# PLANT GROWTH COMPONENT OF A SIMPLE RYE GROWTH MODEL

G. W. Feyereisen, G. R. Sands, B. N. Wilson, J. S. Strock, P. M. Porter

**ABSTRACT.** *Cover cropping practices are being researched to reduce artificial subsurface drainage nitrate-nitrogen (nitrate−N) losses from agricultural lands in the upper Mississippi watershed. A soil-plant-atmosphere simulation model, RyeGro, was developed to quantify the probabilities that a winter rye cover crop will reduce artificial subsurface drainage nitrate−N losses given climatic variability in the region. This article describes the plant growth submodel of RyeGro, Grosub, which estimates biomass production with a radiation use efficiency-based approach for converting intercepted photosynthetically active radiation to biomass. Estimates of nitrogen (N) uptake are based on an empirical plant N concentration curve. The model was calibrated with data from a three-year field study conducted on a Normania clay loam (fine-loamy, mixed, mesic Aquic Haplustoll) soil at Lamberton, Minnesota. The model was validated with data measured from a field trial in St. Paul, Minnesota. The cumulative rye aboveground biomass predictions for the calibration years differed by −0.45, 0.09, and 0.16 Mg ha$^{-1}$ (−17%, 9%, and 32%), and the plant N uptake predictions differed by −10.5, 8.0, and 4.0 kg N ha$^{-1}$ (−16%, 30%, and 21%) from the observed values. The predictions of biomass production and N uptake for the validation year varied by −1.4 Mg ha$^{-1}$ and 16 kg N ha$^{-1}$ (−27% and 24%) from the values observed in the field study, respectively. A local sensitivity analysis of eight input parameters indicated that model output is most sensitive to the maximum leaf area index and radiation use efficiency parameters. Grosub demonstrated the capability to predict seasonal aboveground biomass production of fall-planted rye in southwestern Minnesota within an accuracy of ±30% in years when production exceeds 1 Mg ha$^{-1}$ by mid-May, and to predict seasonal rye N uptake within ±25% of observed values.*

***Keywords.*** *Cover crop, Nitrogen uptake, Plant growth modeling, Sensitivity analysis.*

Hypoxic zones occur in several coastal estuaries around the world, and one of the largest zones can be seen in the northern Gulf of Mexico at the mouths of the Mississippi and Atchafalaya Rivers (Rabalais et al., 2001). The low levels of oxygen in the gulf waters can be traced to a cycle that is exacerbated by high levels of nitrogen (N) entering the gulf from these rivers (Rabalais et al., 1996). Nutrient loading in the Mississippi River has been increasing in quantity since the 1950s (Antweiler et al., 1995). Analysis of the sources of the N in the Mississippi River indicates that the upper Mississippi watershed, including Minnesota and Iowa, is a significant contributor. Agricultural subsurface drainage systems can expedite N losses from agricultural lands to surface waters (Zucker and Brown, 1998). These systems are used to increase crop productivity and reduce the risk of lowered crop yields from root zone excess water stress during wet years (Fausey et al., 1995). However, agricultural drainage systems have created a pathway by which nutrients can escape from the fields they are intended to enhance (Skaggs et al., 1994).

One cropping system modification that is being researched to reduce the field loss of N through subsurface drainage systems is the use of fall-planted cover crops to accumulate residual soil nitrate prior to establishment of the succeeding summer crop. Cover crops can affect the water balance, reduce soil nitrate−N level, and provide residue cover on agricultural fields that are normally fallow between summer crops. In order to measure the effect of a rye cover crop on artificial subsurface drainage nitrate−N losses in a corn-soybean crop rotation, Strock et al. (2004) conducted a three-year field study in southwestern Minnesota. They reported that a cropping system that included a winter rye cover crop reduced drainage volume and nitrate−N loss by 11% and 13%, respectively, compared to a cropping system with no cover crop. This field research also indicated that under favorable conditions autumn-planted cereal rye could reduce nitrate−N losses by up to 50% when planted after corn in a corn-soybean crop rotation.

The question remains for northern latitude climates (e.g., upper Midwest) of how effective the use of a rye cover crop planted after corn will be over the long term given the characteristics of the north central region's cold climate. Increasingly, computer simulation models have been used as a tool to address such questions of the potential agronomic

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and environmental effects of proposed crop management strategies (Wagner-Riddle et al., 1997; Parsch et al., 1991; Richter, 1999; Delgado, 1998).

The goal of this research was to develop a simplified plant growth model that could be incorporated into a soil-plant-atmosphere model for water quality modeling. The soil-plant-atmosphere model RyeGro was developed to predict aboveground biomass production and N uptake of rye planted after the fall harvest of corn in the corn-soybean crop rotation common to southwestern Minnesota, and to simulate subsequent artificial subsurface drainage nitrate−N losses at the field scale during the fall through spring period. Variable climate conditions and selection of dates for fall sowing and spring desiccation were assumed to be significant factors in the simulation. The model predicts surface runoff, infiltration, drainage flow and nitrate−N movement, soil moisture, rye biomass production and N uptake, soil temperature, and snow accumulation and melt on a daily basis, given a set of climatic inputs and soil and crop parameters. Feyereisen et al. (2006a) documented the hydrology and N submodels of RyeGro, and the application of the model to stochastic analysis (Feyereisen et al., 2006b).

Processes simulated in RyeGro were represented only to levels of complexity sufficient to meet the objectives of the proposed research. Limited field data were available for calibration and validation, a factor that deterred development of model components based on more complex algorithms. In addition, simulation of cold-climate conditions allowed some processes to be modeled more simply. The model was intended to simulate mid-September to late-May environmental conditions, when temperatures are cool and precipitation is relatively light in the geographic location under investigation (table 1). During this period, evapotranspiration is low, soil water flow is primarily downward (little upflux), convective precipitation is minimal, and plant growth typically halts when average air temperature is below 0°C.

Holtan's infiltration scheme (Holtan, 1961), based on available storage in the soil surface layer, was used to determine infiltration and surface runoff. The soil profile was represented as a series of three soil layers; percolation from one layer to the next lower layer was calculated when soil moisture in the higher layer exceeded field capacity. Percolation and drainage were calculated as a function of soil moisture content and hydraulic conductivity. Depending on available climate inputs, evapotranspiration was determined by either the Priestley-Taylor method (Priestley and Taylor, 1972) or the Penman method (Penman, 1948). A simplified N cycle was employed to estimate net mineralization, fresh organic N mineralization, plant uptake, and mass flow of nitrate−N. Given that air and soil temperatures are near or below freezing in Minnesota during much of the period of the year under study, mineralization of cellulose and lignin in the fresh stover, denitrification, and volatilization were ignored.

This article describes the development and performance of Grosub, the rye growth component of the soil-plant-atmosphere model RyeGro.

# Methods

## Model Description

The rye growth component of RyeGro, Grosub, was based on the solar radiation interception concept of Monteith (1977). A daily potential biomass was calculated given plant leaf area and shortwave solar radiation; the actual biomass was determined by multiplying the potential biomass by the lesser of air temperature and soil moisture stress reduction factors. Total biomass was divided between aboveground shoot and belowground root fractions based on the maturity of the plant.

Several assumptions and simplifying principles were made during the development of Grosub. The calculation of daily biomass production was based on the leaf area index of the plant canopy. The model was used to predict biomass only, not grain yield; therefore, phenological development after germination was simplified by recognizing only one vegetative growth stage. The assumption was made that the rate of biomass accumulation per unit of solar radiation intercepted by the plant canopy is the same whether the rye was in the tillering or stem elongation stages of development, since both phases are included within the model's single vegetative growth stage. There was no fertilizer application accounted for during rye growth; in the crop rotation being studied, a soybean crop followed the rye and was typically not fertilized. Nitrogen was assumed to be non-limiting in the growth of the rye. Weed, insect, and disease pressures were not modeled; their influence on rye growth was assumed to be negligible. In addition, loss of rye biomass during winter due to respiration was assumed to be minimal and was neglected. According to Nalborczyk and Sowa (2001), rye can survive temperatures to −35°C without snow cover; thus, it was assumed that the rye varieties planted in southern Minnesota would survive in the coldest temperatures experienced there.

## Model Inputs

Rye growth model inputs include the initial planting date and the end date of the simulation run (date of desiccation), seeding rate, optimum growth temperature ($T_{opt}$), base growth temperature ($T_{base}$), heat units to emergence ($HU_{emerge}$), maximum days to emergence (*EmergeDay*), heat units to maturity ($HU_{mat}$), maximum leaf area index ($LAI_{max}$), initial shoot biomass (*InitShootBM*), maximum canopy height ($H_{canopymax}$), and maximum rooting depth ($D_{root\ max}$). Soil model inputs are described in detail in Feyereisen (2005).

**Table 1. Monthly precipitation as a percent of total annual precipitation and monthly mean air temperature at Lamberton for the years 1961 through 2003, and 29-year mean and 2000-2001 measured monthly mean temperatures at St. Paul.**

| Location | | 15-30 Sept. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. | May |
|---|---|---|---|---|---|---|---|---|---|---|
| Lamberton | % of annual precipitation | 3 | 8 | 5 | 2 | 2 | 2 | 6 | 11 | 12 |
| Lamberton | Mean air temperature (°C) | 13.6 | 8.8 | −0.4 | −8.2 | −11.1 | −7.4 | −0.7 | 7.2 | 14.9 |
| St. Paul | 29-year mean temperature (°C) | 16.8 | 9.7 | 0.7 | −6.7 | −9.6 | −6.2 | 0.0 | 8.5 | 15.6 |
| St. Paul | 2000-2001 temperature (°C) | 17.2 | 12.9 | 0.7 | −12.6 | −5.7 | −10.2 | −1.7 | 9.5 | 16.0 |
| St. Paul | Departure from mean (°C) | 0.4 | 3.1 | 0.0 | −6.0 | 3.9 | −4.1 | −1.6 | 1.0 | 0.4 |

Meteorological inputs are either read from a weather file or generated stochastically with an imbedded weather generator. Daily weather variables required include shortwave solar radiation, maximum and minimum air temperature, and precipitation. Additionally, the calculation of evapotranspiration requires either the input of a multiplier for the radiation term, Priestley-Taylor's α (Priestley and Taylor, 1972), or wind speed and minimum and maximum relative humidity for use of the Penman equation (Penman, 1948). Two coefficients, $b_0$ and $b_1$, are needed to calculate net shortwave radiation from the total radiation value read from the input file or generated stochastically. The values used for $b_0$ and $b_1$ in Minnesota (−5.2 and 0.75, respectively) were taken from Jensen et al. (1990).

## Descriptions of Model Components

### *Phenological Development*

The quasi-phenology submodel, PHENOL, recognizes one event after planting, i.e., emergence, followed by one vegetative growth stage. For each simulation year, the submodel accumulates daily heat units from the autumn sowing date, as:

$$HU_{day} = (T_{max} + T_{min})/2 - T_{base} \tag{1}$$

where $HU_{day}$ is daily heat units (°C-d), $T_{max}$ and $T_{min}$ are daily maximum and minimum air temperatures (°C), and $T_{base}$ is the air temperature above which rye grows and develops (°C). A base temperature for cereal rye of 1°C was used. Once either the heat units reach 50°C-d or the time since planting reaches 14 d, the submodel changes the phenological stage from germination to vegetative growth. Setting a maximum length of time prior to emergence was necessary to initiate biomass accumulation in sufficient time for simulated values to match measured values. The maximum days to emergence input parameter (*EmergeDay*) was included in a sensitivity analysis and is discussed in the Results and Discussion section under Sensitivity Analysis. The rye crop remains in the status of developing plant throughout each year's analysis, which typically ends in late spring.

### *Assimilation*

The submodel Grosub estimates biomass assimilation based on radiation intercepted by the growing rye canopy and radiation use efficiency. The basic equation for assimilation, proposed by Monteith (1977) and reiterated by Campbell and Norman (1998), is:

$$A_{nPOT} = \varepsilon \int f_{PAR}\ PAR\ dt \tag{2}$$

where $A_{nPOT}$ is net assimilated biomass (g DM ha$^{-1}$, where DM is dry matter), ε is radiation use efficiency (g DM MJ$^{-1}$), $f_{PAR}$ is the fraction of incident light intercepted by the rye canopy, and *PAR* is the photosynthetically active radiation portion of total solar radiation (MJ per time unit). *PAR* is taken to be 50% of total solar radiation, a common approximation used in plant growth models, e.g., the CERES models (Jones and Kiniry, 1986), which are now parts of the Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al., 2003). The value used in Grosub for ε was 2.8 g DM MJ$^{-1}$, which is toward the middle of the range of values published in the literature. For example, Wilson and Jamieson (1985) cited Kumar and Monteith (1981), who found ε ranges of 2.2 to 2.8 g DM MJ$^{-1}$ for arable crops, while Gillett et al. (2001) reported values of 2.82 to 3.87 g DM MJ$^{-1}$ for winter wheat in the U.K. The range of values for ε used in the Sirius wheat simulation model was 2.2 to 2.5 g aboveground DM MJ$^{-1}$, adjusted according to latitude (Jamieson et al., 1998). Solar radiation interception by the rye canopy ($f_{PAR}$) was represented as a function of the leaf area index (LAI), using a Beer's Law extinction coefficient (Monsi and Saeki, 1953) of 0.65:

$$f_{PAR} = 1 - \exp(-0.65 LAI) \tag{3}$$

This relationship is also used in the DSSAT model (Jones and Kiniry, 1986). Leaf area index was estimated as a function of assimilated aboveground biomass ($A_{nAG}$) according to the relationships used in the EPIC (Williams et al., 1984) and WEPP (Arnold et al., 1995) models:

$$\text{LAI} = LAI_{max} \left( \frac{A_{n_{AG}}}{A_{n_{AG}} + 5512 \exp(-0.000608\, A_{n_{AG}})} \right) \tag{4}$$

where the units of LAI are m$^3$/m$^3$, and the units of $A_{nAG}$ are kg DM ha$^{-1}$. Since LAI estimation assumes a known biomass and biomass accumulation calculation assumes a known LAI, repetitive computation of the model is initiated by assigning an initial total biomass value (*InitShootBM*) of 30 kg DM ha$^{-1}$ to the rye on the day the crop germinates. The LAI is then estimated based on the aboveground portion of the initial total biomass. The day after emergence, potential biomass assimilation is computed using the PAR for that day and the previous day's LAI.

A photosynthetic reduction factor ($K_p$) is used to reduce the quantity of daily potential biomass due to temperature stress and water stress. Each day, the more limiting of the stress reduction factors for temperature ($K_t$) or soil moisture ($K_w$) becomes the photosynthetic reduction factor. The photosynthetic reduction factor is multiplied by the daily potential biomass to calculate actual daily biomass production:

$$A_{nACT} = A_{nPOT}\ K_p \tag{5}$$

where $A_{nACT}$ is actual total assimilated biomass (kg DM ha$^{-1}$), and $A_{nPOT}$ is potential total assimilated biomass (kg DM ha$^{-1}$). The equation for the photosynthetic reduction factor for temperature ($K_t$) is patterned after the one used in CERES-Maize (Jones and Kiniry, 1986):

$$K_t = 0.9 - 0.0025\,(T_{avg} - T_{opt})^2 \tag{6}$$

where $T_{avg}$ is the daily mean air temperature (°C), and $T_{opt}$ is the optimum growth temperature for rye (°C). The reduction factor due to water stress ($K_w$) uses relationships outlined by Larson (1985) based on available soil water ($A_W$) and atmospheric demand, expressed as pan evaporation in inches. High demand is defined as greater than 7.6 mm d$^{-1}$ (0.3 in. d$^{-1}$), moderate demand is between 5.8 and 7.6 mm d$^{-1}$ (0.23 and 0.3 in. d$^{-1}$), and low demand is less than 5.8 mm d$^{-1}$ (0.23 in. d$^{-1}$). The expressions are as follows:

High demand:

$$K_w = -0.15 + 1.53 \frac{A_W}{100} \text{ for } 9.8\% < A_W < 75\% \tag{7a}$$

Moderate demand:

$$K_w = 0.16 + 1.68 \frac{A_W}{100} \text{ for } -9.5\% < A_W < 50\% \quad (7b)$$

Low demand:

$$K_w = 0.57 + 1.72 \frac{A_W}{100} \text{ for } -33\% < A_W < 25\% \quad (7c)$$

where available soil water ($A_W$) is defined as:

$$A_W = 100\,(\theta - \theta_{wp})/(\theta_{fc} - \theta_{wp}) \quad (8)$$

where θ is volumetric moisture content of the soil in the root zone ($cm^3$ of water per $cm^3$ of soil), $\theta_{fc}$ is field capacity soil moisture content ($cm^3$ of water per $cm^3$ of soil), and $\theta_{wp}$ is soil moisture content at −15,300 cm $H_2O$ soil moisture pressure ($cm^3$ of water per $cm^3$ of soil). The value for $K_w$ is zero for available water contents below those listed and is one for available water contents higher than those listed.

The relationship used to partition the total daily biomass production into the aboveground shoot and belowground root portions was based on the heat units experienced by the crop. As the crop matures, the proportion of the daily actual biomass produced that is partitioned to the aboveground shoot increases. Various root-to-shoot relationships were tested, including that of Gillett et al. (2001), which was developed for winter wheat. The closest agreement between predicted and field data for aboveground biomass was obtained using the simple relationship from the Soil Water Assessment Tool (SWAT) watershed-scale model (Arnold et al. 1998):

$$rts_{ratio} = 0.4 - 0.2\, HU_{index} \quad (9)$$

where $rts_{ratio}$ is root-to-shoot ratio, and $HU_{index}$ is the ratio of accumulated heat units during the period of growth and the heat units needed for maturity of the crop. Therefore, equation 9 was incorporated into Grosub.

### *Adjustment of Initial Biomass*

Spring biomass of a fall-planted rye crop can be significantly affected by soil moisture content at the time of sowing and subsequent precipitation in the first weeks thereafter. To account for soil moisture and precipitation effects on the establishment of the cover crop, Grosub makes an adjustment to accumulated biomass 14 d after sowing based on the cumulative precipitation and average soil moisture content during those 14 d. On the 15th day after sowing, the model modifies the existing accumulated aboveground and root biomass with a germination factor, $K_{germ}$. The value of $K_{germ}$ is the minimum value of 1.3 or the result of the following equation:

$$K_{germ} = 0.39 + 0.022\, FDprecip + 0.075\, FD\theta_{avg} \quad (10)$$

where $FDprecip$ is 14-day (FD) cumulative precipitation during the 14 d following sowing (mm), and $FD\ \theta_{avg}$ is average soil moisture content of the surface soil layer (30 cm depth) over the 14-d period. The regression relationship was developed using field data from the three-year study at Lamberton, Minnesota (Strock et al., 2004). Adjusting the aboveground biomass in the autumn accounted for reduced spring biomass yield due to dry autumn conditions and accounted for increased spring biomass yield due to favorable autumn conditions. The field data supported an upper bound of 1.3 for $K_{germ}$ as a limit to the favorable growth response of the cover crop to precipitation and soil moisture conditions.

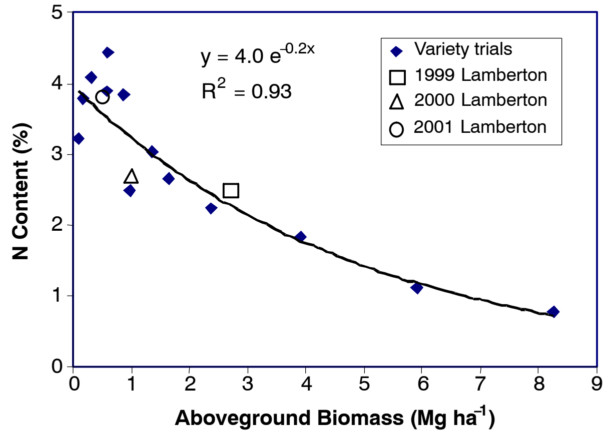


**Figure 1. Rye aboveground N content as a function of cumulative aboveground biomass. Results of 2001 rye variety trials at five locations in Minnesota and the mean measured rye aboveground biomass N concentrations for the three-year calibration study at Lamberton.**

### *Rye N Uptake*

Nitrogen uptake into the rye plant body is estimated using an empirical relationship between the cumulative aboveground biomass and percent N in the plant body:

$$Npct = 4.0\, Exp(-0.2\, A_{n_{AG}}) \quad (11)$$

where $Npct$ is N content of the aboveground biomass (%), and $A_{nAG}$ is aboveground biomass (Mg DM $ha^{-1}$). The relationship is derived from rye growth field studies in Minnesota (Porter, unpublished data) (fig. 1), during which the N content of the rye was checked at regular intervals in the growing season.

### *Canopy Height and Rooting Depth*

Following emergence, canopy height and rooting depth are calculated on a daily basis. The maximum canopy height and maximum rooting depth expected are multiplied by a factor that increases from zero to one. The canopy height factor is a function of cumulative aboveground biomass and a height-biomass factor as follows:

$$H_{canopy} = H_{canopymax}\,[1 - \exp(-0.0001 BMfctr_{height} A_{n_{AG}})] \quad (12)$$

**Table 2. Model soil inputs used for calibration and validation simulations.**

| Property | Calibration (Lamberton) | Validation (St. Paul) |
|---|---|---|
| Holtan's infiltration parameter (cm $h^{-1}$) | 0.9 | 2.54 |
| Depth of surface soil layer (cm) | 30 | 30 |
| $\theta_{sat}$, surface soil layer ($cm^3\ cm^{-3}$) | 0.526 | 0.526 |
| $\theta_{fc}$, surface soil layer ($cm^3\ cm^{-3}$) | 0.320 | 0.320 |
| $\theta_{wp}$, surface soil layer ($cm^3\ cm^{-3}$) | 0.195 | 0.180 |
| Depth of soil layer 2 (cm) | 90 | 75 |
| Sat. conductivity ($K_s$), soil layer 2 (cm $h^{-1}$) | 0.3 | 0.29 |
| $\theta_{sat}$, soil layer 2 ($cm^3\ cm^{-3}$) | 0.400 | 0.453 |
| $\theta_{fc}$, soil layer 2 ($cm^3\ cm^{-3}$) | 0.308 | 0.308 |
| $\theta_{wp}$, soil layer 2 ($cm^3\ cm^{-3}$) | 0.191 | 0.191 |

Table 3. Rye growth field study locations and management dates and initial moisture conditions used for calibration and validation simulations.

| Location | Years of Study | Modeling Purpose | Rye Sowing Date | Rye Aboveground Measurement Date | Initial Moisture Content ($\theta_i$) ($cm^3\ cm^{-3}$) | |
|---|---|---|---|---|---|---|
| | | | | | Surface Soil Layer | Soil Layer 2 |
| Lamberton | 1998-99 | Calibration | 1 Oct. 1998 | 30 Apr. 1999 | 0.32 | 0.23 |
| Lamberton | 1999-00 | Calibration | 29 Sept. 1999 | 2 Apr. 2000 | 0.21 | 0.22 |
| Lamberton | 2000-01 | Calibration | 4 Oct. 2000 | 16 May 2001 | 0.32 | 0.23 |
| St. Paul | 2000-01 | Validation | 18 Sept. 2000 | See note[a] | 0.27 | 0.28 |

[a] Measurement dates: 2 Nov. 2000, 4 Apr. 2001, 13 Apr. 2001, 25 Apr. 2001, 1 May 2001, 7 May 2001, 15 May 2001, 25 May 2001, 4 June 2001, 18 June 2001, and 5 July 2001.

where $BMfctr_{height}$ (ha $kg^{-1}$ DM) is taken to be three, and $A_{nAG}$ is in units of kg DM $ha^{-1}$. The rooting depth ($D_{root}$, in m) is estimated with the heat unit index as the minimum value of $D_{root\,max}$ or $D_{root}$, calculated as:

$$D_{root} = D_{rootmax}\ HU_{index} \tag{13}$$

where $D_{root\,max}$ represents the maximum rooting depth of the rye (m), and $HU_{index}$ is as previously defined.

## Model Calibration

Calibration of Grosub plant growth parameters was performed by comparing predicted rye aboveground biomass with observed values obtained from a three-year rye field study at Lamberton, Minnesota. Rye was planted on or near 1 October in all three years of the study and chemically desiccated in the spring. Prior to desiccation, the aboveground biomass of rye was sampled, weighed, and analyzed for N content. The precipitation and temperature regimes for the three years were highly variable, thus providing a breadth of conditions under which to calibrate Grosub. Precipitation and temperature were above normal (table 1) for the first hydrologic year of the study (1998-1999), providing excellent conditions for rye establishment in the autumn and growth in the spring. Precipitation in the second year of the study was significantly below normal. Temperatures were above normal in November, December, February, and March, resulting in a drier than normal soil profile in the spring. Conditions were wet and cool during the third year of the study, limiting rye growth through mid-May. Complete details of the experimental methods and results and climate patterns from the field study were published by Strock et al. (2004).

Table 2 contains soil property and initial soil moisture content data, respectively, for the calibration and validation simulations. Calibration soil property inputs for the moderately well-drained Normania clay loam (fine-loamy, mixed, mesic Aquic Haplustoll) soil at Lamberton were taken from the SSURGO database. Weather inputs for the calibration simulations were measured at the University of Minnesota Southwest Research and Outreach Center near Lamberton, Minnesota, approximately 1 km from the experimental rye plots. Location, study years, and rye sowing and biomass measurement dates are summarized in table 3. Plant parameter values were chosen within a range common for rye, or for either winter wheat or oats when values for rye could not be obtained from the literature (table 4).

The objective of the calibration was to minimize error between the predicted cumulative aboveground biomass and the observed values at the date of rye desiccation in the spring. The objective function used was the sum of the absolute differences between the predicted and observed cumulative aboveground biomass (Allred and Haan, 1996):

$$ObjVal = \sum_{i=1}^{n} \left|P_i - O_i\right| \tag{14}$$

where $ObjVal$ is the objective function value being minimized, $P_i$ is the predicted value of cumulative aboveground biomass (kg DM $ha^{-1}$), and $O_i$ is the observed cumulative aboveground biomass (kg DM $ha^{-1}$) for each year $i$ of the field study. The chosen objective function places greater weight on observations of smaller magnitude than does the mean square error. Since a database with limited observations was used, this latter advantage was important.

The initial values for the base temperature, optimum temperature, and heat units to emergence and maturity were chosen within ranges obtained from the literature for rye or similar small grains. A value for the initial shoot biomass

Table 4. Rye plant parameter value ranges and selected values for calibration and validation simulations.

| Parameter | Range of Values | Selected |
|---|---|---|
| Plant base temperature (°C) | 0[a] to 4[b] | 1 |
| Plant optimum temperature (°C) | 15[b] to 20[c] | 18 |
| Heat units to emergence (°C-d) | 100[d] | 50 |
| Heat units to maturity (°C-d) | 1700[e] to 2200[a] | 2050 |
| Height from biomass factor (n/a) | 3[b] | 3 |
| Maximum canopy height (m) | 1.14[b] | 1.14 |
| Maximum rooting depth (m) | 0.3[b] | 0.6 |

[a] Denotes values for rye (Nalborczyk and Sowa, 2001).
[b] Denotes values for oats (Arnold et al., 1995).
[c] Denotes value for small grains (Moss, 1984).
[d] Denotes value for spring wheat (Bauer et al., 1984).
[e] Denotes value for spring wheat (Arnold et al., 1995).

Table 5. Measured (*n* = 4) and predicted rye aboveground biomass, N uptake, and N uptake when predicted rye biomass equals measured rye biomass for three calibration years at Lamberton. Values in parentheses represent the standard deviation.

| Year | Observed (Mg $ha^{-1}$) | Predicted (Mg $ha^{-1}$) | Difference (Mg $ha^{-1}$) | Difference (%) |
|---|---|---|---|---|
| Rye biomass | | | | |
| 1998-1999 | 2.7 (0.2) | 2.25 | −0.45 | −17 |
| 1999-2000 | 1.0 (0.1) | 1.09 | 0.09 | 9 |
| 2000-2001 | 0.5 (0.1) | 0.66 | 0.16 | 32 |
| | Observed (kg N $ha^{-1}$) | Predicted (kg N $ha^{-1}$) | Difference (kg N $ha^{-1}$) | Difference (%) |
| Rye N uptake | | | | |
| 1998-1999 | 67.5 (5.4) | 57 | −10.5 | −16 |
| 1999-2000 | 27 (1.0) | 35 | 8 | 30 |
| 2000-2001 | 19 (2.0) | 23 | 4 | 21 |
| Rye N uptake when predicted rye biomass equals measured rye biomass | | | | |
| 1998-1999 | 67.5 (5.4) | 63 | −4.5 | −6.7 |
| 1999-2000 | 27 (1.0) | 33 | 6 | 22.2 |
| 2000-2001 | 19 (2.0) | 19 | 0 | 0 |

parameter was established that provided adequate LAI (eq. 4) to calculate daily biomass (eq. 3) that most nearly matched the rye growth measured in the field experiment. Various root-to-shoot relationships were tried until equation 9 was shown to minimize *ObjVal*. Finally, the temperature and heat unit parameters were adjusted one at a time to further minimize *ObjVal* and arrive at the final calibration settings. The calibrated parameters became the base values about which parameter sensitivity coefficients were calculated.

### Sensitivity Analysis

A local sensitivity analysis was performed for eight model input parameters on the cumulative aboveground biomass output. The parameters evaluated included: maximum LAI ($LAI_{max}$), radiation use efficiency ($\varepsilon$), initial aboveground shoot biomass (*InitShootBM*), heat units until maturity ($HU_{decline}$), heat units to emergence ($HU_{emerge}$), maximum days to emergence (*EmergeDay*), base temperature for growth ($T_{base}$), and optimum temperature for growth ($T_{opt}$). Relative sensitivity coefficients ($S_r$) were determined for six parameters ($LAI_{max}$, $\varepsilon$, *InitShootBM*, $HU_{decline}$, $HU_{emerge}$, and *EmergeDay*) as follows (Haan, 2002):

$$S_r \cong \frac{(O_{P+\Delta P} - O_{p-\Delta P})}{O} / (2\Delta P / P) \qquad (15)$$

where $S_r$ is the relative sensitivity coefficient, $O$ is the model output (aboveground biomass in this case) with input parameters set at base values, $O_{P+\Delta P}$ and $O_{P-\Delta P}$ are model outputs with the input parameter being studied set at a value equal to the base value plus or minus a specified percentage (often taken to be in the range of 10% to 25%), $P$ is the initial value of the input parameter, and $\Delta P$ represents the prescribed absolute change in the value of the input parameter. For these six parameters, $\Delta P$ was taken to be 25% of $P$. Relative sensitivity coefficients are unitless and therefore can be utilized to compare sensitivities among parameters (Haan, 2002). Because $T_{base}$ was near zero and 25% of $T_{base}$ represented a small number, the absolute sensitivity coefficient ($S$) was approximated for the two temperature parameters ($T_{base}$ and $T_{opt}$) by the following relationship (Haan, 2002):

$$S \cong (O_{P+\Delta P} - O_{P-\Delta P}) / 2\,\Delta P \qquad (16)$$

where $S$ is the absolute sensitivity coefficient, and $O_{P+\Delta P}$, $O_{P-\Delta P}$, and $\Delta P$ are as previously described. The values of $T_{base}$ and $T_{opt}$ were perturbed $\pm 1^\circ$C and $\pm 2^\circ$C, that is, $\Delta P$ was 1°C and 2°C, respectively. The absolute sensitivity coefficient was divided by $O$ in order to express the sensitivity of $T_{base}$ and $T_{opt}$ as percent change in output (aboveground biomass yield) per °C change in $T_{base}$ or $T_{opt}$.

The rye growth model was run for each case, changing one parameter at a time for each year of the three-year field study in southwestern Minnesota (Strock et al., 2004). Sensitivity coefficients were calculated for each year. The sensitivity coefficients presented in the Results and Discussion section are the average sensitivity coefficients for the three years.

The purpose of sensitivity analysis is to identify the parameters that have the greatest influence on model results (Hamby, 1994). The division of parameters into various degrees of sensitivity is subjective. For example, Haan and Skaggs (2003a) considered hydrologic parameters with absolute values for $S_r$ of greater than 0.15 and nitrogen cycle parameters with absolute values for $S_r$ of greater than 0.20 (Haan and Skaggs, 2003b) to be sensitive and warranting additional uncertainty analysis. Lenhart et al. (2002) ranked relative sensitivity coefficients into four classes: small to negligible ($0.00 \le |S_r| < 0.05$), medium ($0.05 \le |S_r| < 0.20$), high ($0.20 \le |S_r| < 1.00$), and very high ($|S_r| > 1.00$). We chose to classify the parameters' sensitivity based on the Lenhart et al. (2002) definitions for negligible, medium, high, and very high relative sensitivity coefficients.

### Model Validation

The plant growth model accuracy was evaluated by comparing predicted values of aboveground biomass and N uptake with observed measurements obtained from a rye field trial conducted in 2000-2001 at St. Paul, Minnesota. Five rye varieties were planted in mid-September and grown to maturity. The aboveground biomass of rye was sampled, weighed, and analyzed for N content once in November, approximately weekly in April and May, and then bi-weekly until maturity in early July.

Precipitation in September 2000 prior to rye sowing was above normal (fig. 2), providing for sufficient soil moisture for cover crop establishment. After a dry period at the end of September and into October, precipitation increased and reached a cumulative level above normal over the winter and spring months. During the latter half of April and through June, cumulative precipitation rose above normal for the period, providing fully sufficient soil moisture for rye growth. Temperatures during the fall establishment and spring growth periods were near normal (table 1). Warmer than normal temperatures in October contributed to good conditions for stand establishment and growth prior to winter.

The plant physiological inputs for the validation simulations remained unchanged from the calibration simulation. Soil parameters typical of a silt loam soil were used, as the soil series at the site was a Waukegan silt loam (fine-silty over sandy, mixed, superactive, mesic Typic Hapludoll). Weather inputs came from the weather station located on the University of Minnesota St. Paul campus, within 0.5 km of the experimental rye plots.

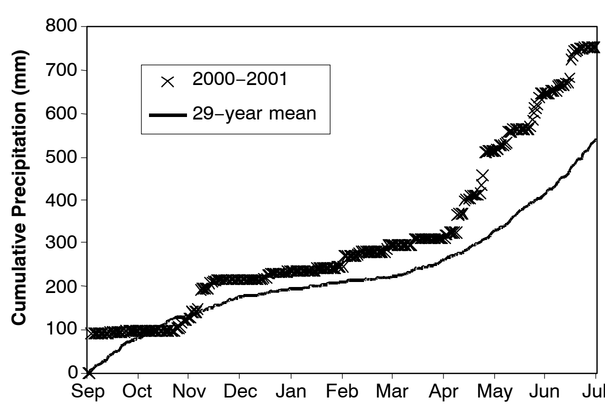


**Figure 2. 29-year mean cumulative precipitation and 2000-2001 cover crop growing season cumulative precipitation at St. Paul.**

## Results and Discussion

### Model Calibration

#### *Biomass Production*

Results of measured and predicted rye aboveground biomass production for the three-year field study at Lamberton are shown in table 5. Predicted values were 0.45 Mg DM ha$^{-1}$ (17%) lower than observed values for the 1998-1999 season, and 0.09 and 0.16 Mg DM ha$^{-1}$ (9% and 32%) higher than observed values for the 1999-2000 and 2000-2001 seasons, respectively; *ObjVal* was 0.70 Mg DM ha$^{-1}$.

The three calibration years provided variation in precipitation and temperature by which to observe the effectiveness of the reduction factors due to water stress ($K_w$) and temperature stress ($K_t$). Figure 3 shows $K_w$ and $K_t$, which range between zero and one, along with the cumulative potential and actual biomass simulated by Grosub for the calibration seasons. Calculated daily biomass production was always limited by the temperature stress reduction factor during the first and third years. Soil moisture and atmospheric conditions were sufficient that the water stress reduction factor was one throughout those seasons. Only for the second season, during which precipitation was below normal and temperature was above normal, was $K_w$ less than $K_t$, for a brief time in the fall. The temperature stress reduction factor shows the positive influence that warm autumns had on biomass production in 1998 and 1999, compared with 2000. In addition, the influence of higher than normal air temperatures in springtime on $K_t$ and biomass production is seen in 2000 versus the cooler than normal conditions in 2001, under which rye growth languished. The relationship for the temperature stress reduction factor (eq. 6) is such that temperatures either below or above an optimum temperature can reduce $K_t$. However, the water stress reduction factor (eq. 7) is structured so that $K_w$ remains at one above an assumed optimum soil moisture content of field capacity. The negative influence of soil moisture contents above field capacity on plant growth are not estimated with the current equation set for $K_w$.

One potential factor influencing the biomass prediction error is the assumption that the radiation use efficiency (ε) of the rye is constant. There are indications in the scientific literature that ε for wheat, for example, is not constant but varies with changes in mean air temperature or vapor pressure deficit (Gillett et al., 2001). In an effort to quantify the uncertainty in Grosub of aboveground biomass output attributable to ε, we adjusted ε by ±0.2 g DM MJ$^{-1}$ (±7%), which is within the range of literature values. We found that this change of ±7% in ε would be sufficient to change the biomass predictions by approximately 20%.

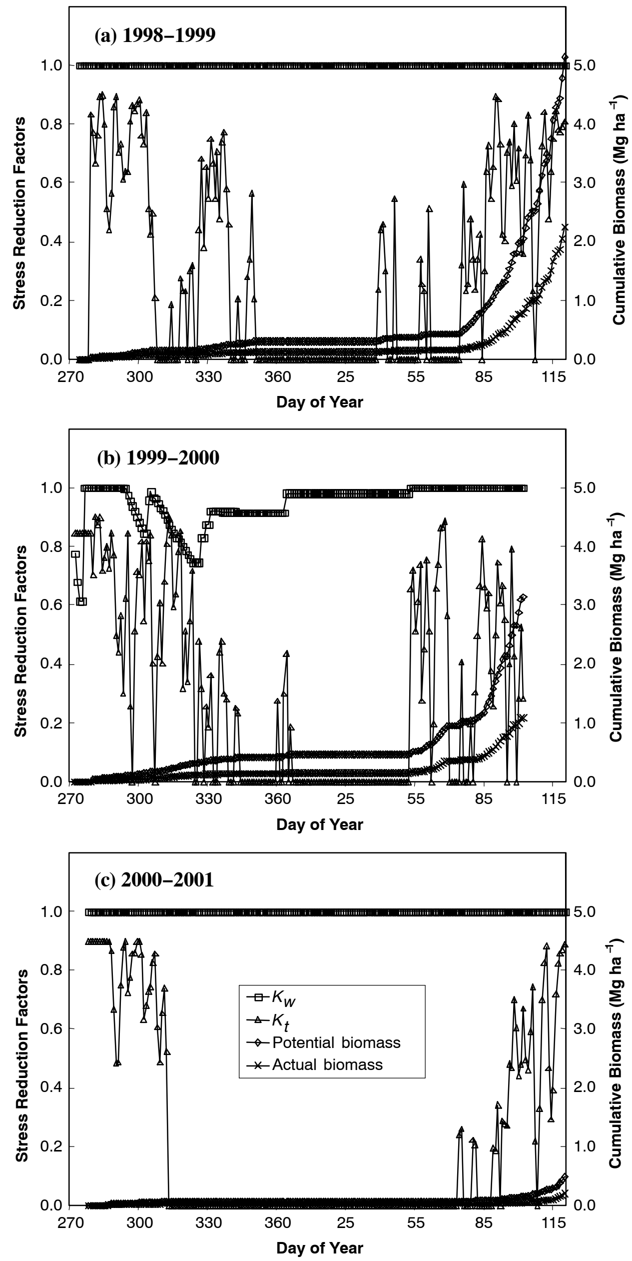


**Figure 3. Precipitation events, water stress reduction factor ($K_w$), and temperature stress reduction factor ($K_t$) for three calibration seasons: (a) 1998-1999, (b) 1999-2000, and (c) 2000-2001.**

#### *Nitrogen Uptake*

Predicted and accumulated N values in the rye aboveground biomass for the field study at Lamberton are listed in table 5. The plant N uptake predictions followed the pattern of the biomass predictions, since N uptake is a function of biomass accumulation. The first calibration season N uptake was underpredicted by 10.5 kg N ha$^{-1}$ (16%), and the second and third calibration seasons were overpredicted by 8 and 4 kg N ha$^{-1}$ (30% and 21%), respectively. The data in the first six rows of table 5 do not provide insight into how well the model is predicting the N concentration of the aboveground biomass at various stages because the predicted/observed biomass values were not in agreement. In an attempt to check the prediction of the N concentration, the predicted and observed N uptake values were compared when the predicted aboveground biomass equaled the observed aboveground biomass, even though the prediction did not occur on the same day on which the observed values were measured. The results of the analysis are shown in the last three rows of table 5. The predicted N concentration is within one standard deviation of the mean for the first and third years of the study: −4.5 and 0 kg N ha$^{-1}$, respectively. The model overpredicted the N content in the second year by 6 kg N ha$^{-1}$ (22%). Figure 1 shows the N concentration versus biomass plot for the three calibration years, along with the exponential curve used by Grosub to predict the N concentration. The observed value for the second year (2000) was below the predicted (curve) value for the particular amount of biomass produced that year. Since the precipitation was abnormally low during autumn 1999 and spring 2000 and temperatures were above normal, environmental conditions could have contributed to reduced N uptake by the rye. Grosub does not adjust N concentration values in the aboveground rye biomass for varying environmental conditions.

### Sensitivity Analysis

The relative sensitivity coefficients or absolute sensitivity coefficients divided by model output for the eight input parameters on cumulative aboveground biomass accumulation are shown in table 6. The relative sensitivity coefficients of the $LAI_{max}$ and radiation use efficiency (ε) parameters were classified as "very high," having values of 2.61 and 1.72, respectively. The $S_r$ value of 2.61 for $LAI_{max}$ essentially means that for each 1% change in value of $LAI_{max}$ there will be a 2.61% change in the model aboveground biomass output. *InitShootBM* and $HU_{decline}$ were classified as "high," $HU_{emerge}$ was classified as "medium," and *EmergeDay* was classified as having negligible sensitivity with respect to the model aboveground biomass output.

It is to be expected that the calculated biomass from a model that is based on the plant's interception and use of incident radiation will be sensitive to the plant's leaf area and the efficiency with which the plant converts the radiation to biomass. Since model results are highly influenced by $LAI_{max}$ and ε, effort to select these parameters carefully or to measure them if possible for a given situation will improve the model accuracy and reduce output uncertainty. The sensitivity analysis shows that change to the maximum leaf area parameter ($LAI_{max}$) has more influence on the biomass output than does change to the original leaf area calculated after emergence using the *InitShootBM* parameter. The model recognizes rye emergence either after accumulation of a specified number of heat units after sowing ($HU_{emerge}$) or a specified number of days (*EmergeDay*), whichever occurs first, assuming model use for colder climates and planting dates from mid-September to the end of October. The sensitivity analysis indicates that $HU_{emerge}$ and *EmergeDay* had little effect on the final biomass result for the scenarios tested.

The absolute sensitivity coefficient divided by model output for $T_{base}$ implies that for each °C increase to $T_{base}$, Grosub will calculate a 6% decrease in aboveground biomass output, and vice versa. The range of literature values for the rye growth base temperature ($T_{base}$) is narrow; thus, uncertainty in $T_{base}$ will have limited influence on model results. The absolute coefficient divided by model output of the optimum growth temperature for rye ($T_{opt}$) is −14% change in aboveground biomass per °C, the negative sign indicating that an increase in $T_{opt}$ results in a decrease in biomass, and vice versa. Thus, model biomass output is more sensitive to changes in $T_{opt}$ than to changes in $T_{base}$ on a per °C basis.

**Table 6. Relative sensitivity coefficients ($S_r$) or sensitivity coefficients ($S$) for Grosub parameters.**

| Parameter | $P$[a] | $S_r$ | $S/O$ |
|---|---|---|---|
| $LAI_{max}$ ($m^2$ $m^{-2}$) | 7 | 2.61 | |
| Radiation use efficiency (ε, kg DM $ha^{-1}$ $MJ^{-1}$ $m^2$) | 2.8 | 1.72 | |
| *InitShootBM* (kg DM $ha^{-1}$) | 30 | 0.76 | |
| $HU_{decline}$ (°C d) | 2050 | −0.22 | |
| $HU_{emerge}$ (°C d) | 50 | −0.15 | |
| *EmergeDay* (d) | 14 | 0.00 | |
| $T_{base}$ (°C) | 1 | | −6[b] |
| $T_{opt}$ (°C) | 18 | | −14[b] |

[a] $P$ = parameter base value.
[b] Units are % change in aboveground biomass per °C change in parameter value.

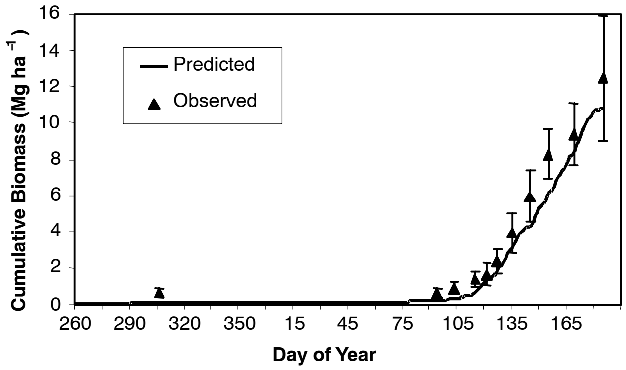


**Figure 4. Predicted and observed aboveground rye biomass accumulation for St. Paul during 2000-2001. The error bars on the measured values extend plus and minus one standard deviation from the mean.**

### Model Validation

#### *Biomass Production*

Figure 4 presents the plot of measured and predicted aboveground biomass accumulation for five rye varieties throughout the September 2000 to July 2001 growing season. Table 7 records the predicted and observed values through 25 May.

The aboveground rye biomass accumulation predicted by the rye growth model closely matches the measured values, particularly in April and May, which are critical months for understanding where N fluxes from artificial subsurface drainage systems are high. The lone biomass measurement in the autumn is higher than the predicted value. However, the first field measurement after spring snowmelt (fig. 4, DOY 94) indicates a loss of biomass, presumably due to respiration losses and winter die-back. The model correctly predicted the upturn in spring growth to begin during the second half of April. Beginning with the 25 April measurement (fig. 4, DOY 115), the predicted biomass lies within one standard deviation of the mean for six of the final eight field measurements. Even though the model does not partition growth among leaves, stems, and grain, the aboveground biomass predictions for June and early July lie within one-half the standard deviation of the measured mean for this time period (fig. 4, DOY 169 and 185).

#### *Nitrogen Uptake*

The validation simulation overpredicted plant N uptake on 25 May by 16 kg N $ha^{-1}$ (table 7). This difference

**Table 7. Measured and predicted rye aboveground biomass and N uptake for 5 varieties ($n$ = 20) for validation simulation at St. Paul on 25 May 2001. Values in parentheses represent the standard deviation.**

| | Observed (Mg $ha^{-1}$) | Predicted (Mg $ha^{-1}$) | Difference | |
|---|---|---|---|---|
| | | | Mg $ha^{-1}$ | % |
| Rye biomass | 5.9 (1.4) | 4.3 | −1.6 | −27 |

| | Observed (kg N $ha^{-1}$) | Predicted (kg N $ha^{-1}$) | Difference | |
|---|---|---|---|---|
| | | | kg N $ha^{-1}$ | % |
| N uptake | 66 (16) | 82 | 16 | 24 |

represents 24%, or one standard deviation, when compared to the observed mean N uptake of the five rye varieties grown in the St. Paul field trial. The field measurements yielded a mean N content of 1.5%, while Grosub predicted an N content of 1.9% on 25 May. By design, the N uptake curve in Grosub represents an average value derived from a set of highly variable field measurements. Thus, use of the curve results in an average prediction of plant N content and does not account for seasonal or situational differences. More accurate prediction of plant N uptake would require determination of the causes of seasonal variations in uptake and development of algorithms to better represent the processes involved.

## Summary and Conclusions

Previous field research in southwestern Minnesota indicated that rye planted after the fall harvest of corn in a corn-soybean crop rotation reduced nitrate−N loss through subsurface drainage systems. This article describes the plant growth submodel, Grosub, of a soil-plant-atmosphere model, RyeGro, which was developed to estimate the long-term effects of introducing rye into the corn-soybean crop rotation. Grosub estimates biomass production with a radiation use efficiency-based approach for converting intercepted photosynthetically active radiation to biomass and N uptake based on an empirical plant N concentration curve. Grosub was calibrated to predict aboveground biomass production and plant N uptake during a three-year field trial at Lamberton, Minnesota. Validation of the model was performed by comparing predicted results with data measured from mid-September through May for fall-planted rye in St. Paul, Minnesota.

Grosub correctly indicated the rank of biomass production for the three-year study. The model results support the hypothesis underlying model development that a simple group of algorithms can provide directional results for a long-term study of the effect of a rye cover crop on subsurface drainage nitrate−N loss. The cumulative rye aboveground biomass predictions for the calibration years differed by −0.45, 0.09, and 0.16 Mg ha$^{-1}$ (−17%, 9%, and 32%), and the plant N uptake predictions differed by −10.5, 8.0, and 4.0 kg N ha$^{-1}$ (−16%, 30%, and 21%) from the observed values. The predictions of biomass production and N uptake for the validation year varied −1.4 Mg ha$^{-1}$ and 16 kg N ha$^{-1}$ (−27% and 24%) from the values observed in the field study, respectively.

The use of the *InitShootBM* parameter appears to be an effective way of calibrating the model. The parameter is sensitive, and thus its value influences the output, yet the parameter is not overly sensitive so as not to be a parameter that dominates model calibration. Knowing that $LAI_{max}$, ε, and *InitShootBM* are the most sensitive parameters to the model output of aboveground biomass indicates the need for careful selection of these parameters for future use of the model. $LAI_{max}$ is generally known for a given crop; however, factors influencing ε, such as soil fertility and variety, could be studied further to improve model accuracy.

The simplified approach to model development resulted in a model that is convenient to use. The weather and soil input data required by Grosub are readily available, and minimal re-calibration is required to perform an analysis for a different modeling scenario.

Suggestions for further research include additional validation testing of the rye growth model, field verification of the effect of climate and soil fertility on the ratio of rye N uptake to biomass production, and incorporation of a relationship to adjust ε based on atmospheric conditions.

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## NOMENCLATURE

$\alpha$ = Priestley-Taylor's radiation term coefficient
$A_{nACT}$ = daily calculated total biomass, actual
$A_{nAG}$ = assimilated aboveground biomass
$A_{nPOT}$ = daily calculated total biomass, potential
$A_W$ = available soil water content
$b_0$, $b_1$ = radiation coefficients to calculate net shortwave radiation from total solar radiation
$BMfctr_{height}$ = height-biomass factor
$D_{root}$ = rooting depth
$D_{root\ max}$ = maximum rooting depth
$\varepsilon$ = radiation use efficiency, biomass per unit PAR
*EmergeDay* = maximum days from sowing to emergence
*FDprecip* = cumulative precipitation for 14 days after sowing
$FD\ \theta_{avg}$ = average soil moisture content in the root zone for 14 days after sowing
$f_{PAR}$ = fraction of PAR intercepted by the rye canopy
Grosub = the plant growth submodel of RyeGro
$H_{canopymax}$ = maximum plant canopy height
$HU_{emerge}$ = heat units to emergence
$HU_{index}$ = ratio of the cumulative heat units since sowing to the heat units required for maturity
$HU_{mat}$ = heat units required for maturity
*InitShootBM* = initial aboveground biomass after germination
$K_{germ}$ = germination factor
$K_p$ = photosynthetic reduction factor
$K_t$ = stress reduction factor for temperature
$K_w$ = stress reduction factors for soil moisture
$LAI_{max}$ = maximum leaf area index
*Npct* = nitrogen percentage of aboveground rye biomass
*PAR* = photosynthetically active radiation
PHENOL = the quasi-phenology submodel within Grosub
$rts_{ratio}$ = ratio of root biomass to shoot biomass
RyeGro = a soil-plant-atmosphere model
$S_r$ = relative sensitivity coefficient
$S$ = absolute sensitivity coefficient
$T_{base}$ = base temperature below which rye suspends growth
$T_{opt}$ = optimum temperature for rye growth