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SIMULATING THE RESPONSE OF POTATO TO APPLIED NITROGEN[1]

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Introduction

In potato production, nitrogen (N) is applied more frequently and in greater amounts than any other nutrient. It is also the nutrient that most often limits yield. Without added N, growing plants often show a N deficiency characterized by yellow leaves, stunted growth, and lower yields. Because it is an important input, N and factors affecting its availability have been the subject of much investigation (Harris 1992). A common objective of many of these studies has been to develop N recommendation systems that can assist growers in determining the amount of N needed and the best time to apply it. Knowledge of when and how much N to apply is essential not only because N inputs have an economic cost, but also because N in excess of that used by the crop may have an environmental cost. The amount of N needed for crop growth, and its ultimate fate, are important issues regardless of whether the source of N is an organic material or a synthetic fertilizer.

An approach often used for estimating the amount of N to apply to potato has involved the measurement, in field experiments, of yield response to increasing rates of N fertilizer. In such experiments, the yield response is quantified by fitting a mathematical equation to the data. This equation is then used together with economic information to investigate returns to investments in fertilizer N. Although this approach has proven useful for demonstrating the concept of diminishing returns, it is nothing more than a "black-box" approach which offers limited information for deriving N recommendations in another year or at another site. Nitrogen is a dynamic and mobile nutrient, hence its effect on crop production is rarely the same from year to year. At best, equations from variable N rate experiments describe only historical relationships in the data, and as such offer little insight into the processes that must be understood to manage N inputs appropriately.

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More informative approaches for making N recommendations have followed from a better understanding of the processes that affect both crop N demand and soil N supply. This understanding has led to the implementation of N recommendation systems based on the simple principle that the amount of additional N to be applied can be estimated knowing both the crop N requirement and the potential soil N supply. While the crop N requirement is set by the internal N needed to obtain a specific yield, the soil N supply is set by the properties of the soil, particularly the organic matter content and other properties that affect the extent and rate of microbial decomposition. Both depend also on the vagaries of weather. For high yielding crops in most soils, the crop N requirement will exceed the soil N supply, and it is the difference between these two that approximates the amount of supplemental N needed by a growing crop.

Generally, the amount of N fertilizer to apply is calculated by estimating the soil N supply, a target yield level, and an expected fertilizer efficiency; the latter since not all of the applied N is normally recovered by the crop (Dahnke and Johnson, 1990). To estimate each of these components, measurements of one or more of the following variables may be needed: whole plant N content required to reach a target yield level, mineral N released during soil incubation, total N content of the soil, mineral N present in the soil profile at planting, and leaf N concentration or chlorophyll content at a specific growth stage. Relationships between any of these variables and the benefit of added N are usually defined in field calibration studies. Because of site-specific effects, such studies need to be conducted across a broad range of soil-crop-climate conditions. There is, however, a practical limit to the number of soil-crop-climate conditions that can be included in field studies.

An additional tool now available for evaluating N management practices and for making N recommendations is one based on computer simulation. Using dynamic simulation techniques, scientists have been able to construct computer models capable of simulating many of the major processes that control N demand and N supply. When assembled within the framework of comprehensive crop growth models, the dynamic nature of these models makes them valuable instruments for exploring different N management options across a theoretically unlimited number of cropping practices, soil types, and weather conditions.

The purpose of this study is to illustrate how we are using a potato growth model to better understand N dynamics in potato-based cropping systems. We do this, however, stressing that simulation models are not a substitute for standard testing and monitoring of the N status in soils and plants. Rather, they are a tool for extending the value of such measurements by facilitating a systematic analysis of how plant, soil, weather, and management factors interact to affect N dynamics. In this study, we use the SUBSTOR-Potato model (Ritchie et al. 1995) to perform a systematic analysis of some of these factors, demonstrating how the model can be used to gain insight into N dynamics on a site-specific basis. We will also show results from model testing in Andean conditions. The version of SUBSTOR used in this study is that released with the Decision Support System for Agrotechnology Transfer (DSSAT) version 3 (Jones et al. 1998).

A Comprehensive Crop Growth Model

The SUBSTOR model provides a useful tool for analyzing the quantitative effect that controlled factors (e.g., management), uncontrolled factors (e.g., weather), and site-specific soil properties have on principal components of the N balance. The model is comprehensive in that it simulates the major processes associated with crop N demand and soil N supply (Table 1). The model provides a balanced approach in the level of detail used to describe soil and plant processes; all of the processes listed in Table 1 are simulated using a daily time step. The comprehensive and dynamic nature of the model means it can be used to evaluate, on a site-specific basis, many alternative management practices against the uncertainties of weather. Simulation results, when based on reliable input data, can then provide critical information for defining the best N management practices from both an economic and environmental perspective.

We have used experimental data from Ecuador and Peru to first test the performance of SUBSTOR under Andean conditions (Figure 1). In Ecuador, Clavijo (1999) showed that the model accurately simulated the response of two cultivars to N fertilizer at two sites in Carchi. In Peru, Yauri (1997) showed that SUBSTOR was able to realistically simulate the growth of two cultivars with and without irrigation at a site in Huancayo. A comparison of simulated and observed tuber yields from the Ecuador and Peru studies is shown in Figure 1. This limited testing shows that the model realistically simulated tuber yields that ranged from 16 to 56 Mg ha^{-1} due to differences in weather, soils, cultivars, and management. Further testing is underway as we continue to critically evaluate the performance of SUBSTOR and search for ways to improve it as both a research and application tool.

Components of a Systematic Analysis

A general approach for estimating the amount of N fertilizer to apply to a crop (N_f) may be based on the following calculation:

$$N_f = (N_y - N_s)/E_f$$

where N_y is the internal plant N required to attain the expected yield, N_s is the N supplied by the soil, and E_f is the expected efficiency or fraction of applied N the crop is expected to recover. This approach provides a useful framework for examining the main factors that must be considered when managing N inputs. Within this framework, the N balance in agricultural fields can be characterized by defining three major components: (i) the crop N demand, (ii) the N supplied by the soil, and (iii) the N added in organic or mineral fertilizer. To optimize N management for a specific situation, quantitative estimates of each of these components are needed along with economic information.

Crop N Demand

Crop N demand is the product of the expected yield and the internal N requirement, which can be thought of as the minimum amount of plant N associated with maximum yield (Stanford and Legg 1984). Although a growing crop may take up more than the minimum N needed, the extra nitrogen (luxury consumption) does not usually result in any yield benefit. Therefore, to optimize N management and avoid its inefficient use, it is important to know the expected maximum yield and its associated internal N requirement. Maximum yield, however, is not a constant. For a single cultivar, maximum yield will be expected to vary from site to site and year to year due to the interaction of genetic traits with photoperiod, temperature, solar radiation, water and nutrient availability, and management. It is possible to capture many of these interactions in the SUBSTOR model.

To illustrate, Figure 2 shows how tuber yields responded differently to applied N when the SUBSTOR model was run using different weather years for a site in Huancayo, Peru. The cultivar simulated was ‘Yungay’, which was planted mid November and harvested early April. Whereas fresh yields reached a maximum of 55 Mg ha^{-1} using daily weather from 1982-83, the same amount of N in 1990-91 produced a maximum yield of only 26 Mg ha^{-1}. The difference in N response between seasons was attributed mostly to a less favorable distribution of rainfall during 1990-91, with the simulation showing the plants suffered a significant water deficit during tuber bulking. Although yield levels varied for the two seasons, the internal N requirement remained constant at about 16 g N kg^{-1} of total dry matter (haulms plus tubers), which is within the range reported by Vos (1995) for several field experiments. The simulated removal of N in fresh tubers was about 2.8 kg N Mg^{-1} of fresh weight in each season, also within the range reported for real data by Harris (1992).

Simulation can be used as well to estimate the time course or pattern of N uptake by a growing crop. With output provided on a daily basis, the model makes it possible to define the period when N is in greatest demand. Such information can then be used to examine how management might improve the synchrony between crop N demand and N supply. For example, the economic and yield impact of split applications of N fertilizer could be easily studied in simulation runs designed to vary the amount and timing of N applications.

Soil N Supply

The N supplied by the soil comes mostly from two sources: (i) mineralization of soil organic N during the growing season, and (ii) mineral N initially present in the soil profile at planting. Both sources should be considered when estimating the amount of supplemental N needed by a growing crop, although the importance of initial mineral N tends to diminish in high rainfall environments where significant leaching can occur.

Since the mineralization of soil organic N is a biological process, the amount of N made available depends primarily on the level of microbial activity and the amount of C substrate. For most mineral soils, the proportion of C and N in the soil organic matter is fairly constant with an average C:N ratio of 10. Such a ratio favors a net release of N to available mineral forms unless organic materials are added with C:N ratios greater than 25. When the C:N ratio is greater than 25 there is usually a loss of plant available N as it becomes tied up through net immobilization.

The amount of mineral N present in the soil profile at planting (initial mineral N) often has a substantial impact on the need for supplemental N, particularly in less humid environments. Initial mineral N usually varies across sites and years, with the amount largely determined by management and growth of the previous crop and the residual N left from earlier applications. If rainfall is not excessive, much of the initial mineral N can remain available to a crop throughout the growing season.

The process descriptions incorporated within SUBSTOR make it possible to capture the interaction of these sources of plant available N with crop N demand for innumerable combinations of soil type, weather conditions, cultivar, and management. For example, simulation could be used to examine how soil N supply might vary across years for different quantities of soil organic matter and mineral N present at planting. Moreover, a simulation study like the one used to derive Figure 2 would obtain somewhat different response surfaces if soil organic matter or initial mineral N inputs were varied.

Sources of Supplemental N

In SUBSTOR, supplemental N can be added as a synthetic fertilizer or as a plant residue (e.g., green manure). Algorithms dealing with the transformation of animal manure have not yet been included, although we have efforts underway to do so. Nitrogen management practices that can be examined with the model include the effect of varying N rates, time of application, placement depth, and fertilizer source. These practices can be studied for their effect on not only tuber yield, but also on nitrate leaching or economic returns. Such studies can be simulated for a single growing season, or across many different seasons to quantify the impact of weather variability and its associated risk.

A simulation example that illustrates how the model might be used to estimate the yield benefit of alternative N management options is shown in Figure 3. In this example, SUBSTOR was run for 19 different seasons using daily weather data from Huancayo. Once again, the cultivar simulated each season was ‘Yungay’, which was planted mid November and harvested early April. The N management options were no external source of N applied (0N), a legume green manure (4 Mg dry matter ha-1 with a N content of 2.5 %) incorporated just before planting (GM), and 250 kg N ha-1 applied as urea in two equal split applications. The simulated tuber yields for the 19 seasons are plotted in Figure 3 as cumulative probability distributions. These distributions clearly show the superiority of the urea treatment in increasing yield, but they also demonstrate the risk of obtaining low yields despite a heavy N application. For example, because of poor rainfall distribution and subsequent drought stress, the probability of obtaining essentially no response to applied N would be about 15%, or about one year in seven. The probability of obtaining a significant response to N is, however, much greater, with yields of 30 to 50 Mg ha-1 expected about 50% of the time.

With this type of information provided on a site-specific basis, decisions regarding N management can be made based on an improved awareness of both the potential and the limitation of a given environment. To make such a simulation even more useful, the model inputs and yields could be used together with actual price and cost data to obtain similar distributions for net returns, which would define better the risk of more interest to a farmer.

Conclusions

Nitrogen management can be improved upon through the insight provided by comprehensive crop simulation models such as the SUBSTOR model. As a continually evolving tool, such models have the potential to help both researchers and farmers better understand how soil, crop, weather, and management factors interact to affect crop N demand, soil N supply, and fertilizer use efficiency on a site-specific basis. With the model and appropriate input data, any number of management scenarios can be examined and compared for their impact on not only economic returns but also the potential for excessive leaching of nitrates. Economic and environmental (nitrate leaching) risks due to uncertain weather can also be quantified.

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Table 1. Major processes that are simulated and environmental factors that affect those processes in the N submodel of SUBSTOR-Potato (version 3).

PROCESS SIMULATED	MAIN FACTORS INFLUENCING PROCESS
Crop N Demand	
Growth	Solar Radiation, Temperature
Development	Photoperiod, Temperature
Soil N Supply	
Mineralization/Immobilization	Soil Temperature, Soil Water, C/N Ratio
Nitrification	Soil Temperature, Soil Water, Soil pH, NH_4^+ Concentration
Denitrification	Soil Temperature, Soil Water, Soil pH, Soil C
NO_3^- Leaching	Drainage
Urea Hydrolysis	Soil Temperature, Soil Water, Soil pH, Soil C
Uptake	Soil Water, Inorganic N, Crop Demand, Root Length Density

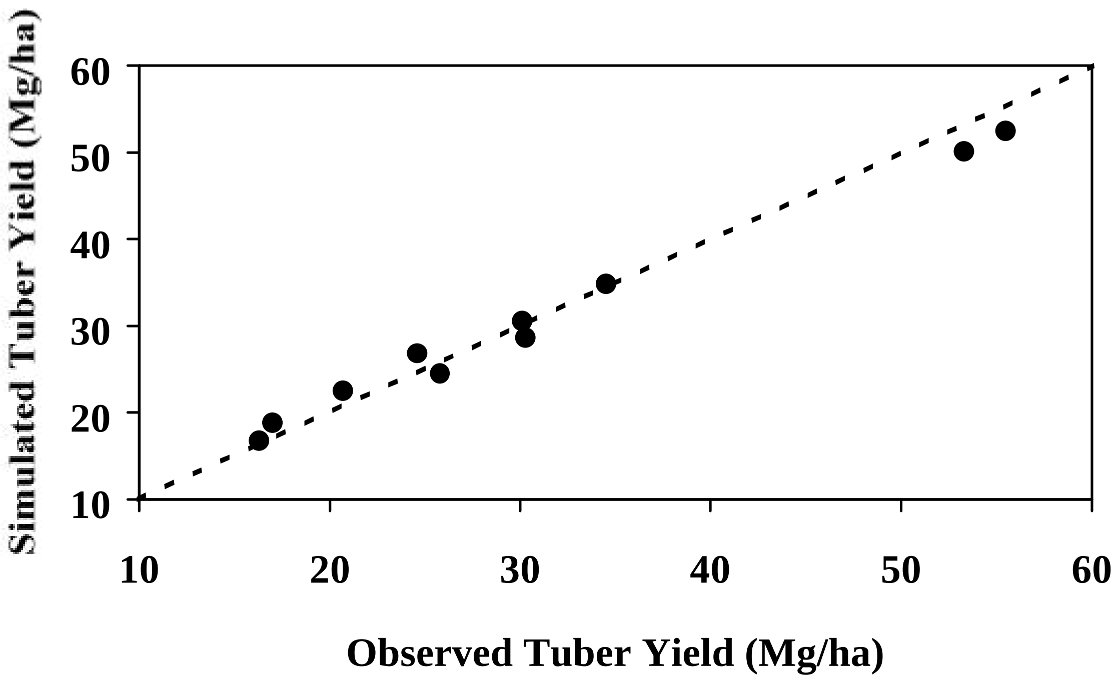

Figure 1. Relationship between simulated and observed fresh weight of tubers for sites in Ecuador and Peru (dotted line is 1:1 line).

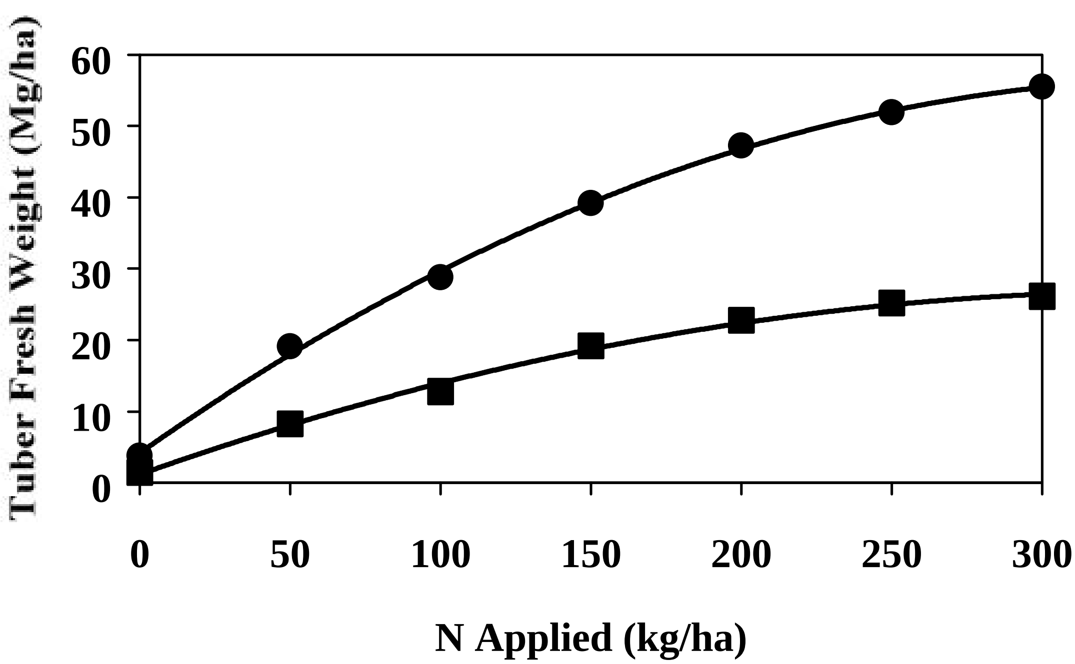

Figure 2. Simulated response of tuber fresh weight to applied N using daily weather data from 1982-83 or 1990-91 for a site in Huancayo, Peru.

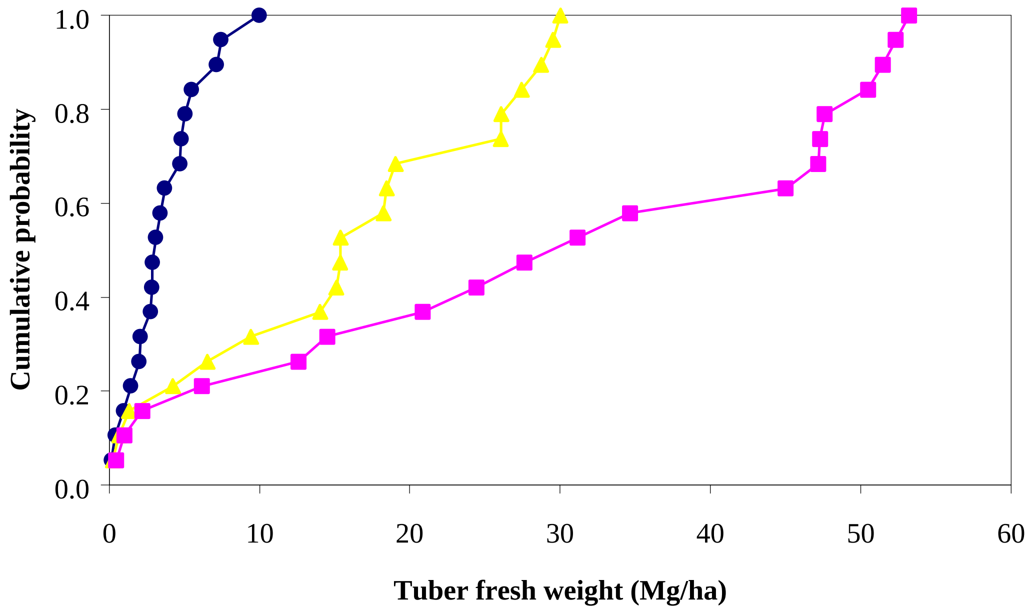

Figure 3. The cumulative probability distributions for tuber fresh weight resulting from simulations made across 19 years of weather from Huancayo, Peru. The N management treatments were no applied N (0 N), green manure incorporated (GM), or urea applied at 250 kg N ha^{-1} (250 N).