Simulation modeling of soil and plant nitrogen use in a potato cropping system in the humid and cool environment

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Abstract

With rising environmental concerns for current practices of fertilizer N management in the humid and cool areas, we simulated soil N dynamics and plant N use in the potato (Solanum tuberosum L.) cropping system using the software Stella. The objectives were to predict in-season N requirements by the potato crop, tuber yield, N uptake, N partitioning within root, leaf, stem and tuber, and N loss in the plant–soil system, and to examine the accuracy of using model predictions for N management in potato. The first-order linear and S-shaped growth processes were used in the simulation. The model was unidimensional and used a daily time step. Sensitivity analysis indicated that N inflow in the system was the key trait affecting potato N uptake and tuber yield. The model was validated by comparisons of the predictions with field study datasets at four sites conducted across Quebec, Canada. The simulated daily N uptake by the potato followed a S-growth pattern from the early vegetative stage to full bloom, and a plateau of N uptake appeared at late tuberization. The predicted maximum daily N uptake rate (4.46 kg ha⁻¹ day⁻¹) occurred at early bloom whereas the predicted maximum N transfer from stems and leaves to tubers (4.31 kg ha⁻¹ day⁻¹) occurred 3 weeks after the peak of N uptake. Simultaneously, high daily N uptake occurred when N concentrations in the root zone ranged between 90 and 120 kg ha⁻¹. The predicted N uptake and potato tuber yield values were correlated to N inflows in the model ($R^2 = 0.91$). The model estimated loss of N was 34% of the field measurements. Using model balancing the amounts of N needed by crops would lead to optimize plant growth and N use efficiency and to minimize N lost to the environment.

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1. Introduction

Potato (Solanum tuberosum L.) is one of the most important agricultural crop in Quebec, Canada. Nitrogen (N) is recognized as the most limiting nutrient to potato crops, and nitrate (NO₃⁻) is the most frequently documented groundwater contaminant in the potato production areas (Tran and Giroux, 1991; Li et al., 1999, 2003). In the Quebec potato growing region, the predominant soil is sandy and strongly acidic (pH < 5). Potato followed by cereal is the typical crop rotation, and potato is often non-irrigated. This practice makes potato tuber yield dependent on the rainfall pattern, and the process appears driven by recent irrigation development associated with the conventional use of N fertilizers (140 kg ha⁻¹ for loamy soil and 175 kg ha⁻¹ for sandy soil). There is still no consensus as to the best way to manage N applications for potato in the region (Tran and Giroux, 1991; Li et al., 1999, 2003).

Studies in many other areas, where weather (rain, temperature and humidity), soil conditions (type, pH and nutrient) and cropping practices (fertilization, irrigation and rotation) are different, have shown that low fertilizer N recovery, high residual fertilizer N and the risk of NO₃ loss to the environment were often associated with inadequate use of N fertilizers (Neeteson, 1990; Joern and Vitosh, 1995;...

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In irrigated areas in Texas, total N uptake of irrigated cotton was only 18–28% of the fertilizer N rates (Li et al., 2002). A long-term study found heavy NO₃ leaching in irrigated potato in Washington State (Peralta and Stockle, 2002). In non-irrigated potato, leaf N content varied with soil moisture, bulk density and organic matter content (Li et al., 2004). Whole plant N uptake was 31–72% (Tran and Giroux, 1991) and 29–61% of the fertilizer N rates (Li et al., 2003).

Matching in-season requirements of N by potato to increase fertilizer N recovery through adjusting rate and time of fertilizer N applications has been the subject of many studies (Neeteson, 1990; Joern and Vitosh, 1995; Li et al., 1999, 2001b, 2003; Delden et al., 2003). Potato N uptake and fertilizer N recovery were unaffected by the rate or time of N applications (Joern and Vitosh, 1995). Pre-side dress soil NO₃ testing, N partitioning within plant parts and the ability of N to transfer from plants to tubers were used to examine the effectiveness of matching in-season fertilizer N applications with the needs of N by potato (Tran and Giroux, 1991; Fishman, 1992; Gayler et al., 2002; Li et al., 2003). However, timing of N application for matching in-season crop needs of N was critical because soil N concentrations changed with soil water availability (Joern and Vitosh, 1995; Li et al., 2001b, 2003). In Quebec, residual N below the root zone at harvest was positively correlated with fertilizer N rates, and unused fertilizer N left in the soil was almost sufficient for the needs of N by oats in the next year (Li et al., 2003). Fertilizer N not recovered by the crop, especially residual N below the root zone, was subject to loss processes (Hodges, 1999; Li et al., 2003).

Mathematic crop N-response equations and curves have often been used to estimate the needs and economical rates of N fertilizers for crops (Neeteson and Wadman, 1987; Fishman, 1992; Li et al., 2003, 2005). These determinations included a quadratic regression model or modified exponential equation (Neeteson and Wadman, 1987; Li et al., 2001c, 2003), kinetics models to take into account plant growth and development (Fishman, 1992), and exponential non-linear mixed models developed using remotely sensed plant reflectance data (Li et al., 2001b,c). Assessment of the optimum rate of fertilizer N was calculated based on the best-fitting model (Neeteson and Wadman, 1987). A model describing N uptake using Michaelis–Menten kinetics with daily time steps was considered as a first approximation to calculate the functions of N-partitioning among plant organs for the simulation of potato crop development compared with the experimental data (Fishman, 1992).

With the introduction of precision farming in the 1990s, precision management of N through monitoring and modeling has received much attention in potato because field data validated model predictions have the ability to match the needs of N by the potato (Izadi et al., 1996; Verhagen, 1997; Hodges, 1999; Gayler et al., 2002; Delden et al., 2003; Haverkort et al., 2003; Li et al., 2005). However, growers lack practical decision aids for managing N requirements by potato, soil N availability, and plant development at different growth stages (Verhagen, 1997; Paz and Ramos, 2001; Gayler et al., 2002; Peralta and Stockle, 2002; Snapp and Fortuna, 2003). The best way to manage plant growth and fertilizer N for crops would be to use a simulation model for predictions (MacKerron and Waister, 1985; Neeteson, 1990; Verhagen, 1997; Franko and Mirschel, 2001; Paz and Ramos, 2001; Haverkort et al., 2003).

To develop a simulation model for monitoring N management for potato, understanding the relationships between the rate, timing, and placement of N fertilizers, N uptake, tuber yield and residual N at harvest was essential (Neeteson, 1990; Hodges, 1999; Li et al., 2003; Snapp and Fortuna, 2003). Simulation modeling of N balance has shown promise in determining the right input of fertilizer N for precision farming (Verhagen, 1997; Gayler et al., 2002). In Quebec, the climate is cool (4.2 °C, 30-year mean annual air temperature), soil is frozen from November to April, the growing season is short (May–September, 11.2–19.0 °C, 30-year mean air temperature), the area is humid (1205 mm, 30-year mean annual precipitation) and the soil is acidic (pH 4–6). There was a need for comprehensive datasets from specific field studies to validate the model predictions.

Following a series of field study of plant growth and fertilizer N recovery by potato with different rates and times of applications conducted in different areas in Quebec, we developed a simulation model of soil N dynamics and N balance in the potato cropping system. The objectives were (i) to simulate daily N requirements of potato crops, daily available N inflows in the soil system, daily N uptake, N partitioning within roots, leaves, stems and tubers, and residual N in the soil related to potato growth stages and N inflows in the system, (ii) to predict daily, monthly and seasonal balance of N in the cropping system to enable N recommendations for potato, (iii) to validate the model using field measurements at different sites and (iv) to evaluate the feasibility of using model predictions for making fertilizer N management decisions. The comparison of predictions with independent field study datasets should enable the model validation, and the developed and validated models should enable improved fertilizer N management in potato production.

2. Materials and methods

2.1. Modeling approach and the conceptual basis of the model

The modeling consisted of quantitative descriptions of soil N dynamics, plant and tuber growth, daily N partitioning within roots, leaves, stems and tubers, and total N loss in the potato cropping system through model diagram mapping, simulation, prediction, validation and
model application (Fig. 1). The simulation of daily, monthly and seasonal N balance was the result of differences between inflows and outflows of N in the cropping system. This approach was simplified by assuming that (i) the ability of N uptake of the crop and N partitioning within the plant–soil system was related to the growth stages (or growing season days) and availability of N in the soil system, (ii) no enhancement of mineralization was caused by adding N fertilizer ($N_{\text{fert}}$), (iii) uses of soil N and other sources of N (crop residue decomposition, soil organic matter mineralization, atmospheric deposition, etc.) were the same in the control and N treatments and (iv) there was no significant immobilization of fertilizer N.

This model of the growth, yield and N uptake of the potato crop has been derived and simplified in concept. In the modeling, processes of growth, yield, N uptake and N partitioning within different plant parts have been related to the development of the crop with time, days of growing season. The model used a daily time step ($D_t$), and the sum of time steps ($t$) was the total growing season days (or variety mature days).

The development of the potato crop has been divided into three easily recognizable phases as: (i) planting to bloom, (ii) bloom to initial tuberization and (iii) initial tuberization to harvest. The planting day would represent a time from which plant growth could begin, and N uptake could start at the time of plant emergence. Following bloom, tuber growth could begin. At plant mature, tuber growth and N flow into tubers would become great. Towards late tuberization, N uptake and tuber growth could decrease with decreasing of N inflow in the plant–soil system (Li, 1997).

2.2. Variables and functions used in the modeling

Nitrogen management information used in the modeling was derived from the variables determined in the specific field studies, and the variables, functions, coefficients and units used in the model are shown (Table 1). Field studies in Quebec found that potato tuber growth ($Y_{\text{tuber}}$) and N uptake ($N_{\text{uptake}}$) had been related to soil N concentrations ($N_{\text{soil}}$):

$$Y_{\text{tuber}} = 10.1 + 0.40N_{\text{soil}} - 0.013N_{\text{soil}}^2, \quad R^2 = 0.70;$$
$$N_{\text{uptake}} = 46.2 + 1.76N_{\text{soil}} - 0.004N_{\text{soil}}^2, \quad R^2 = 0.72 \quad (\text{Li et al., 2003}).$$

Also, it was reported that fertilizer N recovery (NRE) and unused fertilizer N left at harvest (Unused-$N_{\text{fert}}$) been related to N application rates ($N_{\text{fert}}$):

$$\text{NRE} = 26.2 + 0.469N_{\text{fert}} - 0.0018N_{\text{fert}}^2, \quad R^2 = 0.84;$$
$$\text{Unused}-N_{\text{fert}} = 19.2 + 0.047N_{\text{fert}} + 0.0019N_{\text{fert}}^2, \quad R^2 = 0.98 \quad (\text{Li et al., 2003}).$$

Thus, the most important functions used in the modeling have included the effects of soil N on potato growth and N uptake, the effects of total amounts of N uptake on N partitioning rates, etc. (Table 1). The uses of the model variables and functions are detailed in the specific simulation procedures.
2.3. Model development and sensitive analysis

The modeling tool was the software Stella (HPS, 1994). The model was unidimensional. We used the model diagram infrastructures of first-order linear process, S-shaped growth process, overshoot and collapse process, or main chain process for simulation of the processes of growth (i.e., accumulation of N in the plant, growth of potato tubers) and decline (i.e., N partitioning from roots, stems and leaves to potato tubers), as shown in Fig. 1. The elements of infrastructure for constructing the modeling diagram were the accumulators (stocks), transporters (flows), converters (circles) and connectors (arrows), established by the software Stella (HPS, 1994).

Sensitivity of the system was defined by changing the inputs or starting conditions in the modeling (MacKerron and Waister, 1985). We tested the sensitivity of model outputs with modifying the parameters used within the model. Sensitive analysis was done using the Graphic Function (HPS, 1994) to obtain satisfactory outputs in the simulation processes.

2.3.1. Simulation of soil N dynamics and fertilizer N inputs

The simulation of soil N dynamics consisted of a quantitative description of N inflows into the system by relating the fertilizer N inflow to the requirements of N by potato at different crop growth stages (Li et al., 2005). The estimations of the requirements of N by potato were derived from the descriptions in Neeteson (1990), as shown in Eq. (1). The fertilizer N rate \( (N_{\text{fert}}) \) was a function of potential N uptake \( (P_a) \), potential yield \( (Y_a) \), the requirement of N by the potato (RNC), N from soil humus mineralization \( (N_{\text{mh}}) \), N from crop residual mineralization \( (N_{\text{mr}}) \), efficiency coefficient for \( N_{\text{mh}} \) and \( N_{\text{mr}} \) \( (E_{f1}) \) and efficiency coefficient for \( N_{\text{fert}} \) \( (E_{f2}) \) as follows:

\[
N_{\text{fert}} \left( \frac{RNC}{E_{f2}} - \left( \frac{N_{\text{mh}} + N_{\text{mr}}}{E_{f1}} \right) \right)
\]

where RNC was total N uptake, the potential N uptake \( P_a \) was 180 kg ha\(^{-1}\) and the potential tuber yield \( Y_a \) was 45 Mg ha\(^{-1}\) (Table 1). The \( N_{\text{mh}} \) was 60 kg ha\(^{-1}\) (Table 1), based on the results of the studies conducted in Quebec (Simard and N'Dayegamiye, 1993). The \( N_{\text{mr}} \) was 30 kg ha\(^{-1}\) (Table 1). This was because the dry matter of potato crop residues (roots, leaves and stems) at harvest was 1.2 Mg ha\(^{-1}\) (3-year mean), which contributed about 32 kg ha\(^{-1}\) of \( N_{\text{mr}} \) (3-year mean) to the cropping systems (Li et al., 2003). The mineralization of meadow soils in Quebec would contribute 60–65 kg ha\(^{-1}\) of \( N_{\text{mh}} \) to the cropping systems during the growing season (16 weeks), estimated according to the soil N mineralization potential determined from 20 meadow soils sampled across Quebec (Simard and N'Dayegamiye, 1993). The \( E_{f1} \), efficiency coefficient for \( N_{\text{mr}} \) and \( N_{\text{mh}} \), was 0.80 (Neeteson, 1990;
The efficiency coefficient for fertilizer N, $E_{E_2}$, was 0.65, which was based on the means of potato fertilizer use efficiency of 0.59–0.68, determined from the $^{15}$N fertilizers applied to two soils in a 2-year study (Tran and Giroux, 1991), and from NH$_4$NO$_3$ fertilizers applied to a loamy soil in a 3-year study (Li et al., 2003).

The inflows of N fertilizers ($N_{\text{fert}}$) were entered into the system by the PULSE function (HPS, 1994) in two steps (2 days) for the split application of fertilizer N into the system.

2.3.2. Simulation of potato growth, N uptake and transfer within the plant–soil system

Using accumulation and decline simulation processes with main chain generic infrastructure (HPS, 1994), we simulated potato growth, N uptake and N partitioning within different plant parts in the system (Li et al., 2005). We simulated the accumulations of N in stems and leaves at the early plant growth stage, and then the transfer of N from plant parts to tubers during tuberization (Fig. 1). As shown in Fig. 1, the N inflows ($N_{\text{inflow}}$) included $N_{\text{fert}}$, $N_{\text{nh}}$ and $N_{\text{mr}}$, and the N outflows ($N_{\text{outflow}}$) were total N uptake ($N_{\text{uptake}}$) and seasonal N loss ($N_{\text{loss,S}}$). The $N_{\text{loss,S}}$ was assumed to be the difference of $N_{\text{inflow}}$ and $N_{\text{outflow}}$ in the cropping system (Li et al., 2005).

In the model, the total time step ($t$) was 125, the total growing season days for potato. The function $N_{\text{uptake}}$ was an outflow with a time step ($t$) of 120. This was because potato emergence could appear as early as 5 days after the planting in the field (Li, 1997). The definition of N uptake outflow was based on the potato crop development phases as follows:

$$N_{\text{uptake}} = N_{\text{plant}}, \quad N_{\text{tuber}} = 0, \quad t < 30 \text{(before initial tuberization)}$$

$$N_{\text{uptake}} = N_{\text{plant}} + N_{\text{tuber}}, \quad N_{\text{tuber}} > 0, \quad t > 30 \text{(after tuberization)}$$

The estimation of the time step of initial tuberization in the model was because potato tuber initiation was found to begin between 30 and 35 days after planting under the Quebec cropping conditions (Li, 1997). The generic process of overshoot and collapse with an interval of 30 steps (30 days after planting) was used to associate the elements of $N_{\text{plant}}$ and $N_{\text{tuber}}$.

In the simulation, the $N_{\text{uptake}}$ was a function of daily N uptake ($F_{\text{up}}$), which represented the most important daily outflow of N in the system. The $F_{\text{up}}$ was estimated by multiplying N inflow in the soil system ($N_{\text{inflow}}$) and the effects of $N_{\text{inflow}}$ on N uptake ($EN_{\text{inflow}}$) as follows:

$$F_{\text{up}} = N_{\text{inflow}}EN_{\text{inflow}}$$

Soil N concentrations influenced N uptake by potato (Tran and Giroux, 1991; Li et al., 2003, 2004). Therefore, $EN_{\text{inflow}}$ was simulated changing with soil N concentrations and growing season day (Li et al., 2005), and the $EN_{\text{inflow}}$ was a parameter value between 0 and 1 (Table 1). At the vegetative stage ($t < 30$), the N assimilated by roots was accumulated in stems and leaves, which was defined as $N_{\text{plant}}$ (Table 1). A part of the $N_{\text{plant}}$ started to transfer to tubers when the plants reached their point of maturity based on the field measurements ($t > 30$, Eq. (3)).

Tuber growth was affected by N uptake (Tran and Giroux, 1991; Li et al., 2003). Therefore, daily N partitioning to tubers ($N_{\text{tuber,D}}$) was simulated as a result of the amount of $N_{\text{plant}}$ and the N transfer fraction ($F_{\text{tr}}$). The $F_{\text{tr}}$ was related to the potato tuber growth rate ($T_c$) as follows:

$$N_{\text{tuber,D}} = N_{\text{plant}}F_{\text{tr}}$$
$$F_{\text{tr}} = N_{\text{plant}}T_c$$

where $T_c$ was a function parameter with a range of 0–0.20 Mg ha$^{-1}$ (Table 1). The maximum value for the $T_c$ was also based on the potato growth rate measured in the fields (Tran and Giroux, 1991; Li et al., 2003, 2004). The cumulative $N_{\text{plant}}$ and $N_{\text{tuber}}$ were evaluated as follows:

$$N_{\text{plant}}(t) = N_{\text{plant}}(t - \Delta t) + (N_{\text{uptake,D}} - N_{\text{tuber,D}})\Delta t$$
$$N_{\text{tuber}}(t) = N_{\text{tuber}}(t - \Delta t) + N_{\text{tuber,D}}\Delta t$$

Because of the strong correlations between tuber yield and N uptake ($R^2 = 0.62$, Li et al., 2003), potato tuber yield ($Y$) was simulated depending on $N_{\text{plant}}$, $N_{\text{tuber}}$ and daily tuber growth rate ($Y_D$). The $Y_D$ was a function of tuber growth fraction ($F_y$) and growth rate ($T_c$) as follows:

$$Y(t) = Y(t - \Delta t) + YD\Delta t$$
$$YD = F_yT_c$$

Difference between N inflow and N outflow in the system has been considered as the amount of N lost to the environment (Li et al., 2005). In the model, seasonal loss of N ($N_{\text{loss,S}}$) was the sum of daily loss of N ($N_{\text{loss,D}}$), and the $N_{\text{loss,D}}$ was simulated linking to N inflow ($N_{\text{inflow}}$), the effect of $N_{\text{inflow}}$ ($EN_{\text{inflow}}$) and the fraction of N loss ($F_L$) as follows:

$$N_{\text{loss}} = N_{\text{loss,S}}(t - \Delta t) + N_{\text{loss,D}}\Delta t$$
$$N_{\text{loss,D}} = N_{\text{inflow}}EN_{\text{inflow}}F_L$$

Finally, the N balance in the plant–soil system ($\Delta N_{\text{plant-soil}}$) was determined by the difference in N inflows and outflows as follows:

$$\Delta N_{\text{plant-soil}} = N_{\text{inflow}}(t - \Delta t) - (N_{\text{inflow}} - N_{\text{outflow}})\Delta t$$
$$= N_{\text{inflow}}(t - \Delta t)$$
$$\quad - [(N_{\text{soill}} + N_{\text{mr}} + N_{\text{nh}} + N_{\text{fert}})$$
$$\quad - (N_{\text{soill}} + N_{\text{mr}} + N_{\text{nh}} + N_{\text{fert}})]\Delta t$$

$$\Delta N_{\text{inflow}}$$
2.4. Development of comprehensive field study datasets for the model validation

Model validation involved the comparisons of predictions by the model with the results from field studies (MacKerron and Waister, 1985). The comprehensive datasets for the validation of this model were the field measurements at four study sites across Quebec including: (i) a 3-year field study of N management (rates and times) for potato crop conducted in Sainte-Croix, 50 km in the south of Quebec City (Li et al., 1999, 2003), (ii) a 3-year study of N use efficiency of 15N-labeled fertilizers conducted at Saint-Damase site and (iv) at Soulanges site, about 200–250 km in the south of Quebec City (Tran and Giroux, 1991). Other supportive data were from a laboratory incubation study of N mineralization potentials using 20 meadow soils in Quebec (Simard and N’Dayegamiye, 1993).

2.4.1. Field study datasets at Sainte-Croix site

The Sainte-Croix field study was conducted on the Joseph-Rheaume Research Farm (46°37’N, 71°47’W) of Laval University during 1993–1995 (Li et al., 2003). The objectives were to determine the relationships between soil N, potato yield, N uptake, fertilizer N recovery and residual N at harvest related to different rates and times of N applications, and to develop comprehensive datasets for modeling purposes (Li et al., 2003). The site was a 20-year grass meadow prior to the experiment. The soil was a Tilly silt loam, classified as Gleyed Humo-Ferric Podzol in Canadian Soil Classification Systems (Orthic Podzol in FAO systems). Prior to the study, soil characterization in a 8 m × 8 m grid showed that the surface soil (0–0.25 m) had a low pH (4.8 ± 0.6, soil:H2O, 1:1), sand content 230 ± 24 g kg⁻¹ and clay 210 ± 28 g kg⁻¹, a moderately slow permeability (1.6 × 10⁻⁵ m s⁻¹), and an average organic matter content (39 g kg⁻¹).

The potato cv. ‘Superior’ was grown for the 3 consecutive years. The NH₄NO₃ fertilizer treatments consisted of side-dress, split applications and a control. The side-dress treatments were applied at the rates of 70, 105 and 140 kg N ha⁻¹, and the split treatments were the side-dress rates at seeding, plus a fractional rate of 70 kg N ha⁻¹ at hilling (early July) to attain 70 + 70, 105 + 70 and 140 + 70 kg ha⁻¹, respectively. These rates were in the range for non-irrigated potato (Tran and Giroux, 1991; Verhagen, 1997; Waddell et al., 1999; Peralta and Stockle, 2002). The N treatments with three replicates were arranged in a completely randomized design. The control received no N fertilizer but the same rates of P, K, Mg and S (75, 100, 30 and 60 kg ha⁻¹, respectively) as all other plots, based on the soil test and regional recommendations. Each plot was 6 m × 10 m with 0.91 m between rows and 0.25 m plant spacing.

The 3-year in-season monthly air temperatures (10.9–20.2 °C) and monthly rainfalls (55–159 mm) were comparable to the 30-year means (Li et al., 2003). Potato tuber yield, fresh biomass, dry matter and N content of different plant parts (leaves, stems, tubers and roots) and total N uptake were determined at planting, bloom and harvest each year. The soil NO₃ concentrations in two zones (0–0.6 m, the root zone; 0.6–1.0 m, the zone below the roots) were also measured at the times of plant sampling (Li et al., 2003). Two center rows were harvested for marketable tuber yields. The impacts of N rates and application times on N uptake, potato tuber yield, fertilizer N recovery and residual N in soil below the root zone were determined (Li et al., 2003). Apparent N balance was quantified by differences of total N inflows (initial soil NO₃-N and fertilizer N rates) and total N outflows (total N uptake and soil NO₃-N at harvest) in the plant–soil system.

Three sets of independent data were obtained from this 3-year study. One was the in-season growth of potato tubers and biomasses of whole plant and different parts. Second was the total N uptake, and accumulations of N in stems, tubers and roots at different dates, and the third was the N in the soil profile at the dates corresponding to the times of plant N measurements.

2.4.2. Field study datasets at Mistassini site

The Mistassini study was conducted in 1994–1996 to determine the responses of non-irrigated potato to different rates of Sphagnum peat and N–P–K fertilizers (Li et al., 2004). The soil was a loamy sand, classified as a well-drained Ferro-Humic Podzol in Canadian Soil Classification Systems (Orthic Podzol in FAO systems), and had a low pH 5.4 and a low organic matter content 22 g kg⁻¹. The field had been cultivated with the typical rotation of 2-year potato, 1-year cereal and red clover as a winter cover crop prior to the experiment. The Mistassini study was set for 2-year potato ‘Superior’ and 1-year (3rd year) barley (Hordeum vulgare L.) ‘Chapais’ (Li et al., 2004). During the three growing seasons, monthly air temperature was within 12.4–19.9 °C, and monthly rain 32–211 mm. The treatments consisted of Sphagnum peat at the 3-year rates of 0, 29, 48 and 68 Mg ha⁻¹, and granular N–P–K fertilizers (12–7.5–7) at the annual rates of 1.4, 1.6 and 1.8 Mg ha⁻¹, respectively, arranged in a split-block design. Each main plot was 10.9 m × 16.7 m, and each subplot was four rows of 16.7 m long. The rows were 0.91 m apart and plant spacing was 0.3 m. The potato was grown for 90 days (early June to early September). Whole plants including roots were sampled in each plot at bloom and at harvest for plant biomass, dry matter and N uptake were analyzed using the methods described at the Saint-Croix site (Li et al., 2003). Potato tuber yield was determined in a whole center-row in each plot (Li et al., 2004).
2.4.3. Field study datasets at Saint-Damase site and Soulanges site

The Saint-Damase–Soulanges field study was conducted in 1985 and 1986 to determine fertilizer N recovery by potato and the effects of N rates on potato tuber yield harvested at different dates (Tran and Giroux, 1991). The soil was a loamy sand at the Saint-Damase site, and a sandy loam at the Soulanges site. The two soils were classified as systems (Orthic Podzol in FAO systems) and contained 27–38 g kg$^{-1}$ of organic matter, typical values in most of the potato fields in Quebec. The cropping history of the two sites was potato with alfalfa as green manure in the winter. During the experiment, monthly air temperature was 13–21 °C and monthly rain was 46–147 mm. The potato cultivar was ‘Norland’, planted in early May each year. The NH$_4$NO$_3$ fertilizer N rates were 0 and 140 kg ha$^{-1}$ with 1.729% of $^{15}$NH$_4$NO$_3$ in 1985, and 0, 70 and 140 kg ha$^{-1}$ with 1.360% of $^{15}$NH$_4$NO$_3$ in 1986 ranged in a split-plot design (Tran and Giroux, 1991). The potato harvest dates were 70, 80, 90 and 100 days after planting, and single rows of 5.0 m long were harvested to determine potato tuber yields. The total N in plant tissue was determined using colorimetry, and the $^{15}$N in tissue samples was determined using mass spectrometer (Tran and Giroux, 1991).

We used the mean values of potato tuber yield, total N uptake, and fertilizer N use from the Mistassini study (Li et al., 2004) and the Saint-Damase–Soulanges field study (Tran and Giroux, 1991) to compare with the model predictions. The mean of soil N mineralization values ($N_{nmh}$) within 16 weeks of laboratory incubation (Simard and N’Dayegamiye, 1993) were used to include the $N_{nmh}$ in the estimation of fertilizer N rates in the model (Eq. (1)). This incubation study was done using 20 soil samples (0–0.2 m) sampled across Quebec (Simard and N’Dayegamiye, 1993). Most of these soils were classified as Orthic-Humic Gleysol and Orthic Humo-ferric Podzol in Canadian Soil Classification System (Humic Gleysol and Orthic Podzol in the FAO systems). The soils had a pH between 5.3 and 6.9, organic C 7–48 g kg$^{-1}$, clay content 10–600 g kg$^{-1}$ and sand content 70–910 g kg$^{-1}$. The field-moist soils, screened in 6-mm size, were incubated at 20 °C and the mineralized N ($N_{nmh}$) across time of incubation was measured using liquid chromatography every 1.4 weeks over 55.4 weeks (Simard and N’Dayegamiye, 1993).

3. Results

3.1. Predictions of in-season daily inflows and outflows of N between soil and plant system

The simulated effect of N inflow ($EN_{inflow}$) values increased with the increase of predicted $N_{inflow}$ in the system (Table 2). The $EN_{inflow}$ was low when $N_{inflow}$ was high at the early vegetative stage, and the $EN_{inflow}$ reached the maximum value of 1 when $N_{inflow}$ in the soil system was 110 kg ha$^{-1}$ (Table 2). The $EN_{inflow}$ was similarly high for $N_{inflow}$ within 90–120 kg ha$^{-1}$. The predicted daily N uptake ($F_{up}$) peaked with the maximum $EN_{inflow}$ (Table 2). After plant maturity, the $F_{up}$ decreased with decreasing $EN_{inflow}$ and N started to transfer from stems and leaves to tubers at a daily fraction rate ($F_{tr}$) of 0.2 kg ha$^{-1}$ day$^{-1}$ (Table 2). The $F_{tr}$ decreased with decreasing $F_{up}$, $EN_{inflow}$ and $EN_{inflow}$ during tuberization (Table 2). The predicted daily N transfer from plant parts to tubers was significantly related to the predicted daily N uptake ($R^2 = 0.98$, Fig. 2).

The curves of the predicted daily N uptake rate ($F_{up}$) and daily N transfer fraction ($F_{tr}$) show an overshoot and collapse pattern (Fig. 3). Because plant requirements of N were high with the rapid plant growth at the vegetative stage within the first 20–50 days in the growing season, the predicted daily N uptake reached the peak (4.46 kg ha$^{-1}$ day$^{-1}$) at plant maturity within 7 weeks after planting. The daily N transfer fraction $F_{tr}$ was related to daily N uptake rate $F_{up}$. The $F_{tr}$ reached the maximum rate (4.31 kg ha$^{-1}$ day$^{-1}$) within 20 days after the peak of daily N uptake, and the curves showed a lag relationship between the two variables (Fig. 3).

![Fig. 2. Regression relationship of predicted daily fraction N transfer to tuber ($F_{tr}$) vs. daily fraction of N uptake ($F_{up}$) related to the simulated effect of N inflow in the soil system.](image-url)
3.2. Predictions of N partitioning, potato growth and N loss from the system

The predictions of daily changes of N inflows in the soil system ($N_{\text{inflow}}$, curve 1), N in plant parts (including leaf, stem and root, curve 2), N accumulation in tubers (curve 3) and potato tuber yields (curve 4), calculated using Eqs. (1)–(10), were simultaneous in the model (Fig. 4). The peaks of $N_{\text{inflow}}$ appeared in mid-May and in late June (Fig. 4), which corresponded to the split applications of N fertilizers to the soil at planting and at the beginning of bloom (or initial tuberization). The maximum N inflow in the system was 147.4 kg ha$^{-1}$ (Table 3), applied at planting with 58.6% of the fertilizer N rates. The $N_{\text{inflow}}$ was important when the $N_{\text{plant}}$ (uptake outflows) was small in the early vegetative stage (Fig. 4). The corresponding predicted values of $N_{\text{inflow}}$, $N_{\text{plant}}$ and $N_{\text{tuber}}$ at a 5-day time step are shown in Table 3.

Table 3
Predictions of N inflows in the soil system ($N_{\text{inflow}}$), accumulations of N in plants ($N_{\text{plant}}$), N in tubers ($N_{\text{tuber}}$), seasonal N loss ($N_{\text{lossS}}$) and tuber yield related to the growing season days

<table>
<thead>
<tr>
<th>Day of year</th>
<th>Day of season</th>
<th>N inflow in the soil system (kg ha$^{-1}$)</th>
<th>N in plant $N_{\text{plant}}$ (kg ha$^{-1}$)</th>
<th>N in tuber $N_{\text{tuber}}$ (kg ha$^{-1}$)</th>
<th>Seasonal N loss $N_{\text{lossS}}$ (kg ha$^{-1}$)</th>
<th>Tuber yield (Mg ha$^{-1}$)</th>
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<tbody>
<tr>
<td>135 (15 May)</td>
<td>1 (1st rate)</td>
<td>147.4</td>
<td>0.0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>140</td>
<td>5</td>
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<td>0</td>
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<td>145.7</td>
<td>0.6</td>
<td>0</td>
<td>1.12</td>
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<td>150</td>
<td>15</td>
<td>143.2</td>
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<td>0</td>
<td>2.64</td>
<td>0</td>
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<tr>
<td>155</td>
<td>20</td>
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<tr>
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<td>54.1</td>
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<tr>
<td>175</td>
<td>40 (split rate)</td>
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<td>64.0</td>
<td>0.9</td>
<td>6.52</td>
<td>0.1</td>
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<tr>
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<td>6.95</td>
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<td>185</td>
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<td>87.1</td>
<td>16.3</td>
<td>7.64</td>
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<tr>
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<td>12.47</td>
<td>43.9</td>
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<tr>
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<td>115</td>
<td>67.0</td>
<td>35.9</td>
<td>140.8</td>
<td>12.62</td>
<td>44.1</td>
</tr>
<tr>
<td>255</td>
<td>120</td>
<td>66.8</td>
<td>35.6</td>
<td>142.1</td>
<td>12.76</td>
<td>44.2</td>
</tr>
<tr>
<td>260</td>
<td>125 (harvest)</td>
<td>66.7</td>
<td>35.1</td>
<td>142.9</td>
<td>12.88</td>
<td>44.3</td>
</tr>
</tbody>
</table>

* Data listed are in a 5-day time step.
Total N accumulation in plants followed the overshoot and collapse processes (curve 2, Fig. 4). The peak of N in plants appeared after the second portion of the fertilizer N rates was applied to the soil at the time of initial tuberization. The N in plants (curve 2) continued to decline as N in tubers (curve 3) increased to meet the need of potato growth (Fig. 4). The decrease of N in plants and increase of N in tubers resulted from the main chain procedure. Similar to the accumulation of N in tubers, the growth of potato tubers (curve 4) showed an exponential S-shaped pattern (Fig. 5). The predicted maximum accumulation of N in plants was 97.5 kg ha\(^{-1}\) at plant maturity, and the maximum accumulation of N in tubers was 142.9 kg ha\(^{-1}\) at harvest (Table 3). The predicted N in plants declined to 35.1 kg ha\(^{-1}\) at harvest (Table 3). The predicted tuber yield was 44.3 Mg ha\(^{-1}\) at harvest (Table 3), which reached 98.4% of the potential yield (\(Y_a\), 45 Mg ha\(^{-1}\), Table 1).

For a potential N uptake (\(P_a\)) of 180 kg ha\(^{-1}\), the simulated maximum N uptake, or the sum of N in plants and tubers (Table 3), reached 99.4% (179/180) of the potential N uptake. The curve of N accumulation in tubers (curve, Fig. 4) was similar to that of total N uptake (curve, Fig. 5). This is because 79.8% (142.9/179) of the predicted N uptake was predicted to be in tubers at harvest. The predicted N loss was more pronounced after the fertilizer N was applied to the soil (line 1, Fig. 5), and while the uptake outflows were small at the early vegetative stage and at tuber maturity (line 2, Fig. 5). The predicted \(N_{\text{loss}}\) also showed a tendency to increase after the harvest (Fig. 5). The predicted total seasonal loss of N (\(N_{\text{loss,S}}\)) was 12.88 kg ha\(^{-1}\) (Table 3), only 6.5% of the total N inflows in the system. The predicted N concentration in the soil system was 66.7 kg ha\(^{-1}\) at harvest (Table 3), close to the soil N level at planting in the model (58.6 kg ha\(^{-1}\)).

The predicted daily N transfer to tubers was strongly correlated to N in plants (leaves, stems and roots), \(R^2 = 0.98\) (Fig. 6A). The N in tubers at harvest, defined as the harvested N, showed the need for absorption of 4.1 kg of N (179/44.3) to produce 1000 kg of potato tubers in the model. There was a strong power trend of tuber yield against the N in tubers (\(R^2 = 0.98\), Fig. 6B). Higher transfer of N to tubers resulted in higher tuber yield, as predicted by the model (Fig. 6B).

### 3.3. Comparisons of the model predictions with field measurements

In the Sainte-Croix, Mistassini, Saint-Damase and Soulanges field studies, most of the measured variables (total potato tuber yield, N uptake, total tuber dry weight, N in tubers, N in stems and leaves at harvest, and N harvest index) increased with growing season day \(t\), or time step (Table 4). The corresponding model predictions were closer to the measurements at the Saint-Croix site \((t = 125)\) than at the other sites \((t \leq 100)\). The predicted maximum N uptake rate was close to the measurements at the four sites, but per kg of N to produce 1 Mg of tubers was lower in the model predictions than the field measurements (Table 4), which showed that using model predictions would lead to high yield with small N uptake.

The dynamics of soil N in the system was typically characterized by the increase of N in the root zone after applications of fertilizer N, and the decrease of N in the soil system through N uptake and other processes of N loss (Li et al., 2003). At the Sainte-Croix site, the field measurements shown in Fig. 7 were the means of 21 measurements on each day.
The measured daily N uptake and N transfer from plants to tubers (Fig. 7A), and N accumulation in plants (Fig. 7B) showed an overshoot and collapse pattern, which was the basis for daily N uptake and N transfer in the model (Fig. 4). The maximum accumulation of N in plants (95 kg ha\(^{-1}\)) occurred when the plant dry matter was 1.9 Mg ha\(^{-1}\), measured at 50 days into the growing season. The N accumulation in tubers showed a S-shaped growth pattern (Fig. 7B), similar to the measurements in the Saint-Damase–Soulanges study (Tran and Giroux, 1991).

There was a lag relationship of 35 days between the measured daily N uptake by plants and the daily N transfer from plants to tubers (Fig. 7A), which matched the simulated patterns of daily N uptake by plants and daily N transfer to tubers in the model (Fig. 3). The measured daily N uptake was in the range of 0.93–4.21 kg ha\(^{-1}\) day\(^{-1}\) from the early vegetative stage to the beginning of bloom. The measured daily N uptake rate reached the maximum level about 20 days earlier than the maximum measured daily N transfer (Fig. 7A). The maximum and mean values of the 3-year measured total N uptake (Fig. 7C) and potato tuber yield (Fig. 7D) also supported the simulations and predictions of N uptake and potato growth in the model (Fig. 4). The 3-year measured mean and maximum N uptakes were 162 and 206 kg ha\(^{-1}\), respectively (Li et al., 2003). With dry matter of 1.2 Mg ha\(^{-1}\) and N content of 2.96%, the potato crop residues gave a quantity of 36 kg N ha\(^{-1}\) for the cropping system in the next year (Table 4).

Data sources: Sainte-Croix site (Li, 1997; Li et al., 2003), Mistassini site (Li, 1997; Li et al., 2004), Saint-Damase and Soulanges site (Tran and Giroux, 1991). \(t\): time step (day).

Table 4

<table>
<thead>
<tr>
<th>Comparison parameters</th>
<th>Predictions ((t = 125))</th>
<th>Field measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sainte-Croix ((t = 125))</td>
<td>Mistassini ((t = 90))</td>
</tr>
<tr>
<td>Potato total tuber yield (Mg ha(^{-1}))</td>
<td>44.3</td>
<td>39.6</td>
</tr>
<tr>
<td>Total N uptake (kg ha(^{-1}))</td>
<td>179</td>
<td>200</td>
</tr>
<tr>
<td>Total tuber dry weight (Mg ha(^{-1}))</td>
<td>8.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Maximum N uptake rate (kg ha(^{-1}) day(^{-1}))</td>
<td>4.46</td>
<td>4.3</td>
</tr>
<tr>
<td>N in tubers (kg ha(^{-1}))</td>
<td>159</td>
<td>158</td>
</tr>
<tr>
<td>N in stems and leaves (kg ha(^{-1}))</td>
<td>35.1</td>
<td>32.3</td>
</tr>
<tr>
<td>Kg of N to produce 1 Mg of tubers</td>
<td>4.1</td>
<td>5.0</td>
</tr>
<tr>
<td>N harvest index (%)</td>
<td>79.8</td>
<td>78.7</td>
</tr>
<tr>
<td>Residual N in root zone at harvest (kg ha(^{-1}))</td>
<td>66.7</td>
<td>92</td>
</tr>
</tbody>
</table>

\(a\) Values were the 3-year means of potato ‘Superior’ at the N rate of 140 kg ha\(^{-1}\) harvested at 125 days. \(n = 3 \times 3\) (plot \(\times\) year).

\(b\) Values were the 2-year means of potato ‘Superior’ at the N rate of 168 kg ha\(^{-1}\), harvested at 90 days. \(n = 12 \times 2\) (plot \(\times\) year).

\(c\) Values were the 2-year means of potato ‘Norland’ at the N rate of 140 kg ha\(^{-1}\) harvested at 100 days. \(n = 3 \times 3\) (plot \(\times\) year).

Fig. 7. Sainte-Croix study. Field measurements of daily N uptake and N partitioning from plants to tubers (A), accumulation of N in plant part (leaf, stem and root) and in tuber (B), maximum and mean total N uptake (C) and potato tuber yield (D) related to growing season days. Each point represents the mean of 27 measurements.
potato growth curve, we obtained the N uptake equation as follows:

$$\int P_N(t) \, dt = \frac{P}{1 + ((P - P_a)/P_b) e^{-P_c}}$$

$$= \frac{180}{1 + ((180 - 0.08)/0.08)e^{-0.16t}}$$  \hspace{1cm} \text{(14)}$$

The values for the N uptake equation parameters $P_a$ and $P_b$ in Eq. (14) were slightly higher than the values in the equation of Johnson et al. (1987). The regression of the model predicted N uptake values against the 3-year measured N uptake gave a high coefficient of determination ($R^2$) of 0.91.

According to the measured and predicted N uptake data, the N concentrations in the soil system for achieving the highest (or potential) N uptake were in the range of 90–120 kg ha$^{-1}$, and soil N concentrations above or below this range would lead to a decrease in the N take by potato (Fig. 3). There is a significantly exponential relationship between the predicted $N_{\text{inflow}}$ and the effect of $N_{\text{inflow}}$ (ENinflow) on N uptake, as shown by Eq. (15) as follows:

$$EN_{\text{inflow}} = 0.0008 e^{-0.0759N_{\text{inflow}}}, \quad R^2 = 0.94**$$  \hspace{1cm} \text{(15)}$$

By meeting the potato requirements of N, the simulated total loss of N in the system (Table 3) corresponded to less than half of the measured N loss in the field. In the Sainte-Croix study, the measured NO$_3$-N and NH$_4$-N within the root zone (0–0.6 m) varied between 118 and 229 kg ha$^{-1}$ at bloom, derived by the fertilizer N applications, potato N uptake and N loss processes. At harvest, the minimum soil N in the 0–0.6 m zone was 67 kg ha$^{-1}$, measured in the plots with the low rate of N (105 kg ha$^{-1}$), where the 3-year mean fertilizer N recovery (58.7%) was higher than that for the N rates $> 140$ kg ha$^{-1}$ (47%). In other field studies, potato tuber yield decreased only 2% but that residual NO$_3$-N decreased by 30% when the N rate was reduced by 25% (Neeteson, 1990). Using the model predicted N rate could result in an unchanged dry matter yield but a reduction of NO$_3$ leaching from 95.9 to 39.7 kg ha$^{-1}$ (Verhagen, 1997).

4. Discussion

4.1. Model ability and implications

The estimation of in-season N requirements by crops has been an issue. Validated simulation models provide the opportunity to extend the scope of field experiments beyond the experiment itself (Verhagen, 1997). Validated using the field measurements at four sites, our model predictions on soil N dynamics, crop growth and plant N uptake in the potato cropping system have implications in the applied aspects of agroecosystem management for making spring fertilizer N recommendation and in-season fertilizer N adjustment decisions (Fig. 1), and for reducing the impact of agricultural production methods on the environment. The model’s ability to predict potato growth, N uptake and N partitioning within the plant–soil system, and the model’s ability to make accurate predictions have shown that the model has enabled the rates and times of fertilizer N applications to match the requirements of N by the potato for achieving optimum yield and N uptake (Fig. 5). The model’s ability to predict the right rate and time of fertilizer N applications depended on the final yield a grower expected to achieve, and the knowledge of crop N status and how much N was presented in the soil at planting (Haverkort et al., 2003). There are several possibilities for using this simulation model to obtain predictions for future applications. For example, by making changes in some model parameters such as planting day, fertilizer N inflow, or growing season days (time), we could obtain suitable predictions for the specific situations to maintain optimum concentrations of N in the root zone and consequently increase fertilizer N use efficiency.

The advantages of our simplified model are to obtain predictions of daily, monthly or seasonal N uptake, plant growth, potato tuber yield and N concentrations in the root zone and below the root zone, which are not easily measured. This model has simplified the simulation processes by relating N uptake and transfer ratios to N inflow levels and potato growth stages. Approaches to simulate N balance in the potato cropping system have been complicated by the need to account for N uptake from soil, harvested N (or total N in tubers), N in potato residues and in the soil at harvest. It was useful to simplify N uptake related to the system N inflows and growing season days (Table 1). Our model in a simplified mode has shown satisfactory results for predicting plant growth and N use, as shown in other simplified models (MacKerron and Waister, 1985; Fishman, 1992; Izadi et al., 1996; Li et al., 2001c; Snapp and Fortuna, 2003).

4.2. Model validation and field data at different sites

In addition to the comparison with the means of the studies at the four sites (Table 4), the outputs of the model have been tested against three sets of the independent data at the Sainte-Croix site. One was to test the predicted in-season growth of plant biomass and potato tubers, a second was to examine the predicted total N uptake, N partitioning in stems, tubers and roots, and the third to compare the predicted in-season N in the soil. The experimental information incorporated in this model was to establish estimates and coefficients for the model development (Table 1). The model predictions and field measurements were independent datasets, and our model was able to generate correlations with the field measurements over a period of 3 years (Fig. 7).

Farm fields are often heterogeneous and crop development may different locally as a result of different soil types, soil fertility or other factors resulting from farm management (Verhagen, 1997). The cited field measurements in the
Sainte-Croix study (Li et al., 2003) were comparable to the data from the Saint-Damase–Soulanges study (Table 4), in which isotope 15N-labeled and non-isotope fertilizer N was used to quantify the fertilizer N recovery by potato (Tran and Giroux, 1991). Li et al. (2003) have also demonstrated the reliability of the data at the Sainte-Croix site by citing there was no spatial correlation structure for soil variables (pH, clay, sand, NO3 and NH4) by semivariogram analysis, and the regression of these measurements against sampling distance showed no trends in space. Thus, the experimental outcomes were attributable to the effects of the N treatments (not other factors) in the study (Li et al., 2003).

Our model included the management information on potato crop N status and N in the soil system in the humid and cool environment. Environmental model predictions are often practical in some specific areas. A functional model for predicting solute movement to estimate NO3 concentrations in the potato root zone was tested with reasonable success based on data collected from four treatments of N in fields in Idaho (Izadi et al., 1996). The predictions of requirements of N by potato from a simulation model, based on site specific soil conditions, were close to the actual amounts applied to the experimental fields in the Netherlands (Hodges, 1999). Also, when greater than the current N rate was simulated, potato had a larger NO3 leaching amounts, which were still comparable to the field measurements in Washington State (Peralta and Stockle, 2002).

The model predictions showed that the input of N based on yield potential and N uptake potential would be economically and environmentally beneficial (Fig. 3). The similar levels for the predicted soil N at harvest and the initial soil N at planting in the model (Table 4) indicated that meeting of plant requirements of N with the model N inflow predictions could result in a very small amount of unused fertilizer N at harvest. Nitrogen uptake could increase with split applications or with low rates of N fertilizers (Waddell et al., 1999; Li et al., 2003). However, reduced N rates did not mean to match crop requirements of N (Neeteson, 1990; Li et al., 2003). Planning the rates and timing of N applications through model predictions could more precisely meet the actual crop requirements of N as it might vary with growth stages (Fig. 3). The strength of the model predictions was because the simulation was based on a management context.

4.3. Model improvement

This model would be coupled with physical simulation processes within the plant–soil system to enable more complete N recommendations. Future development and improvement of the model would include physical variables such as soil bulk density, water content, pH or organic matter content in the model. Li et al. (2004) showed that potato tuber yield (Y, Mg ha−1) was quadratically correlated to soil bulk density (BD, Mg m−3): $Y = 28.87 + 31.34\text{BD} - 19.32\text{BD}^2$ ($R^2 = 0.54$, $P < 0.01$) and soil organic matter content (SOM, g kg−1): $Y = 14.26 + 0.318\text{SOM} - 0.012\text{SOM}^2$ ($R^2 = 0.53$, $P < 0.01$). To obtain a broader basis for verification of corresponding simulations and predictions, future development of the model would need to model constraints of environment variables on yield and N uptake (for example, examination of the sensitivity by changing N inflows, planting date, etc.). Within-field crop and soil variability are likely the factors causing low yield and N uptake for conventional uniform N applications (Verhagen, 1997; Li et al., 2001a,b, 2002; Delden et al., 2003). Soil properties are spatially variable and crop yield and N uptake are often correlated with soil water, texture, pH, organic matter content, etc. (Li et al., 2002, 2004; Peralta and Stockle, 2002).

Also, another question is how much N can actually be released from potato crop residues in the field under cool climatic conditions? Although the calculations of N inputs in the model have included the $N_{\text{e}}$ and $N_{\text{mn}}$ values that were derived from other studies, there is a need to further verify the amounts of N released by potato crop residues in the mineralization processes. Increasing fertilizer N use efficiency and reducing NO3 environmental impact are critical to agricultural sustainability (Neeteson, 1990; Haverkort et al., 2003; Li et al., 2003). Other efforts to refine the model should concentrate on a dynamic simulation of potato crop responses to changes in environmental conditions such as water and temperature stresses, e.g. the partitioning pattern of N assimilates versus air temperature and rain patterns.

Future efforts could include the development of a decision support system based on model predictions, and also the linking of a geographic information system (GIS) to the model for monitoring site-specific N management, as shown in Franko and Mirschel (2001). Linking a GIS tool to a simulation model has provided a reliable evaluation of NO3 leaching potential in potato/lettuce/onion production areas (Paz and Ramos, 2001).

Suitable plant N management in high-input crops such as potatoes would be derivative (instantaneous N uptake) and integrative (total accumulation) to reflect concurrent soil N availability (Hodges, 1999; Li et al., 2003; Gayler et al., 2002; Haverkort et al., 2003). Simulation model predictions have shown how to apply modeling technology to determine N fertilizer applications in commercial farming (Fishman, 1992; Verhagen, 1997; Delden et al., 2003; Snapp and Fortuna, 2003). Monitoring and modeling of in-season soil N, crop growth and N uptake patterns have provided useful information to optimize tuber yield and fertilizer N use.

5. Conclusions

Optimizing soil N use and potato tuber yield and N uptake can be achieved through monitoring, balancing and modeling daily N changes in the plant–soil system at early crop growth stages. Plant growth is dependent on how well
fertilizer N applications could meet the crop requirements of N, and simulations of potato growth required an accurate representation of N distribution in the developing crops. The model is able to describe potato growth, N uptake and N partitioning in the plant–soil system, and to predict daily, monthly and seasonal N balance for management. The system could be expected to be agronomically and environmentally beneficial because the model is capable of predicting differences higher than 5% in crop yield, N uptake and dry matter, and less than 60% in residual N measured in the field. The strength of the model predictions is to provide a mechanism for adjusting and regulating N use based on a management context in the cool and humid systems. Suggestions are offered on the model applications. The forecasts of the dynamic aspects of N inflows in the cropping system could be useful for meeting potato requirements of N at the early plant growth stage. Possibilities for the model improvements could involve linking a GPS system to the model for forecasting site-specific daily N inflows in the plant–soil system for more accurate and general simulation results.

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References


