.43
45–65	6.47	0.23	6.23	0.32
	1986		1987	
0–10	5.82	0.93	4.93	0.87
10–25	6.13	0.67	4.47	0.17
25–45	5.85	0.62	4.60	0.08
45–65	5.15	0.70	3.97	0.00
	1987		1988	
0–10	6.30	1.12	11.03	1.93
10–25	7.58	0.47	10.22	0.43
25–45	6.15	0.05	9.35	0.28
45–65	5.77	0.05	8.57	0.28

† Values are a mean of six plots in each year. No significant differences due to C/N ratio treatment were measured.
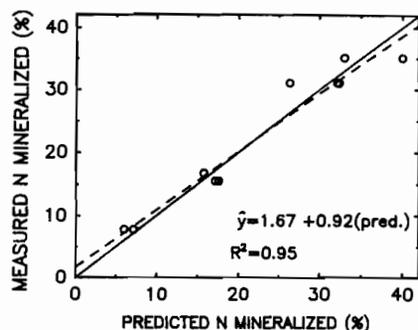
Fig. 3. A comparison between measured and predicted mineralized N recovered by 1097 d after incorporation. The predicted values were determined from a combination of Eq. [4] and the three first-order models.

lignin contents than the other residues (Table 1). The microbes decomposing mature sorghum leaves were able to mineralize only 8.8 and 9.5% of the total residue N applied by 110 d (Fig. 1). But after 110 d, the increase in the amount of N mineralized was greater for mature sorghum leaves than for any of the other residues (Fig. 2). Since the top 12 cm of soil was the same for all microplots, it's likely that residue composition was affecting the difference in the amount of N mineralized. After 110 d, plots treated with mature sorghum leaves could have had a lager pool of readily mineralizable organic N than the other plots, as suggested by the larger N_{or} value associated with these residues, compared with the other residues (Table 4).

The treatments with C/N ratios of 20, 25, and 27 had lower ADF and relatively high N contents, and mineralized the most N by 110 d. After 110 d, the

amount of N mineralized from the treatments with C/N ratios of 20 and 27 was lowest (Fig. 2). It is possible that the N from the residues remaining in these treatments was not as readily mineralizable as the first 22 to 23% mineralized in the first 110 d. It is also possible that some denitrification losses may have occurred.

The best two-parameter regression model fit to the amount of mineralized N recovered by 110 d was:

$$\text{Nmin} = 70.88 - 0.794(\text{C/N}) - 0.942(\text{ADF}) \quad [4]$$

where Nmin is the N mineralized recovered by 110 d as percent of N initially applied in the residue, and C/N is the C/N ratio and ADF is the ADF content of the residue. The R^2, root mean square error (RMSE), and F of regression for Eq. [4] were 0.93, 2,56, and 49.01, respectively. The F of regression was significant at the 0.01 level of probability.

The first-order models (Table 4) were used in combination with Eq. [4] to predict the amount of mineralizable N recovered 1097 d after incorporation. The slope and intercept of the linear fit between measured and predicted mineralized N recovered is not significantly different from one and zero, respectively (Fig. 3 and Table 5).

Simulation Modeling

A comparison between soil water contents measured in 1985 and those simulated using the soil water balance model are described by the following fitted regression equation:

$$\text{Meas.} = 2.664 + 0.9217(\text{Simu.}) \quad [5]$$

where Meas. is soil water content gravimetrically determined and Simu. is soil water content as predicted by the soil water balance model. The slope and intercept of the fitted regression equation are not significantly different from one and zero, respectively, indicating a close relationship between measured and simulated soil water contents. The r^2, RMSE, and F of the fitted regression were 0.92, 1.455, and 153.62, respectively.

The MINIMO model, based on the mineralization-immobilization routine in PAPRAN (Seligman and Van Keulan, 1981), was used to simulate the net amounts of N mineralized (Table 5). In all cases, the

Table 4. The amount of organic N remaining in the crop residue after 110 d that is still potentially mineralizable (N_{or}), the fitted rate constant k, and associated statistics from the modified first-order models fit to relative mineralized N recovered from microplots treated with residue of various C/N ratios.

C/N ratio	N_{or}	k	R^2	RMSE†
		d^{-1}		
20, 27	0.408	0.00148	0.98	0.0135
25, 44	0.753	0.00126	0.89	0.0779
30, 37	1.152	0.00127	0.96	0.0707

† Root mean square error.

Table 5. Measured and predicted mineralized N recovered 110 and 1097 d after incorporation from ^{15}N-labeled sorghum residues of various C/N ratios.

C/N	110 d				1097 d		
	Meas.†	Predicted by Eq. [5]	Predicted by MINIMO		Meas.	Eq. [5] with first-order model	MINIMO adjusted
			Original	Adjusted			
				%‡			
20	22.3(2.6)	23.7	63.0	25.3	29.2(2.9)	31.1	45.2
25	23.0(3.4)	22.8	56.7	20.2	36.5(3.5)	35.1	35.3
27	24.8	23.6	56.5	18.9	32.3	31.0	32.8
30	9.5(0.6)	8.5	55.0	16.6	17.3(0.1)	15.5	28.4
37	8.8	9.2	46.3	9.5	15.7	16.7	16.8
44	4.5(0.6)	5.0	38.8	3.9	6.6(0.6)	7.8	7.7
RSS†		46	2 123 690	209		66	814
LSD¶	6.0				1.5		

† Measured N mineralized are the means for plots of two replications treated with C/N ratios of 20, 25, 30, and 44. Values in parentheses are the standard errors.
‡ Values are the amount of mineralized N recovered expressed as a percent of the amount of N applied in the residue.
§ RSS is the residual sum of squares.
¶ LSD significant at the 0.05 probability level calculated from replicated data only.
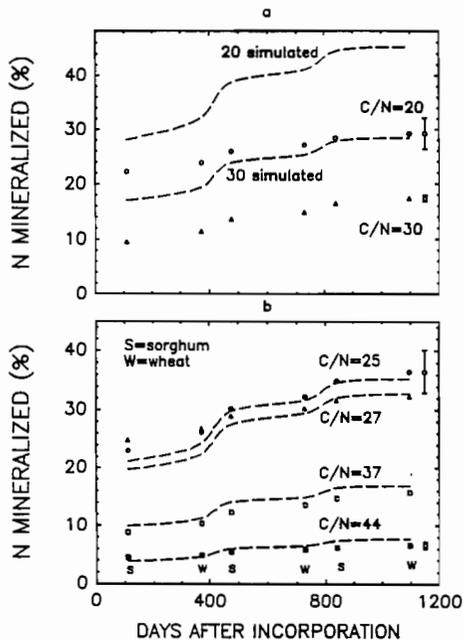
Fig. 4. A comparison between measured and simulated mineralized N recovered using the MINIMO model after adjustment: (a) data points overpredicted by model, (b) accurately predicted data. The symbols are measured values and the dashed lines are predicted by the fitted equations. The error bars are the largest standard errors of the mean for a C/N ratio treatment calculated at any harvest.

amount of mineralized N recovered that MINIMO predicted was two to nine times greater than that measured. Three rate constants are used in MINIMO to calculate the gross rate of decomposition of a crop residue. The rate constants are 0.8, 0.05, and 0.0095 d^{-1}, representing the decomposition rates for residue carbohydrate-like (RDCARB), cellulose-like (RDCELL), and lignin-like (RDLIGN) fractions of a crop residue, respectively. In order to bring the MINIMO-simulated values closer to those measured with the ^{15}N-labeled residues, we decreased the rate constants to 0.05, 0.00425, and 0.00095 d^{-1} for RDCARB, RDCELL, and RDLIGN, respectively. This change in rate constants decreased the size of the difference between measured and simulated N mineralization (Table 5). The values of 0.05, 0.00425, and 0.00095 d^{-1} are nearly the same as those originally used for crop residues by Beek and Frissel (1973) of 0.075, 0.005, and 0.00095 for RDCARB, RDCELL, and RDLIGN, respectively.

The MINIMO routine also contains an equation that adjusts the various rate constants based on the C/N ratio of the mixture of freshly incorporated organic matter (FOM) and soil. This equation in its original form is

$$CNRF = e^{-0.693[(CNR - CNMAX)/CNMAX]} \qquad [6]$$

where CNRF is the adjusting C/N ratio factor for the decomposition rate constant, CNR is a C/N ratio determined by dividing the C in FOM by the sum of the N in FOM and the soil inorganic N, and CNMAX is the C/N ratio when no decrease in the decomposition rate constant is calculated. In MINIMO, if the calculated value of CNRF is greater than one, the value of CNRF is set equal to one. In this way, the decom-

position rate of residues with C/N ratios smaller than CNMAX are never decreased by the CNRF function. The decomposition rates for all residues with C/N ratios larger than CNMAX are decreased slightly. In its original form, CNMAX is set at 25, so that the value of CNRF for residues with C/N ratios of 25, 30, 35, 40, and 45 are 1.0, 0.87, 0.76, 0.65, and 0.57 respectively. If we use Eq. [6] to calculate CNRF values for our residues with C/N ratios of 25, 27, 30, 37, and 44, we get values of 1.0, 0.95, 0.91, 0.72, and 0.59, respectively. The maximum mineralized N recovered by 110 d was 25% from the plot treated with a residue with a C/N ratio of 27 (Table 5). The lowest recovery of 4.5% was from plots treated with residues with a C/N ratio of 44. If we divide 4.5 by 25%, we get 0.18. This means that the residue with a C/N ratio of 44 mineralized about 0.18 of the maximum amount of 25% of the residue N applied. The value of 0.18 is much less than the 0.57 we approximated using Eq. [6]. This suggests that, for the sorghum residues used in our experiment, the decrease in the rate constant as affected by C/N ratio may be greater than the value calculated by Eq. [6]. It is also possible that, for sorghum residues, the maximum release rate is not achieved at a C/N ratio of 25. The C/N ratio at which CNRF is maximum for our field experiment can now be calculated by setting CNR equal to 44 and CNRF equal to 0.18.

$$0.18 = e^{-0.693[(44 - CNMAX)/CNMAX]} \qquad [7]$$

After taking the natural log of both sides of Eq. [7] and rearranging, the value of CNMAX was calculated to be 12.7. The simulation was repeated using 13 in place of 25, which gave better results, particularly with C/N ratios of 30, 37, and 44. However, the predicted amounts of N mineralized in treatments with C/N ratios of 20, 25, and 27, were 30 to 40% less than measured. A final adjustment was made to increase the amount of mineralized N recovered for the narrower C/N ratio by decreasing the N requirement for microbial decay from 0.02 to 0.0165. In the model, the N-requirement value of 0.02 was originally calculated from the product of the fraction of C in FOM (0.4), the biological efficiency of C turnover by soil microbes (0.4), and the N/C ratio of soil microbes (0.125). Microbial efficiencies of C turnover of 40 to 60% are considered realistic for the decomposition of carbohydrates (Paul and Clark, 1989). If we allow for two or more C-turnover cycles to occur, then we could have efficiencies of only 0.20 to 0.36. In the field, where we have more than one cycle of turnover, it is not unreasonable to assume that the microbial efficiency of C turnover could be closer to 0.33 (J.W. Doran, 1990, personal communication). If we make this assumption, then

$$0.0165 = 0.4 \times 0.33 \times 0.125,$$

which demonstrates that a microbial N requirement of 0.0165 is not theoretically unreasonable. More importantly, this allows the MINIMO model to accurately predict the amount of mineralized N recovered. A linear fit between predicted and measured mineralized N recovered at 110 d had a slope and intercept that were not significantly different than one and zero, respectfully, indicating a reasonable simulation (Table

5). The MINIMO model was then used to simulate the amount of N mineralized for the rest of the 1097 d after residue incorporation (Fig. 4). The model was able to mimic the measured data quite well, particularly for residue treatments with C/N ratios of 25, 27, 37, and 44 (Table 5 and Fig. 4b). The model also predicted the measured increase in mineralization during the summer months due to warmer temperatures and generally moist conditions.

The relationship in Fig. 4a between measured and predicted N mineralized shows the increase in mineralized N recovered during the summer months. For residues with C/N ratios of 20 and 30, however, the model overpredicted the amount of N mineralized. We didn't include a denitrification component in the model and it is possible that, for the C/N ratio of 20, we may have had some denitrification loss. The residue with a C/N ratio of 20 was composed of very young sorghum pants with highly available N and C. This, combined with the moist conditions the spring the residues were incorporated, may have caused some loss. The residue with a C/N ratio of 30 had a higher fiber content than the other residues (Table 1), which could have caused the poorer fit observed with this residue. The difference between measured and simulated N mineralized was larger at 1097 d. However, the slope and intercept of the regression fit between measured and simulated N mineralized at 1097 d were not significantly different from one and zero, respectively. In summary the MINIMO model was able to accurately simulate measured N mineralization at 110 through 1097 d after incorporation if: (i) the rate constants for decomposition were decreased, (ii) the value of the C/N ratio at which no decrease in the decomposition rate is calculated is reduced, and (iii) the N requirement for microbial decay is reduced. It would be useful to test the MINIMO parameters selected in this study by running the model on an independent data set (preferably collected under field conditions).

REFERENCES

Alexander, M. 1977. Mineralization and immobilization of nitrogen. p. 136–247. In M. Alexander (ed.) Introduction to soil microbiology. 2nd ed. John Wiley & Sons, New York.

Bartholomew, W.V. 1965. Mineralization and immobilization of nitrogen in the decomposition of plant and animal residues. p. 285–306. In W.V. Bartholomew and F.E. Clark (ed.) Soil nitrogen. Agron. Monogr. 10. ASA, Madison, WI.

Beek, J., and M.J. Frissel. 1973. Simulation of nitrogen behavior in soils. Pudoc, Wageningen, the Netherlands.

Bremner, J.M. 1982. Total nitrogen. p. 699–709. In A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bremner, J.M., and C.S. Mulvaney. 1982. Salicylic acid–thiosulfate modification of Kjeldahl method to include nitrate and nitrite. p. 621–622. In A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Frankenberger, W.T., Jr., and H.M. Abdelmagid. 1985. Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. Plant Soil 87:257–271.

Fu, M.H., X.C. Xu, and M.A. Tabatabai. 1987. Effect of pH on nitrogen mineralization in crop-residue-treated soils. Biol. Fertil. Soils 5:115–119.

Goering, H.K., and P.J. Van Soest. 1970. Forage fiber analyses: Apparatus, reagents, procedures, and some applications. USDA Agric. Handb. no. 379. U.S. Gov. Print. Office, Washington, DC.

Harmsen, G.W., and D.A. Van Schreven. 1955. Mineralization of organic nitrogen in the soil. Adv. Agron. 7:299–398.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize—a simulation model of maize growth and development. Texas A&M Univ. Press, College Station.

Kissel, D.E., O.W. Bidwell, and J.F Kientz. 1982. Leaching classes of Kansas soils. Kansas Agric. Exp. Stn. Bull. 641.

Ladd, J.N., and M. Amato. 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. Soil Biol. Biochem. 18:417–425.

Ladd, J.N., M. Amato, and J.M. Oades. 1985. Decomposition of plat material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labeled legume material and soil organic matter, decomposing under field conditions. Aust. J. Soil Res. 23:603–611.

Ladd, J.N., J.M. Oades, and M. Amato. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. Soil Biol. Biochem. 13:251–256.

Ladd, J.N., J.M. Oades, and M. Amato. 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 15:231–238.

Paul, E.A., and F.E. Clark. 1989. Dynamics of residue decomposition and soil organic matter turnover. p. 120–122. In E.A. Paul and F.E. Clark (ed.) Soil microbiology and biochemistry. Academic Press, San Diego, CA.

Ritchie, J.T., J.R. Kiniry, C.A. Jones, and P.T. Dyke. 1986. Model inputs. p. 37–47. In C.A. Jones and J.R. Kiniry (ed.) Ceres-Maize—a simulation model of maize growth and development. Texas A&M Univ. Press, College Station.

Seligman, N.G., and H. Van Kuelen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. p. 192–221. In M.J. Frissel and J.A. Van Veen (ed.) Simulation of nitrogen behavior of soil–plant systems. Pudoc, Wageningen, the Netherlands.

Smith, J.H., J.O. Legg, and J.N. Carter. 1963. Equipment and procedures for N15 analysis of soil and plant material with the mass spectrometer. Soil Sci. 96:313–318.

Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465–472.

Swallow, C.W., D.E. Kissel, and C.E. Owensby. 1987. Soil coring machine for microplots and large soil cores. Agron. J. 79:756–758.

Technicon Industrial Systems. 1977a. Industrial/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Industrial Method no. 334–74W/Bt. Technicon Industrial Systems, Tarrytown, NY.

Technicon Industrial Systems. 1977b. Nitrate and nitrite in soil extracts. Industrial Method no. 487–77 A. Technicon Industrial Systems, Tarrytown, NY.

Vanderlip, R.L. 1979. How a sorghum plant develops. Kansas Agric. Exp. Stn. Bull. 1203.

Wagger, M.G., D.E. Kissel, and S.J. Smith. 1985a. Uniformity of nitrogen-15 enrichment in different plant parts and subsequent decomposition monitoring of labeled crop residues. Soil Sci. Soc. Am. J. 49:1205–1208.

Wagger, M.G., D.E. Kissel, and S.J. Smith. 1985b. Mineralization of nitrogen from nitrogen-15 labeled crop residues under field conditions. Soil Sci. Soc. Am. J. 49:1220–1226.

Yadvinder-Singh, Bijay-Singh, M.S. Maskina, and O.P. Meelu. 1988. Effect of organic manures, crop residues and green manure (Sesbania aculeata) on nitrogen and phosphorus transformations in a sandy loam at field capacity and under waterlogged conditions. Biol. Fertil. Soils 6:183–187.