Nitrogen modeling of potato fields in the Bolivian Andes using GLEAMS

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Abstract

An increase in population in rural agricultural communities and higher demand for food throughout Bolivia create the need for increased agricultural production. The objective of this study was to assess the suitability of the GLEAMS model as a tool for evaluating fertilization and cropping system practices for potatoes in the Andes of central Bolivia, and make recommendations for the continued development of the model as an analysis tool to improve sustainable crop production. Model suitability was evaluated through assessment of model representation of observed potato farms and behavior of simulated soil nitrogen (N) and N transformation trends; validation with field data taken from six agricultural sites in central Bolivia for runoff volume, soil total Kjeldahl N concentration, crop production, and crop N uptake; and sensitivity analysis.

Validation of model output with observed values was completed both graphically and by determining the root mean square error standard deviation ratio (RSR) and the percent bias (PBIAS). RSR and PBIAS values for runoff volume were 4.0 and 65%, 4.5 and 4%, and 2.7 and 55% for three respective experimental plot repetitions using a calibrated SCS curve number of 90. The RSR and PBIAS, respectively, for soil total Kjeldahl N concentration were 3.0 and -2.2%. The RSR and PBIAS, respectively, for crop dry matter production were 7 and 21%. The RSR and PBIAS, respectively, for crop N uptake were 10 and 21%.

The mineralization processes in GLEAMS must be improved before model application to central Bolivia, where agricultural production is highly dependent on mineralization of organic N from soil and applied animal manure. Recommendations for model improvement and development include modification to the process that determines mineralization from the soil potentially mineralizable N pool; validation of the percolation volume and nitrate leaching losses; and improved model representation of banded manure application.

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Chapter 1. Introduction

1.1 Background

An increase in population in rural agricultural communities and higher demand for food throughout Bolivia are placing more pressure on the fertility of the traditional agricultural systems and the capacity to maintain yields. Interviews with farmers in Bolivian mountain valleys have revealed that there is a noticeable decline in land productivity due to soil degradation (Kessler and Stroosnijder, 2006). Surveys completed by the United Nations Food and Agriculture Organization (FAO) found that there is a rise in rural families cropping on marginal lands within the steep slopes of surrounding ridges in order to grow food for themselves and to sell at markets in surrounding towns (FAO and SNAG, 1995). Improving the nutrient supplying capacity of the soil in established parcels at lower elevations through improved nutrient management may increase yields and decrease the need for farmers to cultivate on steep locations that are more susceptible to soil erosion and the consequential problems that it creates such as sedimentation of streams and reservoirs (Osorio et al., 2008).

The department of Cochabamba in central Bolivia has been renowned for its agricultural capacity for centuries and is known as the “bread-basket” of Bolivia because the temperate climate is ideal for crop production. A challenge in maintaining crop production levels in rural areas of central Cochabamba is the poverty of the majority of the local farmers. Most farmers are unable to afford inorganic fertilizers even with government price support programs. This has increased the attractiveness of animal manures as fertilizers, either from livestock owned by the farmers themselves or purchased chicken litter (Augstburger, 1983).

A better understanding of the effects of agricultural management on nutrient levels in the soil may help decision makers in these regions determine which management practices will better maintain soil nutrient levels, and thus crop yields, over time. Continued research in crop nutrient requirements, nutrient reactions in the soil-plant atmosphere, and potential nutrient supplies from animal manures and inorganic sources is required to determine the fertilizer types and application methods in order to optimize yields on an individual farm basis. The Bolivian non-governmental organization Promocion y Investigacion de los Productos Andinos (PROINPA) with the support of the United States Agency for International Development (USAID) Sustainable Agriculture and Natural Resource Management Collaborative Research Support Program (SANREM CRSP) is currently engaged in research in watershed-based natural resources management in small-scale, sloped Andean regions. The Jatun Mayu River watershed area is of particular interest due to its central location in Cochabamba, the proximity to an established research station managed by PROINPA, and because the surrounding farms and farmers are typical of those in the inter-Andean valleys.

The use of a model designed for nutrient predictions in agricultural systems could have many benefits in researching nutrient management in the Bolivian inter-Andean valleys. A properly selected and calibrated model can help researchers better understand the processes in the natural systems and perform long-term evaluations of soil fertility without the burden of costly and time-consuming field studies (Barfield et al, 1989). The model could be used to perform simulations to provide insight into which management practices or geographical locations are at greatest risk of soil nutrient depletion over time. The results from these simulations could assist researchers in broader watershed management in the search for the most beneficial alternative management practices to maintain soil fertility and yields without oversupplying nutrients to ground or surface water sources. Before this is possible, however, a preliminary model evaluation including sensitivity analysis of the model output to input parameters and validation based on comparison of predicted outputs with observed data should be completed for the region of interest (Moriasi et al., 2007).

One model that could assist in research related to nutrient management in agricultural systems is the Ground Water Loading Effects of Agricultural Management Systems (GLEAMS) model from the United States Department of Agriculture (USDA) (Knisel and Davis, 1999). GLEAMS (Ver. 3, Agricultural Research Service; available at http://www.tifton.uga.edu/sewrl/Gleams/gleams_y2k_update.htm accessed on November 14, 2007) is a continuous field scale model that predicts edge of field and bottom of root zone loadings of nutrients based on hydrology, erosion, and nutrient input parameters (Leonard et al., 1987). The FORTRAN source code is available, so changes in model algorithms are possible. Although the model was not designed to make absolute predictions, it can provide a useful tool for comparing nutrient loadings in runoff or from the root zone of different management practices. The model has been studied extensively for applications in the United States and has been adapted for other regions such as the tropics (Caiado, 2005), but little information is available for its use in the inter-Andean valleys in Bolivia.

1.2 Objectives

The goal of this study was to assist in research towards increasing long-term crop productivity in the central Bolivian highlands with improved nutrient uptake efficiency and sustainable management of soil and water resources. The study focused on the Jatun Mayu watershed area in Tiraque Province, Cochabamba, and the use of the GLEAMS model to represent nutrient dynamics in cropping systems considering long-term weather variability, local differences between soil and micro-climate altitude zones in the watershed area, and nutrient management alternatives used in the region. The objective of this study was to assess the suitability of the GLEAMS model as a tool for evaluating fertilization and cropping system practices in the Jatun Mayu watershed area and make recommendations for its continued development as an analysis tool.

Chapter 2. Literature review

Development of a model as an analysis tool to improve nutrient management and crop production in Bolivia should consider the current environmental conditions and agricultural management practices that dictate nutrient movement within the system and affect crop production. The local climate and precipitation patterns, soil characteristics, organic manure properties as crop fertilizers, and local crop growth requirements in Andean systems must be well understood before they can be adequately simulated in a model. The goal of this literature review is to highlight the environmental and managerial conditions of Andean agricultural systems with a focus on potato production and nitrogen (N) dynamics in the inter-Andean valleys in central Bolivia and to discuss potential models to apply to agricultural systems there.

2.1 Bolivian inter-Andean valley agricultural conditions

2.1.1 Climate and social conditions

The three main agricultural regions in Bolivia are the Altiplano, the central inter-Andean valleys, and the tropical eastern lowlands. The inter-Andean valleys, especially the Cochabamba and Tarija valleys, are an important transition zone between the Altiplano and eastern lowlands. They cover 213,287 km^2 of the 1,098,581 km^2 in Bolivia (FAO and SNAG, 1995). The most cultivable altitude ranges from 2000-3500 meters above sea level (masl), with an average temperature range of 15-18°C, and average annual precipitation of 400-800 mm (depending on location) falling during a summer rainy season from October to March (FAO and SNAG, 1995). The temperate climate during the rainy season allows for a range of crops such as potato, corn, wheat, barley, and legumes such as fava bean, tarwi, and alfalfa. Typical plots are from 2 to 10 ha and are managed by families with an emphasis on community support in decision making and sharing resources (PROINPA, 2006). This region is important in terms of its agricultural capacity because of its central location in the country and because it has a high population density of rural inhabitants (53.4% of the total population in Bolivia (CIPD, 1994)). The average household has eight children and, although a percentage of the young adults leave their home communities permanently to find work in cities or other countries, there is also an increase in rural population which often leads to a reduction in parcel size of land passed down to the next generation (FAO and SNAG, 1995). This has encouraged many farmers to reduce traditional fallow periods and/ or seek additional land in more marginal conditions such as steep slopes or locations that have been historically less productive (Bottner et al., 2006a).

2.1.2 Potato production

Potato production is important to the rural communities in Bolivia. Potato varieties were first discovered in the Andean region 8000 years ago by pre-Incan civilizations (FAO, 2008). Today, potatoes are still an important nutrient source for rural Bolivian populations providing 20.13 g of carbohydrates, 1.87 g of protein, 13.0 mg of vitamin C, and 5.0 mg of calcium for every 100 g after boiling (Prokop and Albert, 2008). Potatoes bring in more income per hectare than corn, wheat, and barley combined for the farmers in the Jatun Mayu watershed (PROINPA, 2006). In the Andes, potatoes are usually planted the first year in a crop rotation followed for one or two years by small grains such as barley or oats. Potatoes are usually the only fertilized crop in the rotation, typically being fertilized with animal manure applied at planting (Couteaux et al., 2008; Pestalozzi, 2000). After the small grain crop, the plot is usually left in fallow for 3-7 years to restore fertility through the accumulation of organic material through uncultivated successive plant growth (Pestalozzi, 2000; Sarmiento and Bottner, 2002). The successive plant growth that occurs during the fallow period restores the soil fertility by increasing the microbial biomass, decreasing the proportion of nitrate (NO_3^-) leaching losses from the soil's mineral N pool through plant uptake, and increasing potentially mineralizable carbon (C) and N (Sarmiento and Bottner, 2002).

Potato tuber nutrient extraction depends highly on the nutrient and water availability in the soil as well as other growing conditions. A soil fertility field study in Bolivia estimated that 1 t ha^{-1} of fresh tuber yield removes 3.2 kg N ha^{-1}, 1.8 kg P_2O_5 ha^{-1}, and 6 kg ha^{-1} K_2O (FAO and SNAG, 1995). Nutrient recommendations for production of Andean potatoes are shown in table 2.1.

Table 2.1. Nutrient recommendations for potatoes in Andean regions.

Source	Nutrient recommendation			Comments
	N ($kg\ ha^{-1}$)	P_2O_5 ($kg\ ha^{-1}$)	K_2O ($kg\ ha^{-1}$)	
Augstburger (1983)	80	120	0	
FAO and SNAG (1995)	120-130	120-130	80	Expected yield >15,000 kg ha^{-1} fresh tubers
Reyes (2003)	150-200	40-60	0	

Potatoes have shallow rooting systems and grow best in coarse-textured, porous soils so that the tubers can easily expand during the tuber bulking stage. These properties can lead to both NO_3^- leaching and water stress in potato systems (de Paz and Ramos, 2004). The plants are typically hilled after plant emergence to allow the tubers more room to expand.

The most common potato variety in the Bolivian inter-Andean valleys is Waycha (*Solanum tuberosum* spp. andigena).The leaf area index (LAI) for Waycha was determined under optimal conditions at the Toralapa Research Station in Cochabamba, Bolivia (Condori et al., 2008). The maximum LAI was approximately 3.7 $m^2\ m^{-2}$ at 110 days in a 140 day growing season. The average final fresh yield based on the trials from this experiment were 34.4 t ha^{-1}, which the authors described as a reasonable potential yield for the Waycha variety under normal local conditions (Condori et al., 2008). This is also consistent with Devaux et al. (1997) who found that the highest Waycha fresh yield of 35 t ha^{-1} under four different fertilizer treatment was obtained with 160 kg N ha^{-1} and 240 kg P_2O_5 ha^{-1}.

The method used to calculate evapotranspiration (ET) from potatoes growing in the Andes is important in correctly characterizing the water and subsequent nutrient uptake by the crop. Garcia et al. (2004) found that temperature-based ET methods such as Thornthwaite (1954) and Hargreaves-Samani (1985) greatly under-predicted the potential ET measured from lysimeters for a grass reference crop in the Altiplano due to the absence of an aerodynamic term. The inclusion of an aerodynamic term is important to account for higher ET due to lower vapor pressure over the crop surface for locations at high altitudes such as in central Bolivia. This was confirmed when drainage water collected in lysimeters was compared to the ET determined from the three methods (observed seasonal ET=764 mm) (Garcia et al., 2004). The FAO Penman-Monteith ET method (Allen et al., 1998) had the lowest mean bias error (-0.2 mm) in the study by Garcia et al. (2004). One challenge when attempting to use the FAO Penman-Monteith method is the high level of detailed climate data that is required to make the predictions. Garcia et al. (2004) also tested the use of the FAO Penman-Monteith method using recommended missing data estimates from Allen et al. (1998), including a global wind speed average of 2 m s^{-1}, minimum temperatures in place of dew point temperatures, and solar radiation derived from air temperature differences using the Hargreaves equation. The FAO Penman-Monteith equation still predicted the measured lysimeter data for ET suitably using the estimates for missing climatic data (root mean square error of less than 0.4 mm per day) (Garcia et al., 2004).

2.1.3 Fertilizer sources and applications

The principle production limiting factors in the Altiplano and inter-Andean valleys are and historically have been water and nutrients (Devaux et al., 1999). One of the main outcomes from crop nutrient studies in Bolivia was the elucidation that crop yields are increased through the use of a combination of mineral nutrients and organic amendments of green or animal manures (FAO and SNAG, 1995). The multiple benefits of organic matter inclusion in agricultural systems are described in detail in Brady and Weil (2008) and summarized here. Organic material improves soil structure and aggregate stability which can reduce erosion through development of lignin and mycorrhizae that act as adhesives during the decomposition process. The organic material complex has several negative electromagnetic sites that can attract positive nutrient ions such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{+2}), and magnesium (Mg^{+2}), keeping these available to the crop and avoiding loss through leaching or fixation to soil clay minerals. The organic material provides a habitat for soil microfauna and microflora which decompose organic material and convert it to inorganic forms which can be taken up by plants (NO_3^- and NH_4^+). The soil organic material also increases the surface area of soil particles providing more micropores for water storage.

The high cost of inorganic fertilizers relative to farmers' incomes has encouraged more use of animal manures as fertilizer in central Bolivia, especially chicken litter purchased from commercial facilities and cattle or sheep manure collected from the farmers' own livestock in their yards (Augstberger, 1983). The addition of soil organic material in the form of animal manure can help increase soil quality and provide a source of nutrients for crops. Hirzel and Walter (2008) found that an application 20,000 kg ha^{-1} poultry litter (2.9% total N content) produced similar dry matter production of corn silage to that using 400 kg inorganic N ha^{-1}, 300 kg P_2O_5 ha^{-1}, and 280 kg K_2O ha^{-1} in a silt loam in Chile. Augstberger (1983) also concluded that fresh poultry manure applied at 10,000 kg ha^{-1} (2.2-2.6% total N content) produced similar potato yields to those fields with inorganic fertilizer applications of 80 kg N ha^{-1},120 kg P_2O_5 ha^{-1}, and 0 kg K_2O ha^{-1} at a research site in central Bolivia.

Bolivia produces approximately 15 million tons of livestock manure annually and another 250,000 tons of plant residue from agro-industrial operations in the eastern lowlands, typically from rice husks and sugarcane stalks (FAO and SNAG, 1995). However, a high percentage of the manure is not suitable for use as a fertilizer, either because it is too difficult to collect from range animals or is of poor quality. Poor fertility of grazing land leads to low nutrient content in foliage and thus manure. This has been demonstrated in studies where Bolivian cattle manure was ranked lower in N, P, and potassium (K) content and chicken manure lower in N and P than that from livestock in Brazil and the United States, as shown in table 2.2 (FAO and SNAG 1995).

Table 2.2. Nutrient contents (dry weight basis) for two types of manure from three countries (from FAO and SNAG, 1995).

Manure type	Nutrient content								
	N (% dry wt)			P_2O_5 (% dry wt)			K_2O (% dry wt)		
	Bolivia	Brazil	USA	Bolivia	Brazil	USA	Bolivia	Brazil	USA
Chicken manure	2.04	3.40	3.95	1.04	3.60	1.90	1.44	1.50	0.92
Cow manure	1.24	1.80	3.33	0.39	1.30	0.93	1.65	2.60	2.53

The Andes receive some N atmospheric deposition in addition to applied N in fertilizers. Godoy et al. (2003) found that the Andes in Chile received more N deposition than coastal areas. They estimated from a research station located at 1120 masl in southern Chile that 1.0 kg NO_3^- ha^{-1} yr^{-1} and 1.4 kg NH_4^+ ha^{-1} yr^{-1} were deposited via cloud water and fog. This was based on analysis of 12 cloud/fog samples that revealed N concentrations of 87.1 µg NO_3^- L^{-1} and 108.6 µg NH_4^+ L^{-1} at a location that receives 5500-6600 mm of precipitation annually (Godoy et al., 2003). For their nutrient balance in the Ecuadorian Paramo, deKoning et al. (1997) estimated the N deposition in rainfall based on the precipitation amount according to the method described by Stoorvogel et al. (1993). Stoorvogel et al. (1993) estimated values of 2.6 kg N ha^{-1} yr^{-1} and 3.8 kg N ha^{-1} yr^{-1} atmospheric N deposition for 200-500 mm and 500-1000 mm annual precipitation, respectively.

2.2 Andean soil nutrient properties

2.2.1 General soil properties

Some studies have been completed to characterize soil nutrient properties in high-altitude Andean regions such as the Altiplano and inter-Andean valleys in Bolivia and Peru; the Paramo in Venezuela, Colombia, and Ecuador; and Patagonia in Chile and Argentina. The soil properties within the respective high-altitude ecosystems can be very diverse, especially in those locations that have volcanic ash soils (USDA taxonomic soil order Andisol) such as the Paramo and Patagonia. Table 2.3 shows C:N ratio, total N, and pH for Andean soils as reported in the respective studies.

Table 2.3. Properties of agricultural soils (surface layer) prior to experimental amendments or after fallow in multiple studies in Andean regions.

Source	C:N	Total soil N (%)	pH	Region, Country
Bottner et al. (2006a)	5.8	0.09	6.3	Altiplano, Bolivia
Bottner et al. (2006b)	7.6	0.06	6.6	Altiplano, Bolivia
Couteaux et al. (2008)	10	0.06	6.2	Altiplano, Bolivia
Pestalozzi (2000)	11.2	0.2	4.7	Inter-Andean valley
Samiento and Bottner (2002)	15	0.69	5.0	Paramo, Venezuela
Bottner et al. (2006b)	15.3	0.65	4.5	Paramo, Venezuela
Abreu et al. (2007)	16	0.61	4.5	Paramo, Venezuela
Abadin et al. (2002)	18	0.45	4.8	Paramo, Venezuela
Aruani et al. (2007)	10.5	0.16	7.0	Patagonia, Argentina

2.2.2 Organic matter decomposition

Organic matter decomposition in Andean systems is a key process in increasing crop available nutrients since most of the mineral N and P in the soil originates from organic residues from the previous fallow period or applied animal manures. Some studies have been completed to characterize organic matter decomposition in Andean systems to better understand the nutrient dynamics that make N and P available for crop uptake.

Couteaux et al. (2008) completed a study in Patacamaya in the Bolivian Altiplano (mean annual air temperature 8.7°C, mean annual precipitation 437 mm over study period) that developed a relationship for the decomposition of sheep dung and potato plant residue in a sandy soil cultivated with potato. They considered the applied organic material to have two components, labile and recalcitrant, where the remaining mass of the material in the soil over time is

$$RM = Ae^{-kt} + (100 - A) \tag{2.1}$$

Where RM = remaining mass of organic material (%)
A = decomposable fraction of the organic material (%)
k = decomposition rate of the decomposable fraction (d^{-1})
t = time (d).

The decomposable fraction A ranged from 65.9- 77.7 % and 81.3- 84.7% with k from 0.004- 0.005 d^{-1} and 0.019- 0.108 d^{-1} for the sheep dung experiments and potato residue experiments, respectively.

In research on organic matter decomposition in the Venezuelan Paramo (3400 masl, mean annual air temperature 8.5°C, mean annual precipitation 1329 mm), Sarmiento and Bottner (2002) used a double exponential model to describe the decomposition of the labile and recalcitrant C fractions:

$$C_t = C_0(1 - e^{-kt}) + C_r(1 - e^{-ht}) \tag{2.2}$$

Where C_t= cumulative released CO_2 (g kg^{-1})
C_0= labile C fraction (g kg^{-1})
k = decay rate constant for labile fraction (d^{-1})
C_r= recalcitrant C fraction (g kg^{-1})
h= decay rate constant for recalcitrant fraction (d^{-1})
t = time (d).

They found decay rate constants for the labile fraction of total soil C (k) of 0.125 d^{-1} and 0.189 d^{-1} for a soil that had been in fallow and a soil after two years of potato production, respectively. The decay rate constants for the recalcitrant fractions (h) were 0.00008 d^{-1} and 0.0001 d^{-1} for the respective sites.

An earlier model by Couteaux et al. (2002) also used a two component model to estimate remaining C from decomposing wheat straw in the soil along an altitudinal transect (65- 3968 masl) in the northern Andes in Venezuela. Three organic C decomposition models were fitted to experimental data to determine if climate influenced organic C decomposition. All the models followed the general form:

$$RC = Ae^{-k_a t} + Be^{-k_b t} \tag{2.3}$$

Where RC= remaining C (%)
A and B = initial percentages of labile and recalcitrant C (%) (A+B=100)
k = decay rate constant for the respective C fraction (d^{-1})
t = time (d).

In addition to the general model, one of the tested models included a cumulative temperature term and one model included a cumulative temperature and soil moisture term in the exponent of each fraction that replaced the time exponent. They concluded that the inclusion of a climatic variable that considered temperature and soil moisture improved the model performance but that there were probably other variables that would also affect the decomposition rates of the two components that were not accounted for. They also determined that the labile carbon fraction decomposed independently of the climate factor and so the climate factor had a greater impact on the recalcitrant fraction (Couteaux et al., 2002).

A re-analysis of the data from Couteaux et al. (2002) by Braakhekke and Bruijn (2007) revealed that temperature may have a greater effect on both carbon components than previously assumed. Rather than varying the initial component sizes (A and B) for each set of data from the sites along the altitudinal transect, they used constant values for the decomposable fraction (A=41.4%). They also omitted the cumulative temperature and soil moisture term and replaced the original time term (t) and allowed the rate of decomposition (k) to be governed by the temperature and moisture effects for each site. This provided a model that predicted the data just as accurately as the more complicated model of Couteaux et al. (2002) and allowed the decomposition rates of both C fractions to be affected by temperature which seemed more biologically appropriate. This method also showed that the rate of decomposition of the recalcitrant fraction (k_b) decreased with altitude. Decomposition rates for the organic material at the high altitude site (3968 masl) were determined to be k_a= 0.0147± 0.001 d^{-1} and k_b 0.00027±0.0001 d^{-1} using the constant decomposable fraction above.

Bottner et al. (2006a, 2006b) also completed studies that observed mineralization rates of wheat straw in fallow plots in the Altiplano. In their study, the MOMOS-6 model was used to determine mineralization rates for two different C:N ratio quality straw materials in soils with different fallow periods and under different climatic conditions. The straw material was partitioned by the model into five components: labile and recalcitrant plant residue, labile and recalcitrant humus, and microbial biomass. The matter partitioning between each component was driven by kinetic constants. Similar to the models developed by Couteaux et al. (2002, 2008), the labile and recalcitrant components of both the plant residue and the labile and recalcitrant humus components decomposed at different rates, with the labile component decomposing much faster. For example, the minimum rate of microbial biomass accumulation from the labile and recalcitrant plant residue, respectively, were 0.1 d^{-1} and 0.000005 d^{-1} depending on the initial C:N ratio of the plant residue, where a higher C:N ratio meant a lower decomposition rate (Bottner et al., 2006b). It was also determined from the study that for organic matter deposition being compared in two different locations (one the Bolivian Altiplano and the second the high moister and warmer grasslands of the Venezuelan Paramo) the driving processes of organic matter mineralization are the same, and only the rate of the processes (k) changes. They determined the porous, sandier soils in the Altiplano that lacked clay particles and allophane properties were the reason why a higher rate of organic matter mineralization (k_{resp}) was observed at the Altiplano site (k_{resp}=0.083 d^{-1}) over the Paramo site (k_{resp}=0.030 d^{-1}) (Bottner et al., 2006b).

2.2.3 Nitrogen mineralization

Couteaux et al. (2008) measured the N release from sheep dung and potato residue in a sandy soil cultivated with potato plants in the Altiplano. They found that after an initial lag period, the mineralized N from the organic amendments could be defined with a first order exponential model as

$$N_{rel} = N_{max}(1 - e^{-rt}) \tag{2.4}$$

Where N_{rel} = mineral N released as a function of the initial N content (%)
N_{max} = maximum proportion of release (%)
r = mineralization rate (d^{-1})
t = time (d).

The N_{max} ranged from 47.1- 71.8% and 48.7- 72.4% and r from 0.004-0.006 d^{-1} and 0.022- 0.101 d^{-1} for the sheep dung experiments and potato residue experiments, respectively.

Sarmiento and Bottner (2002) similarly described the rate of N mineralization in the Venezuelan Paramo as

$$N = N_0(1 - e^{-mt}) \tag{2.5}$$

Where N= cumulative mineralized N (g kg^{-1})
N_0= potentially mineralizable N (g kg^{-1})
m= mineralization rate (d^{-1})
t= time (d).

The potentially mineralizable N amounts for a field after 15 years fallow and a field after three consecutive years in potato were 0.58 g kg^{-1} and 0.24 g kg^{-1}, respectively. They found that 1.16- 2.70% of the total N mineralized.

Bottner et al. (2006a, 2006b) observed that N mineralization was closely linked to organic matter mineralization and the C:N ratios of the remaining organic material in the soil. Bottner et al. (2006a) found that at a research site in the Altiplano, N mineralization, like organic matter decomposition, followed a two stage process. After a 100 day incubation period for wheat straw in fallow plots, 60-70% of the initial N in the straw was mineralized when the initial material had a low C:N ratio (C:N=26.8) and 55-60% when the initial material had a high C:N ratio (C:N=130.1).

Videla et al. (2005) measured mineralization rates of N in straw over incubation periods of 35 days in no tillage, conventional tillage, and fallow plots in a Mollisol in Argentina. The conventional tillage plots had much lower rates of N mineralization (0.25-0.50 mg kg^{-1} soil d^{-1}) compared to the fallow plot (1.00 -1.25 mg kg^{-1} soil d^{-1}).

2.2.4 Losses through leaching and runoff

Inorganic and organic fertilizers applied to agricultural soils have the potential to be leached after mineralization. This is especially true in potato cropping systems that have shallow roots, in coarse textured soils that have a large percentage of macropores, and in regions with short, intense rainy seasons like those seen in the

Andes (Peralta and Stockle, 2001). Abreu et al. (2007) measured an N balance in a potato plot in the Venezuelan Andes including N levels in the leachate beneath the root zone. They found that 52.8 kg N ha^{-1} leached from a potato plot that had an initial total soil N level of 0.6% before being fertilized with 75 kg N ha^{-1} as NH_4Cl. A nutrient balance study using the NUTMON model in Ecuador found that the Andean regions that cultivated seasonal crops had estimated leaching losses of 8.8 kg N ha^{-1} and erosion losses of 53.4 kg N ha^{-1} (de Koning et al., 1997).

Few studies in Andean regions have directly quantified nutrient loss attached to eroded sediment, but erosion studies have nonetheless recognized the potential negative impact on sustainable agriculture in terms of nutrient loss (Osorio et al., 2008; Rymshaw et al., 1997; Vanacker et al., 2002; Zehetner and Miller, 2006). Osorio et al. (2008) estimated the annual sediment yield from a subwatershed of the Jatun Mayu River, Bolivia, with the Soil and Water Assessment Tool (SWAT) model to be 13.15 ± 21.28 t ha^{-1} with some areas of the watershed yielding over 140 t ha^{-1}. Dercon et al. (2006) found that where terraces were constructed on slopes in the Ecuadorian Andes, higher wheat yields were observed from plants on the downhill end of the terrace, closer to where deposition of eroded soil had occurred, and lower yields on the uphill end of the terrace where the erosion had originated. This observed effect was in part due to nutrients being relocated with the eroded sediment. Though it is difficult to quantify the loss of production due to soil erosion, the World Bank (2006) estimates that 41% of Bolivia has lost productivity due to soil erosion and desertification.

2.3 Crop-soil-environment comprehensive models

Several models exist that couple crop growth with soil nutrient dynamics (most often N dynamics) and use climate data to determine yield, nutrient uptake, and N losses through leaching, denitrification, and volatilization. Often these models are developed by individual institutions and are tailored to complete simulations that suit specific research in their region.

Highlighting the potential nutrient losses in a given agricultural system can help managers determine which management practices could be altered to maximize crop availability and uptake. A model that simply makes nutrient recommendations based on potential crop yield and soil nutrient holding capacity may help increase profit for the farmer, but a model that is also capable of determining N loss pathways to the environment could prove invaluable in preventing loss of valuable nutrients to the environment. Included here is a summary of different models related to potato growth and N dynamics that have been validated and calibrated for individual studies. The models included are CropSyst, WAVE, LINTUL-POTATO, Stella software for environmental modeling, GLEAMS, STICS, and NuMaSS.

2.3.1 CropSyst model

The model CropSyst, developed by researchers in the Biological Systems Engineering department of Washington State University, is a field-scale, daily time step, crop growth model that can produce several years of simulation with multiple crops with a mechanistic approach (BSYSE WSU, 2009). Four input files are created by the user for location, soil, crop, and management that allow the user to describe weather, soil physical properties, irrigation, fertilization, and tillage scheduling. The N budgeting of the model accounts for NH_4^+ sorption, symbiotic N fixation, crop N demand and uptake, net mineralization, nitrification, and denitrification. The model has a user-friendly interface. Several of the N sections in the user manual were still under development (Stockle and Nelson, 1996; downloaded from http://www.bsyse.wsu.edu/cropsyst/ on May 2, 2009).

Simulations using the CropSyst model have examined NO_3^- losses under typical irrigated potato systems in Washington, USA (Peralta and Stockle, 2001). Five year studies were used to calibrate and validate the model for tuber yield, dry matter content, leaf area index, and N content in tuber yield. Through the model simulations, it was determined that fertilization rates over the recommended rate of 448 kg N ha^{-1} produced excessive NO_3^- leaching. It was also determined that leaching varied year to year depending on precipitation; periods of low rain led to a build-up of NO_3^- in the soil that was leached at the next strong precipitation event.

2.3.2 WAVE model

The Water and Agrochemicals in Soil and Vadose Environment (WAVE) model developed in Belgium has also been used in research of crop uptake and N losses from excessive fertilization at the field scale (Timmerman and Feyen, 2003). WAVE is based on four component models of water balance, soil N, heat and solute transfer, and crop growth. Inputs for the model include data on climate, soil physical properties, and land use, including fertilization rates. The outputs for soil include total C and N, NO_3^-, NH_4^+, mineralized N, and leached NO_3^- from the vadose zone as well as C and N uptake in plants. The model has been used in groundwater pollution research, but is no longer available for distribution (REM, 2002).

The WAVE model was used in a study in the Netherlands to determine N fertilization rates that would reduce NO_3^- leaching rates and still provide profitable crop yield for potatoes, considering soil type variations in the field. Seven N fertilization rates were simulated from the recommended rate of 250 kg N ha^{-1} to 50 kg N ha^{-1} (Verhagen, 1997). The model output was compared with 1994 field data and the authors cited the model performance as "reasonable" although it was noted that poor model predictions in some instances for final yield and mineral N content may have been due to the model's inability to differentiate between initial N in the soil and N application. The subsequent simulations of NO_3^- leaching led the researchers to determine that the recommended 250 kg N ha^{-1} fertilizer rate led to unacceptable leached NO_3^- levels.

2.3.3 LINTUL-POTATO model

Researchers in the Netherlands have also developed a potato-N uptake model with the goal of matching N mineralization from manure applications with crop N uptake without P accumulation over time. The model, Light Interception and Utilization of Light-Potato model (LINTUL-POTATO), was used in a study to quantify tuber yields and mineralization of N under different manure applications, variations in cultivar maturity, and manure N:P ratio (Van Delden et al., 2002). The LINTUL-POTATO model is composed of three subcomponents for soil moisture dynamics, soil N dynamics, and crop growth N uptake. The N dynamics and crop growth portions were modified from a previous model, NPOTATO, which was calibrated and validated independently of this study. The model output for tuber weight, tuber N uptake, and soil mineral N content were validated with previous experimental data based on root mean square error and Pearson's correlation coefficient between the predicted and experimental data. The model was used to simulate seven scenarios and the researchers determined that a spring cattle slurry application for a late-developing potato cultivar reduced N losses the most while allowing profitable potato yields.

2.3.4 Stella software modeling

Potato growth and N uptake modeling has also been completed by researchers in Canada using the Stella II software program for developing models of environmental systems (Li et al., 2006). The Stella software allows the developers to define the algorithms, inputs, and outputs for the systems they would like to represent. The researchers in this study used potato yield-N response curves, an S-shaped potato growth curve for N accumulation; regression equations for tuber growth; tuber N uptake; and residual soil N; and information from past studies to develop a potato growth model with a daily time step using Stella. The objectives were to simulate N flows into the soil; N partitioning in the potato crop at three growth stages; perform daily, monthly, and seasonal N balancing to determine N requirements; validate the model; and explore the feasibility of the model’s use for making N predictions in Canada. The researchers compared the model predictions with field data from four sites and declared that it worked favorably, even though some sites showed high percentage differences from the model predictions for certain output parameters. The cited weakness of the model was that, although the model considers weather data, it does not consider soil parameters such as bulk density, pH, and organic material and so does not completely represent physical processes in the soil-plant system that drive water movement and, thus, crop uptake of N (Li et al., 2006).

2.3.5 STICS model

The Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS) model is an agricultural field scale model with a daily time step that considers crop growth in the crop-soil-climate environment (Brisson et al., 2003). The goal of the model is to evaluate agricultural management practices on water and N budgets and crop yields. Another important aspect of the model is that it is interactive with the user and provides a generic framework through which the user can include site and crop specific parameters to better define the system (Brisson et al., 2003). The model simulates N transformation and movement processes such as mineralization, immobilization, leaching, volatilization, denitrification, and crop uptake. Although the STICS model is available at a nominal fee, the Fortran-77 code is license protected.

Applications of the model in Spain on potato and sugar beet plots assisted researchers in determining precise N application rates and timing in order to reduce NO_3^- leaching losses (Jego et al., 2008). The researchers determined that the model simulated the general trends of the soil nitrate levels satisfactorily, though it did not perform as favorably in exact predictions of observed soil nitrate levels (Jego et al., 2008).

2.3.6 GLEAMS model

The Ground Water Loading Effects of Agricultural Management Systems (GLEAMS) model from the United States Department of Agriculture (USDA) is a continuous field scale model that predicts edge of field and bottom of root zone loadings of nutrients based on hydrology, erosion, and nutrient input parameters (Leonard et al., 1987). These three components allow the user to define soil properties, ET method, physical field configuration, crop specific LAI, and crop nutrient extraction patterns, though many default parameters are included if the user does not have extensive site data. The model documentation and FORTRAN source code are available for download. Although the model should not be used for absolute predictions, it can provide a useful tool for comparing nutrient loadings in runoff or from the root zone for different management practices (Knisel and Davis, 1999).

The GLEAMS model has also been used to make nutrient recommendations. A study completed in Spain sought to determine an N recommendation for potato and citrus farms that would minimize NO_3^- leaching to groundwater (dePaz and Ramos, 2003). The GLEAMS model was linked to a GIS to produce maps that outlined areas at risk of NO_3^- leaching. The model inputs were based on local field and weather data and the model was calibrated and validated using data from two research plots in the study area. Four mineral N fertilizer rates were simulated (typical farmer application, 50% and 20% reduced farmer application, and minimum N recommendation based on soil mineral N content at planting). The minimum application produced the least NO_3^- leaching losses and so would be communicated to the farmers as the desired rate to conform to the Code of Good Agricultural Practices for this region of Spain. The modelers were satisfied with GLEAMS's performance when comparing the model predictions to past studies that observed NO_3^- leaching rates under different fertilizer application rates, though they also noted that there were uncertainties due to assumptions and model procedures.

2.3.7 NuMaSS nutrient recommendation program

One model that provides output related to crop nutrient requirements is the Nutrient Management Support Systems (NuMaSS) model. The model was developed by university and field researchers with funding from USAID to provide a user-friendly computer program to make site-specific mineral and manure fertilizer and lime recommendations for tropical and equatorial regions (Smyth et al., 2007). The model has five subcomponents to accept input to describe the agricultural system including geography, diagnosis, prediction, economics, and results. The diagnosis section allows the user to define soil physical and chemical properties and crop type (26 cultivar varieties included for potato) as well information on previous crops and desired yield. This section helps define if a nutrient problem exists. If it does exist, then application rates for fertilizer and lime are provided for the desired yield in the results section. N requirements are based on crop N need, soil N, N in plant residues, and residual N in manure from previous applications. The program has several default databases built in and only a few key values are actually required to run the program. However, the precision of N recommendations is reduced each time a default value is used in place of measured data (Smyth et al., 2007). The conclusions from each of the previous components are presented in a report-like format in the results section, which can be used by technicians with minimal training.

2.4 Conclusions

Poverty and population pressures on the soil, water, and nutrient resources in Andean agricultural systems creates the need for improved crop production that will not mine nutrient sources or pollute surrounding water systems with sediments or nutrients in runoff or leachate. Understanding the current environmental and crop management conditions in a given location is the first step towards developing alternatives to sustainably increase food production. A crop system model can assist in this development but it should offer the users adequate flexibility to define the climate, soil, crop, and management practices specific for Andean systems.

The climate in inter-Andean valleys is driven by both their high altitude and location near the equator which is observed in year-round cool temperatures and a short intense rainy season during the summer. These conditions are suitable for potato production, and local farmers typically utilize manures as fertilizers because of their lower cost and increased availability over inorganic fertilizers. Understanding the organic matter breakdown and N mineralization from these fertilizer sources is important to determine N supply for a crop. Studies on organic matter and organic N mineralization have shown that the decomposition occurs in two stages where the labile fraction decomposes at a much faster rate than the recalcitrant fraction. Site specific rates depend on climate conditions and C:N ratio of the initial decomposable material. Few studies have been completed on quantifying nutrient losses due to runoff and leaching.

Selection of a model for nutrient modeling in potato systems depends on the availability of model and documentation, whether the desired output can be confidently predicted with the available data for input, and if data are available for calibration and validation for use of the model in the area of interest. The GLEAMS model was selected for this research because it considers pertinent processes related to hydrology, erosion, and nutrient dynamics (Knisel and Davis, 1999), the input parameter files allow the user to use regional and crop specific data, and the source code is available so that model modifications can be made to better represent agricultural systems in central Bolivia.

Chapter 3. GLEAMS nitrogen processes

3.1 Background

The GLEAMS model was initially developed for use in the United States, though the original model and the incorporated nutrient component have been utilized satisfactorily (as reported by the users) in water quality studies in countries such as Finland, China, Spain, and South Africa (Yli-Halla et al., 2005; Cao and Wang, 2007; dePaz and Ramos, 2004; Campbell et al., 2001). Whenever a model is applied in a region outside that in which it was developed, the appropriateness of the conceptual framework, model algorithms, and any default parameters should be critically evaluated to reveal any incongruity compared to what is known about the application region. It is important to understand the model's processes in relation to the environmental system being simulated to determine if the model algorithms reflect the relationships revealed from past studies, and, if not, where the deviations occur. This kind of model review can also reveal where there is limited research in a particular process for the application region. The GLEAMS user manuals and model documentation for the nutrient component (Knisel and Davis, 1999) were used to determine if the GLEAMS N processes and parameters represent those for Andean systems as found in the literature. Empirical relationships developed in the United States that were used in GLEAMS and any constant values with unknown sources used in the model equations are also reviewed.

3.2 Nitrogen mineralization

Nitrogen mineralization is represented in GLEAMS as a two stage process, ammonification and nitrification. The mineralization rate depends on the C:N ratio of the active C pool. Ammonification takes place from labile organic N pools such as soil potentially mineralizable N, plant residue N, and animal waste N. The recalcitrant N pool includes soil stable organic N (soil organic N not considered potentially mineralizable). The flux of organic N between the soil potentially mineralizable N and soil stable N pools is represented as

$$RON = BKN\left[POTMN\left(\frac{1}{RTN}\right) - SOILN\right] \tag{3.1}$$

Where *RON* = flux of organic carbon between active and recalcitrant pools (kg $ha^{-1}d^{-1}$)
BKN = rate constant, 1 x 10^{-5} (kg $ha^{-1}d^{-1}$)
POTMN = soil potentially mineralizable N (kg ha^{-1})
RTN = ratio of mineralizable N to total soil N
SOILN = soil stable N (kg ha^{-1}).

Soil N mineralization in each layer occurs from the soil potentially mineralizable N pool to the ammonia pool at the rate

$$MN = CMN\,(POTMN)[(SWFA)(TFA)]^{0.5} \tag{3.2}$$

Where *MN* = mineralization rate from potentially mineralizable N (kg $ha^{-1}d^{-1}$)
CMN = mineralization constant, 0.0003 (kg ha^{-1} d^{-1})
SWFA = soil water factor for mineralization
TFA = soil temperature factor for mineralization.

Climatic influences on the mineralization rate are represented in the soil water factor and soil temperature factor. The soil water factor for mineralization (*SWFA*) is

$$SWFA = \frac{SW - WP}{FC - WP} \tag{3.3}$$

Where *SW* = soil water content (cm cm^{-1})
FC = soil water content at field capacity (cm cm^{-1})
WP = soil water content at wilting point (cm cm^{-1}).

The temperature factor for mineralization (*TFA*) is defined as

$$TFA = \frac{T}{T + \exp(9.93 - 0.312T)} \tag{3.4}$$

Where *T* = soil temperature on that day for the respective soil layer (°C).

TFA is represented graphically as a function of soil temperature with the nitrification temperature factor (*TFN*) in figure 3.1.

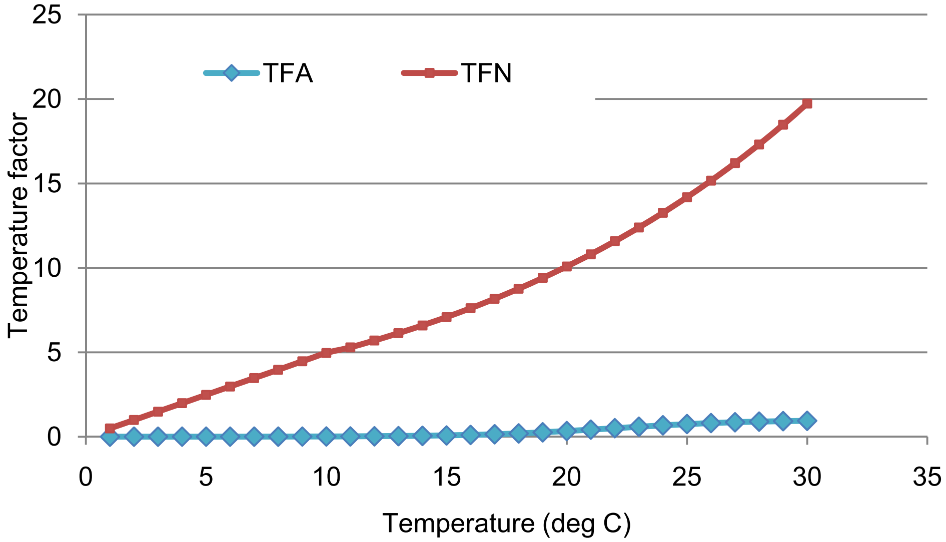

Figure 3.1 GLEAMS soil temperature factors for soil ammonification (*TFA*) and soil nitrification (*TFN*).

Mineralization from crop residue and animal waste both depend on their combined C:N and C:P ratios. The crop residue N and animal waste N mineralization rates are, respectively

$$RMN = (DCR)(FON) \tag{3.5}$$

Where *RMN* = crop residue N mineralization rate (kg ha^{-1}d^{-1})
DCR = residue decay rate constant
FON = fresh organic N from roots, initial default value of 40 (kg ha^{-1})

and

$$AWMN = (AWDCR)(ORGNW) \tag{3.6}$$

Where *AWMN* = animal waste N mineralization rate (kg ha^{-1}d^{-1})
AWDCR = animal waste decay rate constant
ORGNW = fresh organic N from animal waste (kg ha^{-1}).

The crop residue and animal waste mineralization rates are functions of the combined residue and animal waste nutrient composition, soil water and temperature, and the degree of previous decomposition. They are respectively represented as

$$DCR = (CNP)(RC)[(SWFA)(TFA)]^{0.5} \tag{3.7}$$

Where CNP = ratio factor for residue mineralization
RC = residue decomposition factor

and

$$AWDCR = (CNP)(AWRC)[(SWFA)(TFA)]^{0.5} \tag{3.8}$$

Where $AWRC$ = residue decomposition factor.

The ratio factor for mineralization (*CNP*) used to calculate the mineralization rates of crop residue and animal waste (*DCR* and *AWDCR*, respectively) is based on whether N or P is most limiting to the microbes in the crop residue and animal waste mineralization. Nitrogen is limiting when the C:N ratio ≥ 25 and P is limiting when the C:P ratio ≥ 200. *CNP* therefore is the minimum of the following:

$$CNP = minimum \begin{cases} \exp\left[-0.693 \frac{CNR-25}{25}\right] \\ \exp\left[-0.693 \frac{CPR-200}{200}\right] \\ 1.0 \end{cases} \tag{3.9}$$

Where CNR = C:N ratio in combined residue and animal waste
CPR = C:P ratio in combined residue and animal waste.

The C:N ratio in combined residue and animal waste (*CNR*) is expressed as

$$CNR = \frac{0.58(FRES+OMAW)}{FON+ORGNW+SNO3+AMON} \tag{3.10}$$

Where $FRES$ = fresh residue (kg ha^{-1})
$OMAW$ = organic matter in applied animal waste (kg ha^{-1})
$ORGNW$ = organic N in animal waste (kg ha^{-1})
$SNO3$ = soil NO_3^- (kg ha^{-1})
$AMON$ = soil NH_4^+ (kg ha^{-1}).

The C:P ratio in combined residue and animal waste (*CPR*) is expressed as

$$CPR = \frac{0.58(FRES+OMAW)}{FOP+ORGPW+PLAB} \tag{3.11}$$

Where *FOP* = fresh organic P from roots, initial default value of 10 (kg ha^{-1})
ORGPW = organic P from animal waste (kg ha^{-1})
PLAB = labile P (kg ha^{-1}).

The decomposition factors for crop residue and animal waste (*RC* and *AWRC*, respectively) are estimated from the simulated decomposed residue or animal waste amount as a percent of the initial residue or waste amount where the decomposition factor is 0.8 for ≤ 20% decomposition, 0.05 for 20-90% decomposition, and 0.0095 for >90% decomposition. In the case for both crop residue and animal waste mineralization, 80% of the mineralized N moves to the soil NH_4^+ pool (*AMON*) and 20% to the soil potentially mineralizable N pool (*POTMN*). The initial NH_4^+ content in the soil is set in GLEAMS as 2 µg g^{-1} for each horizon.

Nitrification is simulated in GLEAMS as a zero-order process independent of the NH_4^+ content. The simulated nitrification rate is

$$NIT = \frac{(TFN)(SWFN)}{SOILMS} \tag{3.12}$$

Where *NIT* = nitrification rate (kg $ha^{-1}d^{-1}$)
TFN = temperature factor for nitrification
SWFN = soil water factor for nitrification
SOILMS = soil mass of the layer (kg ha^{-1}).

The maximum simulated nitrified N in the soil is 100 mg kg^{-1} wk^{-1}. The NO_3^- is added to the soil NO_3^- pool (*SNO3*) and subtracted from the soil NH_4^+ pool (*AMON*).

The GLEAMS nutrient component represents the following stages individually: movement from soil stable N pool to soil potentially mineralizable N pool; mineralization from soil labile N pool to soil NH_4^+; mineralization from crop residue and animal waste to the soil NH_4^+ and potentially mineralizable N pools; and nitrification. There is only mineralization from the soil potentially mineralizable N pool rather than mineralization from both the soil potentially mineralizable and stable pools occurring simultaneously but at different rates. This differs from representations of N mineralization as a single first order exponential relationship (Couteaux et al., 2008; Sarmiento and Bottner, 2002) or as a first order exponential relationship with two components that have different mineralization rates for labile and recalcitrant components as used for organic matter mineralization (Braakhekke and Bruijn, 2007; Bottner et al., 2006a and 2006b). GLEAMS simulates the rates of mineralization for soil, plant residue, and animal waste as being dependent on climate factors represented in the soil water (*SWFA*) and soil temperature (*TFA*) factors. The mineralization rate also depends on the C:N ratio of the soil organic material, which is consistent with Bottner et al. (2006a).

Ammonification of soil potentially mineralizable N appears to be minimally affected by temperatures below 20°C, as shown in figure 3.1. This limits the daily mineralization rate to less than the mineralization constant (*CMN*). Some researchers have noted the inability of GLEAMS to adequately represent N mineralization (Dukes and Ritter, 1999; and Webb et al., 2001). Webb et al. (2001) overcame this shortfall by calibrating *CMN* from 0.0003 kg ha^{-1} d^{-1} to 0.0016 kg ha^{-1} d^{-1} through calibration which greatly increased the agreement between observed and simulated annual net mineralized N.

3.3 Immobilization

Immobilization of soil N onto residue occurs when the crop residue has a C:N ratio>25. The immobilization rate from the residue is

$$WIMN = (DCR)(FRES)(0.016 - C_{nfr}) \tag{3.13}$$

Where *WIMN*= immobilization rate from residue (kg ha^{-1} d^{-1})
C_{nfr} =concentration of N in *FRES* (kg ha^{-1})
FRES= fresh residue (kg ha^{-1}).

The 0.016 value is an estimation of the N concentration for the microbial biomass in the soil with the assumptions that the carbon is 0.4 times the fresh residue (*FRES*), 0.4 of that carbon is assimilated, and the microbial biomass has a C:N ratio of 10. A lower immobilization rate is simulated when the mineral N is limited so that only 95% can be immobilized. The fractions of soil NO_3^- and NH_4^+ immobilized are proportional to their relative amounts in the soil mineral N pool and are subtracted from their respective pools and added to the fresh organic N pool (*FON*).

3.4 Denitrification

Denitrification occurs when the soil water content is 10% greater than field capacity and maximizes at saturation. Denitrification depends on soil NO_3^- levels, temperature, soil water content and rate of decay of soil carbon (*SC*). The denitrification amount is simulated as

$$DNI = SNO3(1 - exp[-(DK)(TFDN)(SWFD)]) \tag{3.14}$$

Where *DNI* = N denitrified (kg ha^{-1})
DK = decay rate of active soil carbon (mg g^{-1} soil C)
TFDN = temperature factor for denitrification
SWFD =soil water factor for denitrification.

The daily decay rate of active soil carbon depends on soil carbon (*SC*) and is represented as

$$DK = 24[(0.0022SC) + 0.0042] \tag{3.15}$$

The soil carbon is estimated as

$$SC = \frac{18POTMN + 0.58(FRES + OMAW)}{SOILMS} \tag{3.16}$$

Where *SC* = active soil carbon (mg g^{-1} soil)
POTMN = soil potentially mineralizable N (kg ha^{-1})
FRES = fresh reside (kg ha^{-1})
OMAW = organic matter from animal waste (kg ha^{-1})
SOILMS = soil mass for the respective layer depth (kg ha^{-1}).

3.5 Runoff, sediment, and percolation

Runoff of NO_3^- and NH_4^+ occurs from the surface soil layer to 1 cm depth and depends on the concentration in the soil water in that layer. A partitioning coefficient (K_d) is defined for each layer where K_d= 0 for NO_3^- and K_d for NH_4^+ is a function of clay content in the surface layer as

$$CNHK_d = 1.34 + 0.083(CL) \tag{3.17}$$

Where $CNHK_d$ = ammonium partitioning coefficient
CL= clay content (%).

The concentration of NO_3^- or NH_4^+ that is available for runoff is represented as

$$c_{av} = C_1 exp\left[\frac{-(F-ABST)}{K_d\left(\frac{1-POR}{2.65}\right)+POR}\right] \tag{3.18}$$

Where C_{av} = concentration available for runoff on soil surface (µg g^{-1})
C_1 = concentration of chemical in soil mass in surface cm layer (µg g^{-1})
F = total storm infiltration (cm)
$ABST$ = initial abstraction, estimated as 0.2 times saturation-soil water content (cm)
POR = porosity of the surface cm layer (cm^3 cm^{-3}).

The concentration in the soil water on the surface is

$$C_w = \frac{C_{av}\beta}{1+\beta K_d} \tag{3.19}$$

Where C_w = concentration in the soil water (mg L^{-1})
β= extraction coefficient dependent on K_d.

The N loss in runoff is

$$RON = 0.1(CNW)Q \tag{3.20}$$

Where RON = NO_3^- or NH_4^+ in runoff (kg ha^{-1})
CNW= concentration of NO_3^- or NH_4^+ in soil water in surface cm layer (mg L^{-1})
Q = runoff (cm).

The sediment losses in runoff for soil NH_4^+ (*AMON*), soil potentially mineralizable N (*POTMN*), soil stable N (*SOILN*), and organic N from residue and animal waste are all calculated as

$$SEDN = 0.1(SY)(ER)CNS \tag{3.21}$$

Where $SEDN$ =sediment loss of one of the N species listed above (kg ha^{-1})
SY = sediment yield (kg ha^{-1})
ER = enrichment ratio
CNS = concentration of the N specie in the soil (µg g^{-1}).

Runoff and sediment losses are then subtracted from their respective pools. The runoff and sediment yield are both determined in the hydrology component, runoff by the USDA Soil Conservation Service (SCS) curve number method and sediment yield using components of the universal soil loss equation (USLE).

The mass of either NO_3^- or NH_4^+ available for percolation is determined as the dry soil mass concentration minus the concentration available for leaching and then multiplied by the soil mass for the surface layer (kg ha^{-1}) so that

$$PRNMS = (CN - C_{av})SOILMS \tag{3.22}$$

Where *PRNMS* = percolation component of available NO_3^- or NH_4^+ mass (kg ha^{-1})
CN = concentration of NO_3^- or NH_4^+ in the dry soil mass (kg kg^{-1})
SOILMS = soil mass for the respective layer depth (kg ha^{-1}).

The concentration of NO_3^- or NH_4^+ in the percolate is

$$PERCN = \frac{0.1(PRNMS)}{PERC} \tag{3.23}$$

Where *PERCN* = concentration of NO_3^- or NH_4^+ in percolate (mg L^{-1})
PERC = percolation water mass (cm).

The percolated NO_3^- or NH_4^+ are then added to the subsequent layers and the concentration in the layers below the surface is calculated as C_w (equation 3.19).

3.6 Crop uptake

The concentration of N in the crop biomass is represented with the first order exponential relationship

$$CN = C1(GRT)^{C2} \tag{3.24}$$

Where *CN* = concentration of N in crop biomass (%)
C1 = scale factor for exponential function
C2 = shape factor for exponential function
GRT = growth rate, simulated LAI over the potential LAI for optimal growing conditions.

The total dry matter is computed as

$$TDM = (GRT)(PY)(DMY) \tag{3.25}$$

Where *TDM* = total dry matter production (kg ha^{-1})
PY = potential harvestable yield dry matter (kg ha^{-1})
DMY = ratio of total dry crop biomass to yield biomass.

The total N in the dry matter is the concentration of N in the biomass times the biomass,

$$TDMN = 0.01(CN)(TDM) \tag{3.26}$$

Where *TDMN* = total N in dry matter (kg ha^{-1})
0.01 is a unit conversion factor.

The crop's N demand is the difference in total N in dry matter (*TDMN*) on successive days. Uptake of NO_3^- and NH_4^+ is relative to their abundance in the soil water and the transpiration rate by the crop on that day. Crop N uptake in each soil layer is driven by the concentration of NO_3^- or NH_4^+ in the soil water and the transpiration rate determined in the GLEAMS hydrology component. Uptake is calculated as

$$UPN = 0.1(C_w)(TR) \tag{3.27}$$

Where *UPN* = uptake of NO_3^- or NH_4^+ (kg ha^{-1})
C_w = concentration of NO_3^- or NH_4^+ in the soil water (mg L^{-1})
TR = crop transpiration (cm)
0.1 is a unit conversion factor.

Only the demanded N is taken up by the crop (i.e. no luxury N uptake). When the demanded N is greater than the available N in the soil water, then an N stress factor is applied that reduces accumulated LAI in the event that the N stress is less than water stress on that day. In this case, first an uptake factor is calculated on that day as

$$UPFAC = 2\left[1 - \frac{UPN}{DEMN}\right] \tag{3.28}$$

Where *UPFAC*= uptake factor
UPN = total uptake of both NO_3^- and NH_4^+ (kg ha^{-1})
DEMN=daily crop N demand (kg ha^{-1}).

The stress factor is then determined as

$$SFN = 1 - \left[\frac{UPFAC}{UPFAC + \exp(3.39 - 10.93UPFAC)}\right] \tag{3.29}$$

Where *SFN*= crop N stress factor.

When the N stress factor is greater than any moisture stress calculated on that day, then it is applied to reduce the cumulative sum of the LAI used to determine the growth rate (*GRT*). Phosphorus uptake is calculated according to the concentration in the soil water and the transpiration rate; no stress factor is applied in the event that P limits crop growth.

3.7 Input parameters

GLEAMS allows the initialization of some of the N and P pools via input parameter selection. Input parameters may be selected based on measured data, estimations from literature, or guides from the tables in the GLEAMS user manuals. Model output is likely to be more site-specific when actual site data are used in place of estimates developed from conditions in the US.

The parameters in table 3.1 can be input to the model; the default value is used if no value is entered. Nitrogen additions from surface residue, rainfall deposition, irrigation, and animal manure applications are all assumed to be zero unless specified by the user. The GLEAMS default initial soil total Kjeldahl N (TKN) when none is specified is determined from the soil initial organic matter content input (%) based on an average soil C:N ratio of 10 (Knisel and Davis, 1999). The soil C:N ratio is taken from an average C:N ratio from research by Stanford and Smith (1978) for eight soil orders (Knisel and Davis, 1999). The initial soil potentially mineralizable N is also determined from the organic matter content and for each soil layer when no initial value is provided. The default initial soil NO_3^- concentration is 5 μg g^{-1}, though it is described by the GLEAMS user manual (Knisel and Davis, 1999) as being highly dynamic. The GLEAMS user manual (Knisel and Davis, 1999) also states that the model output is not sensitive to initial soil NO_3^- values.

Table 3.1 GLEAMS nutrient component input parameters and default values.

Input GLEAMS parameter	Parameter abbreviation (unit)	GLEAMS default value
Surface crop residue	*RESDW* (kg ha^{-1})	0
Rainfall N	*RCN* (mg kg-1)	0
Irrigation NO_3^-	*CNI* (mg kg-1)	0
Soil total Kjeldahl N	*TN* (%)	$\frac{OM^{+}}{(100\ x\ 10\ x\ 1.724)}$
Soil NO_3^-	*CNIT* (µg g^{-1})	5
Soil potentially mineralizable N	*POTMN* (kg ha^{-1})	$OM\ x\ (9.3\ x\ 10^{-5})$
Organic N from animal waste application to plow layer	*ORGNW* (%)	0

[+] OM is initial organic matter model input (%)

Chapter 4. Methods

4.1 Field studies

Field studies were completed to both determine some of the model input parameters and to collect data with which to validate model output. The field data were collected in order to run a site-specific model simulation for each of six sites. The data were obtained through direct soil and plant tissue sampling, field observations, and interviews with farm owners or local agronomists. Certain parameters required special consideration due to the complexity of the potato hill-furrow field configuration and sample timing.

4.1.1 Site description

. The Jatun Mayu watershed area in Tiraque, Cochabamba, where this study was based, is 117 km^2 and represents landscapes and farming communities typical to those found in the inter-Andean region in Bolivia (PROMIC, 2008). All sites were cultivated with a local potato variety called Waycha (*Solanum tuberosum* spp. andigena). The six selected sites for the study are referenced here according to the community name of their location: Cebada Jichana (CBJ), Dami Rancho (DMR), Totora Kocha (TTK), Sankayani Alto-Puruma (SAR), Sankayani Alto- Papa (SAP), and Villa Flores, the only site outside the watershed boundary. These six sites were selected based on farmer willingness to cooperate with the study and distribution in and around the watershed. The exception was the Villa Flores site which consisted of nine experimental plots each 10 m^2 and managed by PROINPA researchers for an erosion study. The experimental plots at Villa Flores consisted of three repetitions each of three surface cover treatments: potato, first year fallow, and native vegetation. Only the data from the three potato treatment plots were used in this study. The three potato plot repetitions from the Villa Flores site are referred to here as VF2, VF4, and VF8.

The sites' identification, coordinates, area, elevation at field outlet, and slope are shown in table 4.1. Figure 4.1 depicts the locations of the sites in the watershed area with a false-cover IKONOS satellite image as a background. The sites CBJ and DMR are considered to be in the transition agro-climatic zone of the Jatun Mayu watershed area from the warmer and drier valleys below; TTK, SAR, SAP, VF2, VF4, and VF8 are considered to be in the upper agro-climatic zone locally called Puna for its higher altitude, and generally cooler temperatures and greater rainfall (PROINPA, 2006). As can be seen in table 4.1, all but one of the sites are on slopes greater than 7%. To reduce soil losses by erosion many farmers direct the hilled potato rows along the contour of the slope.

Table 4.1 Sites evaluated in GLEAMS study, altitude at field outlet, area, and mean percent slope of field.

Site	Community	Coordinates	Altitude (masl)	Area (ha)	Mean slope (%)
CBJ	Cebada Jichana	W 65° 38’ 45.1” S 17° 28’ 44.9”	3554	0.584	7.72
DMR	Dami Rancho	W 65° 38’ 24.5” S 17° 28’ 56.1”	3575	0.414	4.49
TTK	Totora Kocha	W 65° 37’ 44.8” S 17° 26’ 59.7”	3784	0.253	8.72
SAR	Sankayani Alto-Puruma	W 65° 36’ 55.3” S 17° 26’ 55.0”	4036	0.224	22.68
SAP	Sankayani Alto- Papa	W 65° 36’ 57.7” S 17° 26’ 55.3”	4026	0.146	25.13
VF2;VF4;VF8	Villa Flores	W 65° 36’ 43.2” S 17° 26’ 39.7”	3971 (median)	0.001 (each)	25.54

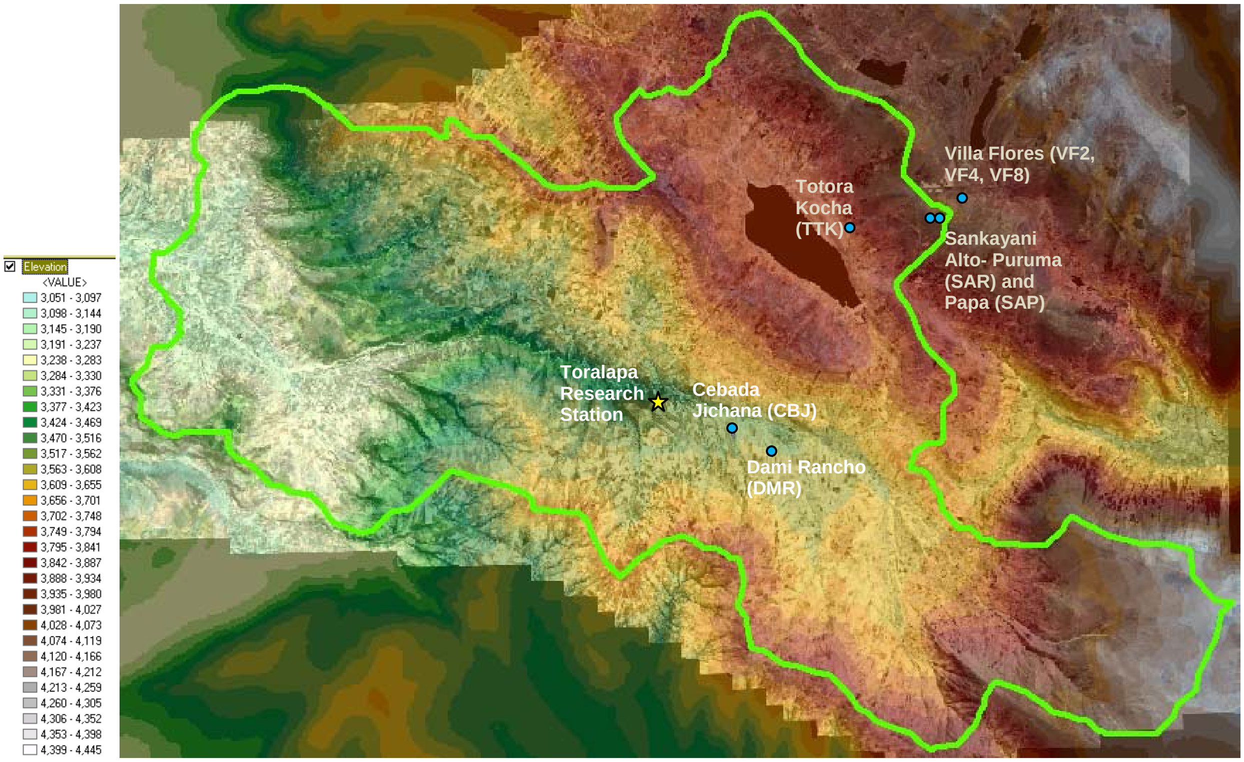

Figure 4.1 Jatun Mayu watershed boundary (green outline) and six sites used for study (blue points). The elevation scale is in meters and the Toralapa Research Station where the study was based is depicted with the yellow star.

A study completed by Comite Interinstitucional para el Desarrollo de Tiraque in 1994 surveyed the soils in the Province of Tiraque and classified them according to USDA soil taxonomic groups (CIDETI, 1994). The soil groups were in the soil orders of Entisols, Inceptisols, Alfisols, or Mollisols. All the sites were described as being on the foot of the mountain ridge, having temperate-cold temperatures and a sub-humid climate. The sites, CIDETI designated map unit, and the soil subgroups for the map unit are shown in table 4.2. The soils in the Jatun Mayu watershed in Tiraque generally have the properties shown in table 4.3 according to FAO and SNAG (1995).

Table 4.2 Sites, map unit, symbol, and soil subgroups corresponding to the map unit of CIDETI (1994).

Site	Map Unit	Symbol	Soil subgroups
CBJ	Comlejo Qowari	3.M.2.1. U.u.-E.g.-T.u.-T.a.	Udic Ustocrepts, Eutric Glossoboralfs, Typic Ustorthents, Typic Argiborolls
DMR TTK	Asociación Pucara	3.A.1.2. E.g. - U.u. - T.u.-T.h.a.	Eutric Glossoboralfs, Udic Ustochrepts, Typic Usthorthents, Typic Haplumbrepts
SAR SAP Villa Flores	Complejo Qayarani	3.M.2.2. T.u. - U.u. - T.h.	Typic Ustorthents, Udic Ustocrepts, Typic Haplustalfs

Table 4.3 Typical soil property values and interpretation found in central Bolivia (from FAO and SNAG, 1995).

Soil Property	Value range and interpretation
pH (soil: water = 1:5)	5.0- 6.0
Soluble salts	<300 umho cm^{-1}, low
Cation exchange capacity	<10.0 meq 100 g^{-1} soil, medium to low
Base saturation	>70%
Organic material content	1-3%, low

4.1.2 Climate data

Daily precipitation data were collected at three locations in the study area. Precipitation data were collected with an electronic tipping bucket rain gage and recorded with an automatic data logger. Simulations for sites CBJ and DMR used precipitation data collected from an automatic weather station located at the Toralapa Research Station. Simulations for sites TTK, SAR, and SAP used precipitation data from a weather station located in the Sankayani Alto area. A rain gage and data logger were installed at Villa Flores but the unit malfunctioned during the study period. Simulations for plots VF2, VF4, and VF8 at the Villa Flores site used precipitation data recorded from the Sankayani Alto weather station until 16 January 2009. Precipitation data that had been recorded manually from a standard rain gage at the Villa Flores site were used from 16 January until the study period end for the Villa Flores site. Temperature data for the CBJ and DMR sites were based on the temperature data from the weather station at the Toralapa Research Station. Temperature data for the TTK, SAR, SAP, and Villa Flores sites were taken from the Sankayani Alto weather station data. A 10 year precipitation record from the Toralapa Station was used to complete long-term simulations for model evaluation.

4.1.3 Soil data

Soil sampling for physical and chemical properties to set model inputs for each site took place at potato flowering, after the potato rows at each site were planted, fertilized, and hilled. The exceptions were the VF2, VF4, and VF8 plots that had an additional sample taken between hilling and potato flowering. The following soil properties were determined from within the potato hills (0-30 cm depth) at potato flowering (or prior to flowering for VF2, VF4, VF8) from each site to establish initial conditions for the model simulations: texture; water holding capacity at -30 kPa (field capacity) and -1500 kPa (wilting point); and bulk density. Samples from VF2, VF4, and VF6 were composited for analysis of texture, field capacity, and wilting point measurements.

Since the model simulations ran from planting to harvest, soil data to represent initial conditions for dynamic soil nutrient parameters were taken from samples at potato flowering from the furrow beside the hill that was neither hilled nor fertilized. Although the furrow was considered to have less organic matter than the soil where the tuber was actually planted, this sampling location was selected since it would be more representative of the soil prior to fertilization than samples taken from the potato hill after fertilization. The following dynamic soil parameters were sampled from the furrows (0-15 cm depth) at potato flowering (or prior to flowering for VF2, VF4, VF8) from each site to establish initial conditions for the model simulations: organic matter, pH, total Kjeldahl N (TKN), and Olsen P. Additional soil samples for TKN and Olsen P were taken from two soil depths within the hills (0-15 cm and 15-30 cm) at flowering and again at harvest to validate model simulations of soil nutrient concentrations over the growing season for each site. The VF2, VF4, and VF8 plots had an additional sample depth taken for TKN and Olsen P from the surface (1 cm) over the plot prior to flowering and at flowering, which were also used in the model validation for soil nutrient concentration.

Laboratory analyses were completed by Centro de Investigacion Agricola Tropical (CIAT) laboratory in Santa Cruz, Bolivia according to the methods provided by them in appendix A for all soil parameters except bulk density. Each sample sent to the laboratory for analysis was taken as a subsample from multiple field samples that were collected in a zig-zag pattern and well mixed in a plastic bucket. Sampling was completed with a soil probe (1.7 cm diameter) that was marked off down the length at 15 cm increments. Samples for each depth were mixed by hand in separate buckets. A subsample was taken for each depth from the respective plastic bucket, sealed in a sterile plastic bag, and refrigerated until delivered to the laboratory for analysis. Bulk density samples were taken with an undisturbed core from a cylinder of known volume (98.05 cm^2), dried at 65°C overnight to a constant weight, and weighed at the Toralapa Research Station. An average of at least three bulk density replicates was recorded for each site.

4.1.4 Crop data

Crop tissue samples were taken from the potato plant's first fully mature leaf from the top of the plant at flowering, above-ground foliage at frost kill, and tubers at harvest to determine the potato crop nutrient uptake (N, P, and K). Leaf samples were taken to see if there was a nutrient deficiency at flowering, the potato's peak nutrient uptake stage. Multiple leaf samples were collected from the fourth leaf from the top of the plant in a zig-zag pattern throughout the field from each site at flowering. Samples were oven dried at 65°C overnight in paper bags before being sent to CIAT for analysis.

Foliage samples were taken from surviving potato plants just after the first killing frost at each site. All potato plant tissue on the surface was removed and weighed fresh from at least three repetitions of three meter linear samples along the potato row. Potato tuber yield samples were taken at harvest for each site. All the unearthed tubers were removed and weighed fresh from at least three repetitions of three meter linear samples along the potato row.

The total fresh foliage and tuber yields per area were determined as

$$Y = \frac{W_{avg}}{3\ x\ RS}\ x\ 10{,}000 \qquad (4.1)$$

Where Y = foliage or tuber yield (kg ha^{-1})
W_{avg} = average weight from all repetitions taken from 3 meter linear samples (kg)
RS = row spacing (m).

The 3 represents the 3 meter linear sample and 10,000 is a conversion factor from m^2 to ha. Since the Villa Flores sites were only 10 m^2, the entire yield from each plot was weighed and converted to kg ha^{-1}.

Sites CBJ, DMR, and TTK had significant weed growth and so weed samples were taken at these sites as well. The weed samples were taken by removing all the weed above-ground biomass from the hills and furrows from at least three repetitions of a delineated 3 m^2 area. The total fresh weed weight divided by the total area sampled gave the weed yield for the applicable sites (kg ha^{-1}). A subsample from each site of the foliage, tuber, and weed samples, respectively, was weighed, dried for 24-48 hours at 65°C, and reweighed to obtain a dry matter content (*DM*) calculated as

$$DM = 1 - \frac{W_f - W_d}{W_f} \qquad (4.2)$$

Where DM= dry matter content (g g^{-1})
W_f=fresh weight (g)
W_d= dry weight (g).

The dry matter content was multiplied by the fresh yield to obtain a dry yield estimate (kg ha^{-1}) for foliage, tubers, and weeds from each site. Total potato crop dry matter was calculated as the sum of the foliage and tuber dry yield estimates. The dried subsamples for the foliage, tubers, and weeds were sent to the CIAT laboratory for analysis of N, P, and K fractions of dry matter. The nutrient fractions reported in the analysis were multiplied by the dry yield estimate to obtain the nutrient content in foliage, tubers, and weeds, respectively (kg ha^{-1}). The total potato crop nutrient uptake (kg ha^{-1}) was estimated as the sum of the N or P content in the foliage and tubers for each site. The potato crop yield nutrient removal was considered the N or P content in the tubers (kg ha^{-1}). The weed dry yield multiplied by the weed N or P fraction was considered to be additional nutrient uptake (kg ha^{-1}) at the applicable sites.

4.1.5 Management data

Additional data such as field area, elevation, and hill-furrow configurations were measured at each site. Dates required for updateable parameters in the GLEAMS simulations were obtained from information provided by the farmers.

The farmers also provided an estimate of the fertilizer they applied at planting. At all sites the applied fertilizer included a moist manure volume of chicken litter purchased from a local supplier, mixture of chicken litter and cattle manure from the farmers' livestock, or a mixture of chicken litter and inorganic fertilizer. All the applied manure included bedding and was stored outdoors uncovered for at least one month prior to application. The manure volume was provided by the farmers in the form of number of sacks or approximated m^3 volume from truck deliveries. The sack dimensions were measured so that the volumes supplied in sacks could be converted to m^3 where one sack filled to within 0.15 m from top was approximately 0.2 m^3. The manure volume applied over the site was converted to dry applied manure rate (kg ha^{-1}) by multiplying it by the applied manure bulk density and the dry matter content.

Manure samples were taken to determine total N and total P content. Three chicken litter samples were taken from outdoor piles which had been purchased by local farmers from commercial chicken houses located in the Bolivian departments (states) of Cochabamba and Santa Cruz and included some bedding such as rice husks. One cattle manure sample was provided from a farmer's home. It had been mixed with straw bedding and stored outdoors uncovered for approximately a year at the time the sample was taken. A subsample from the chicken litter samples and the cattle manure sample were sent to the CIAT laboratory for analysis. The additional manure nutrient content parameters required by the model were taken from those reported for Bolivian livestock by FAO and SNAG (1995). Field observations and interviews with farmers clarified typical fertilizer application methods.

4.1.6 Runoff data

Daily runoff data over the study period were provided by the PROINPA researchers who had completed a runoff and erosion study at experimental plots at Villa Flores (VF2, VF4, and VF8). The 10 m^2 (5 m lengthwise, running down-slope by 2 m across the slope) experimental plots were delineated with a metal barrier at the ground surface level that directed runoff towards an outlet at the downhill portion of the plot. The outlet led the runoff into a barrel for each plot. Each day over the rainy season the depth of runoff in the barrel was recorded and converted to a depth over the plot area (cm).

4.2 Model evaluation

4.2.1 Model representation and behavior

Model representation of manure application by soil layer was analyzed to verify that the model output represented the partitioning of soil N components according to the routing specified by the GLEAMS nutrient documentation (Knisel and Davis, 1999) and input parameters. Observations were made regarding the general field configuration of the potato hill-furrow system seen at the sites and the implications of the GLEAMS two-dimensional representations.

A 10 year simulation of the base conditions for the DMR site with continuous potato production was used to produce an annual water balance to assess if the GLEAMS hydrology component was producing a reasonable water balance. Annual values for runoff, percolation, ET, and average soil water were tabulated from the GLEAMS standard hydrology output files. Monthly output (GLEAMS selected output code in parentheses) of the following hydrology parameters was produced (all units cm): precipitation (2001), runoff (2002), percolation (2003), and evapotranspiration (2004). This was completed to verify that there was no erroneous simulation beyond the range of expected values of key hydrology components that might affect the simulated N dynamics in the crop-soil system for the base simulation.

Daily model output was produced to determine the simulated trends for soil N pools over the 2008-2009 growing season for each site. This was completed to better understand the model's representation of N processes and how they affect the model output used for validation, especially crop production and N uptake. The following daily model output of soil nutrient parameters was produced for each site (GLEAMS output code in parentheses, all units kg ha^{-1}): soil NO_3^- (950), soil NH_4^+ (955), organic N from crop residue (965), organic N from animal waste (966), soil potentially mineralizable N (975), and soil stable N (976). Monthly N transformations over the 2008-2009 growing season were analyzed to better understand how the model partitions N within and from the soil system into the crop and the environment. The following monthly N partitions were analyzed from the standard GLEAMS nutrient output parameter file (all units kg ha^{-1}): crop N uptake, N mineralization, N leached, N denitrification, and ammonia volatilization. The model behavior for simulating both soil N pools and N partitions was analyzed with regards to the suitability in representing the potato systems found in central Bolivia.

4.2.2 Validation

The developers of GLEAMS state that the purpose of the model is to compare agriculture management alternatives and not to make absolute predictions (Knisel and Davis, 1999). However, model validation between observed and simulated outputs was completed to determine the general degree of agreement for some output parameters and to better evaluate the overall model performance. Model input parameters were developed from the site specific data collection, literature, and guidance from the GLEAMS user manuals (Knisel and Davis, 1999). Details documenting how individual model input parameters were obtained for the model validation are included in appendix B. Precipitation and model parameter input files are included in appendix C. The evaluated output parameters (GLEAMS output code in parentheses where applicable) were daily runoff volume (2); concentration of soil TKN (958) for at least two crop stages and soil depths; final crop dry matter and harvestable yield production; and final crop dry matter and harvestable yield N uptake (printed from standard nutrient output). Simulations and comparisons with observed data for soil phosphate concentration and crop P uptake are included for completeness in appendix D though they are not discussed. No published studies were found that provided a standard model evaluation statistic or qualifications with which to judge the accuracy of the model’s predictions for these parameters or this region and so only preliminary interpretation of the quality of the model’s predictions based on statistics was included. The selected output parameters were evaluated graphically and by calculating the root mean square error standard deviation ratio (RSR) and percent bias (PBIAS) between the observed and simulated data sets. The RSR was calculated as

$$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})}\right]^2}{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}\right]} \tag{4.3}$$

Where Y^{obs} = observed value
Y^{sim} = simulated value.

The PBIAS was calculated as

$$PBIAS = \frac{\sum\left(Y_i^{obs}-Y_i^{sim}\right)}{Y_i^{obs}}(100) \tag{4.4}$$

An optimum value of RSR and PBIAS is zero (Moriasi et al., 2007). Large values for RSR indicate poor agreement between observed and simulated values considering the standard deviation seen in the observed data. Large values for PBIAS indicate an overall large average difference between simulated values and observed values.

The daily runoff data collected from the Villa Flores site were used to validate simulated daily runoff for VF2, VF4, and VF8. The data set was limited to days with precipitation greater than 0.8 cm that occurred after 16 January 2009 (the date when site-specific daily precipitation recording began). Only the hydrology and erosion input components were used to run the model simulations for runoff predictions.

The initial curve number (82) for all sites including Villa Flores was selected according to guidelines in the GLEAMS user manual (Knisel and Davis, 1999) for silt loam soil texture with no observed impeding layers and in good condition, which reflected the soil conditions observed at the site. The curve number was calibrated based on the lowest RSR computed from the runoff analysis for five tested curve numbers (82, 86, 90, 95, and 99) at Villa Flores. The results from the calibration of curve number for Villa Flores were taken under consideration when selecting curve numbers for the other sites.

The soil TKN and Olsen P concentrations at flowering and potato harvest collected from each site for the 0-15 cm and 15-30 cm potato hill soil depths and the additional soil nutrient samples taken at VF2, VF4, and VF8 prior to flowering at 1 cm, 0-15 cm, and 15-30 cm and at 1 cm depth at flowering were used to validate simulated TKN and phosphate concentrations at these sampling dates and soil depths. The daily simulated values over the growing season were compared graphically with observed point data.

RSR and PBIAS were determined for each soil nutrient concentration between the observed and simulated data sets which combined all data for soil horizons and crop stages from all the sites. GLEAMS produced output for soil nutrient concentration by the following soil layers: 0-1 cm, 1-8 cm, 8-15 cm, 15-27.5 cm, 27.5-40 cm. The weighted average of the output by soil depth for the 0-1 cm, 1-8 cm, and 8-15 cm simulated soil layers was compared to the 0-15 cm depth nutrient concentration sampled from the potato hill for each site. The output for the 27.5-40 cm simulated soil layer was compared to the 15-30 cm depth nutrient concentration sampled from the potato hill for each site. The surface 0-1 cm simulated soil layer was compared to the 0-1 cm surface sample from the Villa Flores site (VF2, VF4, and VF8).

Final crop dry matter and yield production and final crop dry matter and yield N and P uptake data determined from each site were compared graphically. The RSR and PBIAS for each respective parameter were calculated with combined data from all sites.

4.2.3 Sensitivity analysis

A sensitivity analysis was completed for selected input and output parameters using a base input and output parameter set from the DMR site for a 10-year continuous potato crop with annual manure application using a 10-yr precipitation record from the Toralapa Research Station. The sensitivity analysis was completed individually by parameter using iterative changes from the base conditions. The relative sensitivity for selected parameters was calculated as

$$S_r = \left(\frac{O - O_{base}}{P - P_{base}}\right)\frac{P_{base}}{O_{base}} \tag{4.5}$$

Where S_r = relative sensitivity

O = selected output parameter

P = selected input parameter

'base' indicates value from base scenario.

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The range of values for the increment changes were beyond the range observed in the field during this study. The relative sensitivity of the model for each respective input and corresponding output parameter range were qualified based on guidelines from Storm et al. (1988) shown in table 4.4.

Table 4.4. Relative sensitivity qualifications for GLEAMS model analysis based on Storm et al. (1988).

Relative sensitivity range (absolute values)	Sensitivity qualification
<0.01	Insensitive
0.01-0.10	Slightly sensitive
0.10-1.00	Moderately sensitive
1.00-2.00	Sensitive
>2.00	Extremely sensitive

The input parameters (GLEAMS abbreviation in parentheses) from the hydrology component selected for the sensitivity analysis were SCS curve number (CN), soil porosity (POR), and soil rooting depth (RD) to determine their effects on the following model outputs (GLEAMS selected output code in parentheses): annual runoff volume (3002) and percolation volume (3003); annual N soil losses from dissolved NO_3^- and NH_4^+ in runoff (combined 3910 and 3911), attachment of NH_4^+ and organic N to sediment (combined 3915 and 3917), percolated NO_3^- (3920), ammonia volatilization (3925), denitrification (3926), and crop N uptake (3927). The average annual output generated for each year was used to calculate the relative sensitivity. The input parameters from the nutrient component selected for sensitivity analysis were potential dry crop yield (PY) and dry rate of chicken litter application (RATE) to determine their effect on the annual N soil losses (same as those listed for the hydrology component).

Additional nutrient input parameters were used to complete a 2008 to 2009 season simulation of the DMR site to determine the effects of initial organic matter (OM), initial soil TKN (TN), initial soil nitrate (CNIT), and initial soil potentially mineralizable N (POTMN) parameters on model output for crop dry matter and yield production and nutrient uptake (printed in the standard nutrient output file).

Sensitivity of model output for N losses and crop N uptake to changes in the base temperature set were completed to visually evaluate the effect temperature had on these outputs. This was done to gage if low temperatures observed in the region were limiting simulated crop N uptake. Outputs using the base temperature set were plotted with outputs using a temperature set where each monthly low temperature was increased 10°C, each monthly high temperature was increased 10°C, and both high and low monthly temperatures were increased 10°C.

Chapter 5. Results and discussion

5.1 Summary of field data

Sampling for soil and plant tissue took place at different dates depending on the crop condition and management activity dictated by the farmers at each site. Table 5.1 shows the major crop management events and relative sampling dates for each site.

Table 5.1. Dates for crop management activities and sampling at each site.

Event	Site							
	CBJ	DMR	TTK	SAR	SAP	VF2	VF4	VF8
Planting/ fertilization	10/9/08	10/16/08	11/6/08	10/2/08	10/2/08	----------11/15/08----------		
Hill formation	11/8/08	12/12/08	12/21/08	1/29/09	1/29/09	----------1/8/09----------		
Flowering/ leaf sampling	1/23/09	2/4/09	2/4/09	2/4/09	2/4/09	----------3/3/09----------		
Frost damage/ foliage sampling	2/12/09	3/15/09	3/15/09	3/15/09	3/15/09	----------3/29/09----------		
Harvest sampling	4/21/09	4/1/09	4/21/09	4/30/09	4/30/09	----------4/30/09----------		

5.1.1 Climate data

Figures 5.1- 5.3 show the precipitation data used in the study for the 2008-2009 crop season. The Toralapa precipitation data were used for sites CBJ and DMR in the middle zone. The Sankayani Alto precipitation data were used for TTK, SAR, and SAP in the high zone. The Sankayani Alto precipitation data were also used for simulations of the Villa Flores site up to 16 January 2009 when the manually recorded site specific precipitation data were used. Daily precipitation input values used in model simulations are included in appendix C.

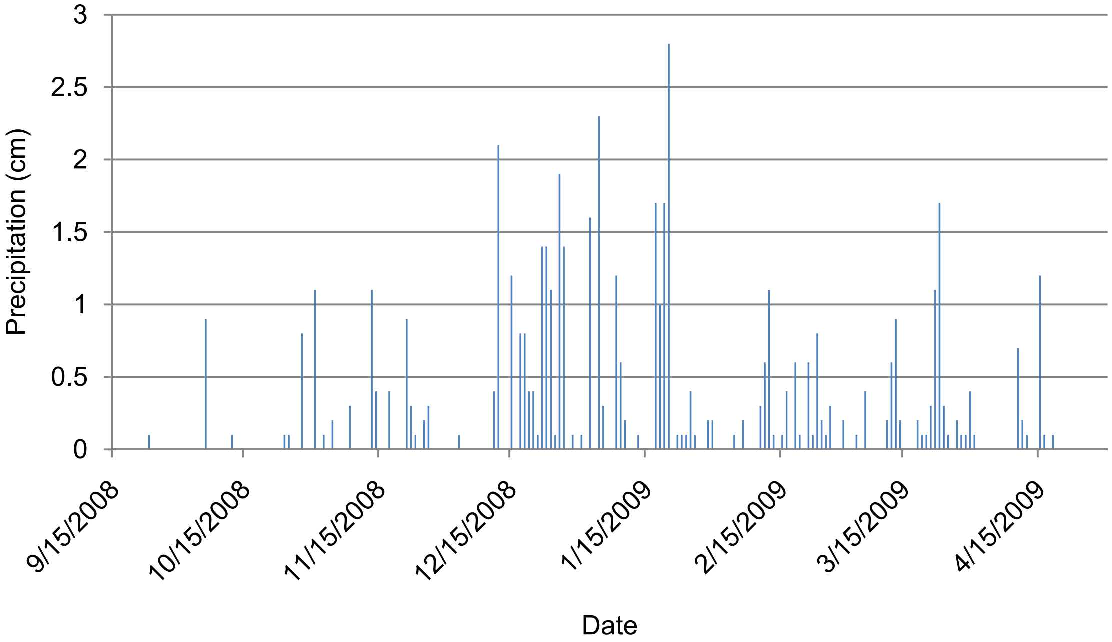

Figure 5.1 Toralapa daily precipitation for 2008-2009 study period.

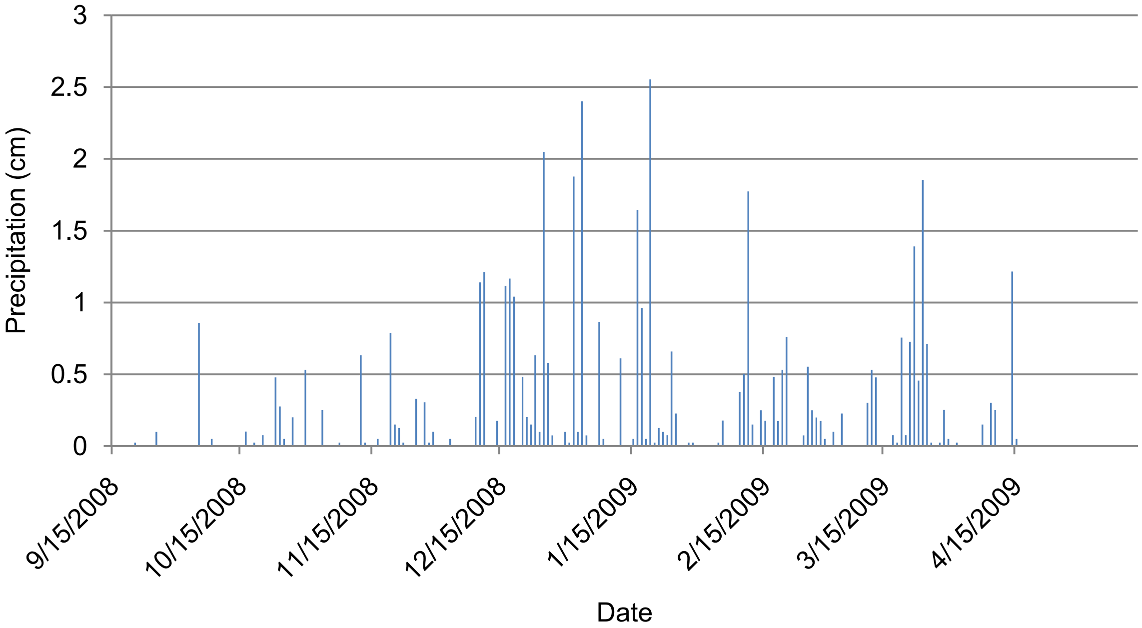

Figure 5.2 Sankayani Alto daily precipitation for 2008-2009 study period.

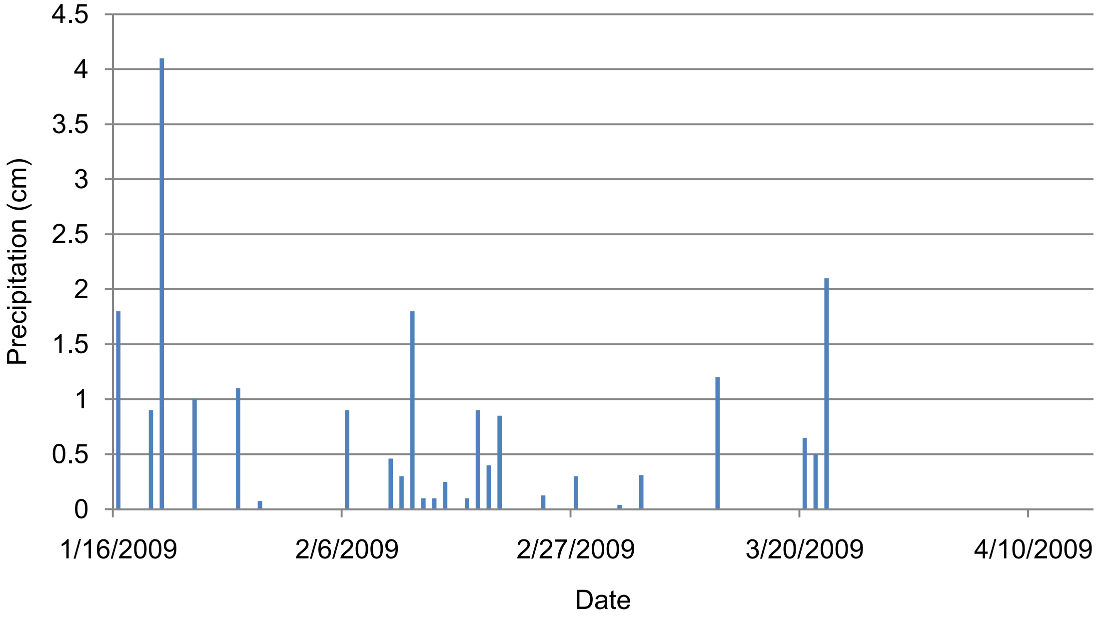

Figure 5.3 Villa Flores precipitation from 16 January 2009 to end of study period.

Figure 5.4 shows the temperature data used for the validation simulations and the sensitivity analysis simulations. The middle zone temperature data were used for simulations of the CBJ and DMR sites. The upper zone data was used for the TTK, SAR, SAP, VF2, VF4, and VF8 sites.

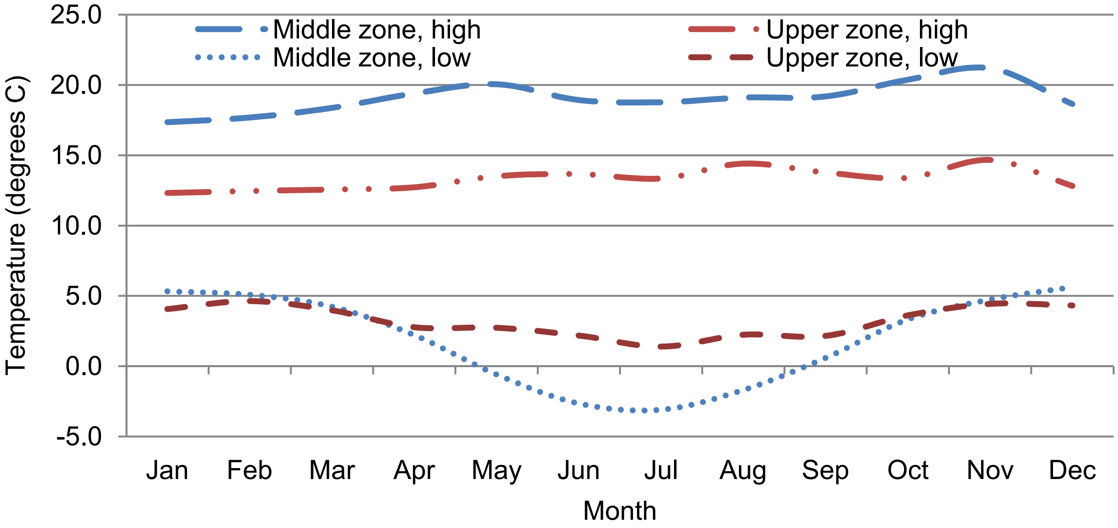

Figure 5.4 Average monthly high and low temperatures for the middle and upper zones for the 2008-2009 study period.

5.1.2 Soil data

All of the sites had silt loam texture soils**.** The results from the analysis of soil samples taken at potato flowering (or prior to potato flowering for site Villa Flores) that were used for the initial conditions for the GLEAMS simulations for each site are shown in table 5.2. The soil sample results from the furrow samples were used to provide the initial conditions for the GLEAMS simulations for pH, organic matter (OM) content, and soil TKN.

Table 5.2 Initial soil parameter values from soil sample analysis used for initial conditions in GLEAMS simulations.

Site	pH	OM[a] (%)	TKN[b] (%)	Olsen P (mg kg^{-1})	Porosity (cm^3 cm^{-3})	FC[c] (cm^3 cm^{-3})	PWP[d] (cm^3 cm^{-3})
CBJ	6.1	2.0	0.13	9.5	0.56	0.18	0.09
DMR	5.3	2.1	0.13	11.6	0.53	0.18	0.07
TTK	5.2	2.0	0.22	13.7	0.55	0.29	0.15
SAR	5.5	2.5	0.28	9.5	0.68	0.26	0.12
SAP	5.1	2.7	0.31	19.1	0.63	0.26	0.13
VF2	5.4	2.3	0.25	34.1	0.63	0.24	0.10
VF4	5.6	2.2	0.23	15.9	0.61	0.24	0.10
VF8	5.3	2.0	0.22	10.5	0.60	0,24	0.10

[a] OM, organic matter
[b] TKN, total Kjeldahl nitrogen
[c] FC, field capacity
[d] PWP, permanent wilting point

5.1.3 Crop data

Table 5.3 shows the results from the potato leaf nutrient analysis taken at flowering for each site. The leaf N concentrations were all slightly below the 5% N content considered adequate by Rosen (1991) for potatoes grown in western Minnesota. Although Rosen (1991) did not include the Waycha variety, this may still indicate that there was an N deficiency at the crop growth stage of peak N uptake (flowering) which may have had a decreasing effect on tuber yield at each site.

Table 5.3 Recommended nutrient contents for leaf analysis from potato plants 45-55 days after emergence by Rosen (1991) and leaf sample nutrient contents from each site taken at potato flowering.

Site	N (%)	P (%)	K (%)
Rosen (1991)	5	0.30	4.5
CBJ	4.28	0.36	4.57
DMR	4.56	0.38	4.32
TTK	4.76	0.36	3.60
SAR	4.90	0.42	5.36
SAP	4.28	0.37	4.73
VF2	2.72	0.24	3.75
VF4	2.72	0.24	3.75
VF8	2.72	0.24	3.75

Tables 5.4-5.5 summarize the dry matter yield, moisture content, N content, total N uptake, and dry matter ratio (ratio of total dry biomass production to dry tuber production) for the potato crop at each site, and weeds at the sites with significant weed cover (CBJ, DMR, and TTK). There was no apparent difference between tuber yields from the middle and upper zones. The highest tuber yield was from DMR (7931 kg ha^{-1}) and the lowest yield from SAR (3402 kg ha^{-1}). DMR may have had the highest yield because it had the highest N application rate (169 kg ha^{-1}) and suitable soil conditions. SAR may have had the lowest yield because it was in native vegetation and was tilled approximately 12 days prior to planting. A high rate of organic matter breakdown after the incorporation of the organic material may have created competition between the microbes decomposing the organic material and the potato crop, limiting the N availability for crop uptake and reducing the yield (Brady and Weil, 2008). A high amount of organic matter in the soil may have also increased the soil's ability to retain moisture due to the increased soil particle surface area. The increased soil moisture content may have kept the soil cool, especially since it is the site at the highest elevation (4036 masl). This may have lowered the hydraulic conductivity of the soil and limited the crop's ability to uptake N which could have reduced the yield. The SAR site had much wider row spacing than other sites (described in management data below)

and this may have also reduced the relative yield from this site in relation to those sites with narrower and, consequently, more rows per hectare to grow potatoes.

The greatest total crop N uptake was from TTK due to the high foliage yield and N content in foliage (yielding 162 kg ha^{-1}). The lowest total crop N uptake was from SAR (94 kg ha^{-1}). The sites with significant weed growth (CBJ, DMR and TTK) were located at the lower elevations, and had higher monthly average high temperatures than the sites in the upper zone. TTK had the greatest N uptake by weeds (73 kg ha^{-1}). Crop competition with weeds could not be simulated in GLEAMS.

Table 5.4 Summary of measured dry matter yield, N content (dry basis), and moisture content (MC, wet basis) for crop tubers and foliage with total crop N uptake and dry matter ratio.

Site	Tuber			Foliage			Total crop N uptake	Dry matter ratio
	Dry matter	MC	N	Dry matter	MC	N		
	(kg ha^{-1})	(fraction)	(%)	(kg ha^{-1})	(fraction)	(%)	(kg ha^{-1})	(total crop biomass:tuber biomass)
CBJ	6580	0.75	1.15	2297	0.83	2.40	148	1.46
DMR	7931	0.73	1.20	2102	0.84	2.80	154	1.27
TTK	5137	0.76	1.12	3066	0.85	3.40	162	1.60
SAR	3402	0.80	1.48	1838	0.87	2.40	94	1.54
SAP	5621	0.78	1.46	1772	0.87	2.90	133	1.32
VF2	5608	0.79	0.98	3353	0.87	2.60	142	1.65
VF4	5504	0.79	0.98	3353	0.87	2.60	141	1.65
VF8	6438	0.79	0.98	3353	0,87	2.60	150	1.65

Table 5.5 Summary of measured dry matter yield, N content (dry basis), moisture content (MC, wet basis), and N uptake for weeds at applicable sites.

Site	Weeds			Weed N uptake
	Dry matter	MC	N	
	(kg ha^{-1})	(fraction)	(%)	(kg ha^{-1})
CBJ	906	0.77	1.43	13
DMR	2237	0.80	1.90	42
TTK	4673	0.73	1.57	73

5.1.4 Management data

Figure 5.5 shows a two-dimensional representation of the potato hill and furrow dimensions. The widest row spacing was observed for the SAR site (0.72 m). This may have been because it was the first time the plot had been cultivated and so it was difficult to work the soil, especially due to the steep slope. Large clods and a high amount of surface residue from the tilled-in native vegetation were observed at this site. Wider row spacing may have been created at this site to reduce the amount of labor that would have been necessary to break all the clods to make narrower rows. This wide spacing meant that fewer rows could be installed over the plot area compared to narrower row spacing. This may explain part of why the yield production at SAR (3402 kg ha^{-1}) was the lowest for all the sites in spite of having one of the highest fertilizer N application rates (217 kg ha^{-1}). The smallest row spacing was observed at Villa Flores (VF2, VF4, and VF8) (0.60 m), which may have been because these were experimental plots and so it was desired to reduce the row spacing to increase the number of rows that could be included in the 10 m^2 experimental plot area.

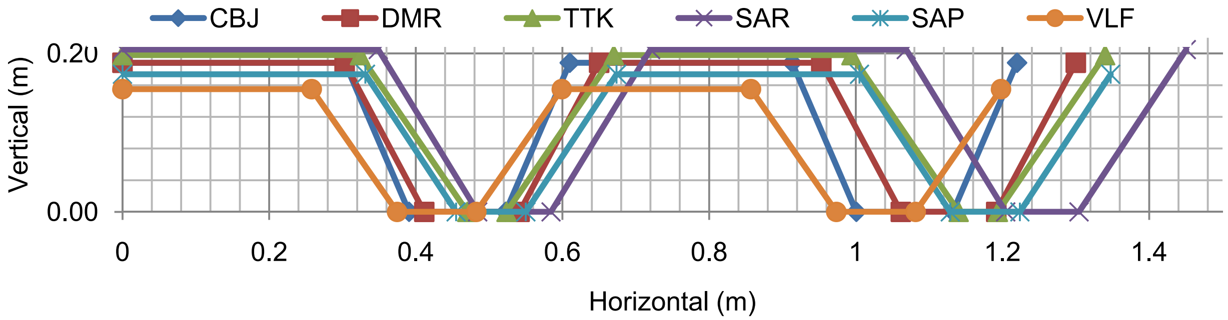

Figure 5.5 Cross section comparison looking down the row of potato hill and furrow dimensions for each site.

Table 5.6 shows the determined manure properties for chicken litter and cattle manure based on manure sample analysis and FAO and SNAG (1995) for Bolivian livestock. Purchased chicken litter, which had a higher N and P content than cattle manure, was used at greater rates by the farmers than cattle manure at the sites observed in this study.

Table 5.6 Manure properties determined for chicken litter and cattle manure.

Manure type	Bulk density$^+$ (kg m^{-3})	Moisture content$^+$ (fraction)	TKN$^+$ (%)	Org N^a (%)	TP^{+b} (%)	Org P^c (%)	OM$^+$ (%)
Chicken litter	220	0.09	2.7	2.1	2.0	1.5	44.7
Cattle manure	381	0.18	1.5	1.0	0.5	0.3	37.2

$^+$ indicates measured value
[a]Org N, organic N
[b]TP, total P
[c]Org P, organic P

Table 5.7 shows the applied fertilizer for each site. SAP had the greatest amount of applied N (246 kg ha-1) due to the high manure application rate plus an additional 108 kg ha^{-1} of diammonium phosphate (DAP) applied at planting. CBJ had the lowest applied N (79 kg ha^{-1}).

Table 5.7 Fertilizer application rates of dry chicken litter, dry cattle manure, and diammonium phosphate (DAP) applied at potato planting for each site during the 2008-2009 growing season

Site	Fertilizer			Total applied N
	Chicken litter (kg ha^{-1})	Cattle manure (kg ha^{-1})	DAP (kg ha^{-1})	(kg ha^{-1})
CBJ	1566	2437		79
DMR	6267			169
TTK	3943			106
SAR	7291		108	216
SAP	8405		108	246
VF2	5784			156
VF4	5784			156
VF8	5784			156

All farmers applied the fertilizer at planting by first creating a furrow with an ox-drawn plow, dropping in a seed tuber, and applying manure by pouring it out of a sack or bucket as they walked down the length of the row. A second pass was then made with the plow to cover the seed tuber and fertilizer with about 15 cm of soil. This essentially represented banding of solid manure to the 15 cm soil depth.

5.2 Model representation and behavior

5.2.1 Manure application method

The application method for manure (specified in the nutrient component input parameter file) greatly affected the soil N partitioning and subsequent simulated crop dry matter production. Initial model simulations specified the injection manure application method to represent banded manure application observed at each site. However, with this representation, very little mineralization of the organic N from animal waste occurred and the crop uptake was substantially reduced. This happened because the organic N from animal waste was being directly added to the soil potentially mineralizable N pool at the injection soil layer depth (15 cm) and negligible subsequent mineralization was occurring to become crop available. This is in contradiction to the model's documentation of the representation of animal waste mineralization where 80% of the daily mineralized organic N from animal waste goes to the soil NH_4^+ pool and 20% goes to the soil potentially mineralizable N pool (Knisel and Davis, 1999). This effect is demonstrated in figures 5.6-5.7, which show, respectively, organic N from animal waste in the soil and soil potentially mineralizable N for a 10-year continuous potato simulation with annual manure application for the DMR site when the injection manure application method is specified. It can be seen that no organic N from animal waste remains in the soil after the day of injection and that the soil potentially mineralizable N pool grows by the organic N from the animal waste each year. Table 5.8 shows the total simulated crop N uptake using the injection method to show the low values in relation to those observed in the field (from 94-162 kg N ha^{-1}). Crop N uptake may be limited using this method because nearly all the organic N added from the manure is remaining in the soil potentially mineralizable N pool and is not mineralizing to become crop available.

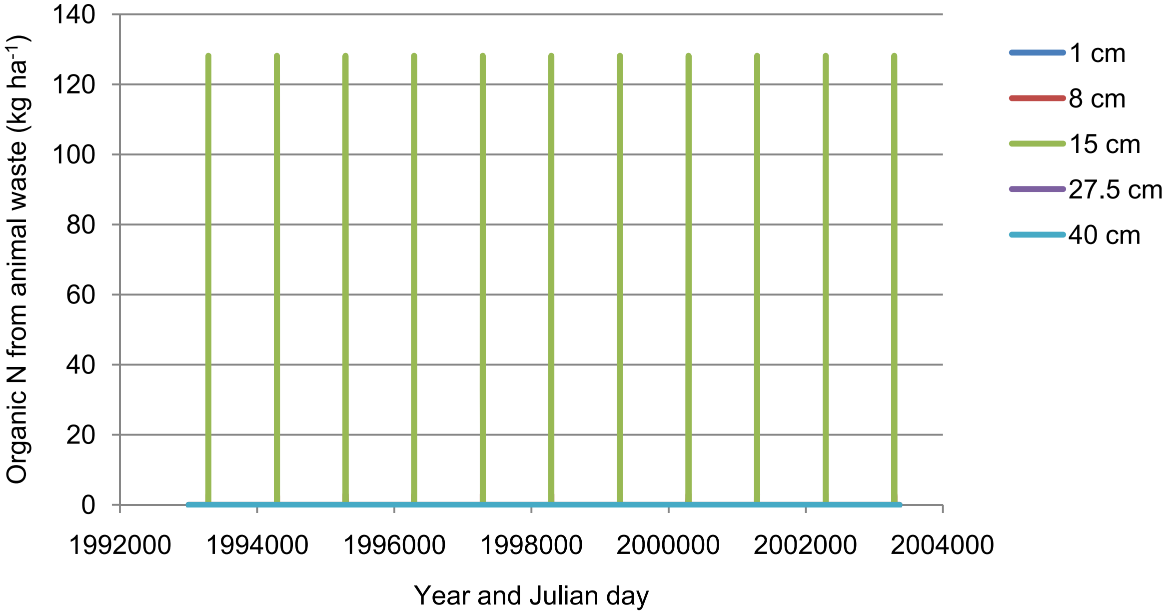

Figure 5.6 Simulated soil organic N from animal waste by soil layer depth for 10-year continuous potato simulation at site DMR using the injection manure application method.

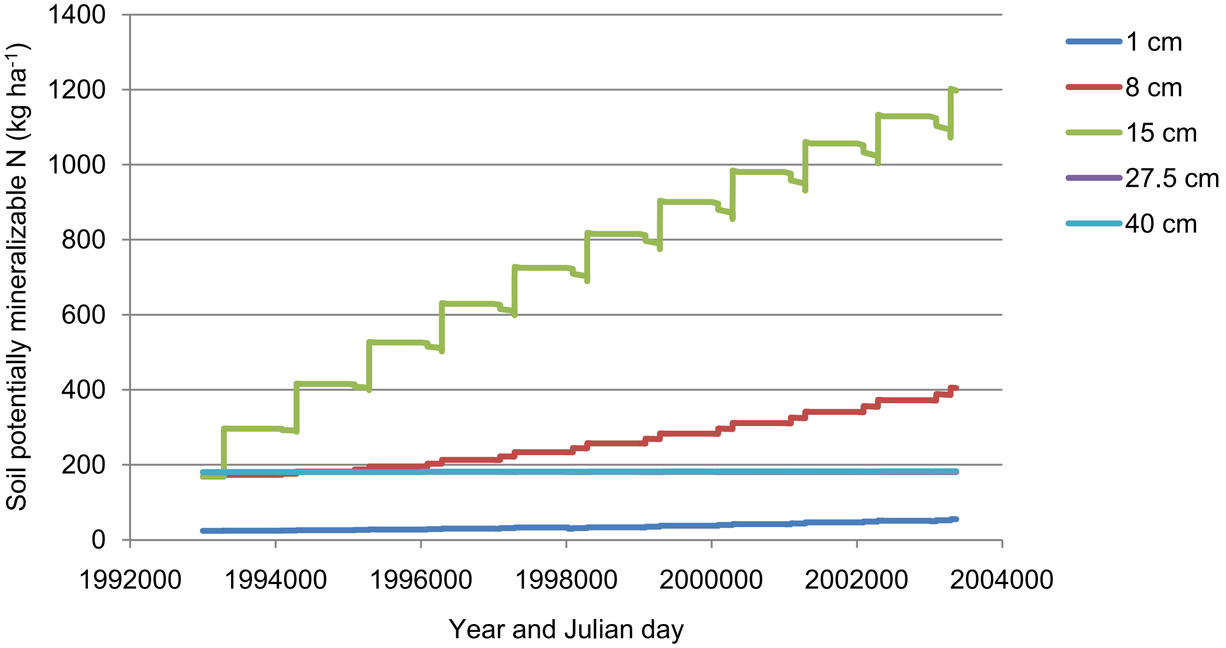

Figure 5.7 Simulated soil potentially mineralizable soil N by soil layer depth for 10-year continuous potato simulation at site DMR using the injection manure application method.

Table 5.8 Annual N uptake values for continuous potato simulation of DMR site using the injection and incorporation manure application methods.

Year	N uptake	
	Injection method (kg ha^{-1})	Incorporation method (kg ha^{-1})
1993	43	49
1994	56	95
1995	37	100
1996	35	84
1997	37	108
1998	41	119
1999	43	123
2000	39	147
2001	45	85
2002	40	123
2003	33	81

The inappropriate partitioning of organic N from the manure application and resulting reduced N uptake using the injection method was avoided by specifying the incorporation method in GLEAMS to describe the manure application method. With the incorporation method, a user-defined tillage implement was specified to simulate a completely-mixed manure application to a 15 cm depth. The improved representation of the soil N partitioning using the incorporation method is demonstrated in figures 5.8-5.9. It can be seen that the organic N from animal waste is slowly released through mineralization. The soil potentially mineralizable N pool is not immediately increased by the organic N from the manure addition, but rather slowly rises over time using the incorporation method. Higher N uptake was also simulated with this method as shown in table 5.8. Using the incorporation method, the manure is depicted as being well mixed throughout the whole soil volume to the 15 cm depth which may result in over-prediction of N losses to volatilization and surface runoff, and under-prediction of NO_3^- losses compared to the injection method. The incorporation method was used for all validation and sensitivity analysis simulations.

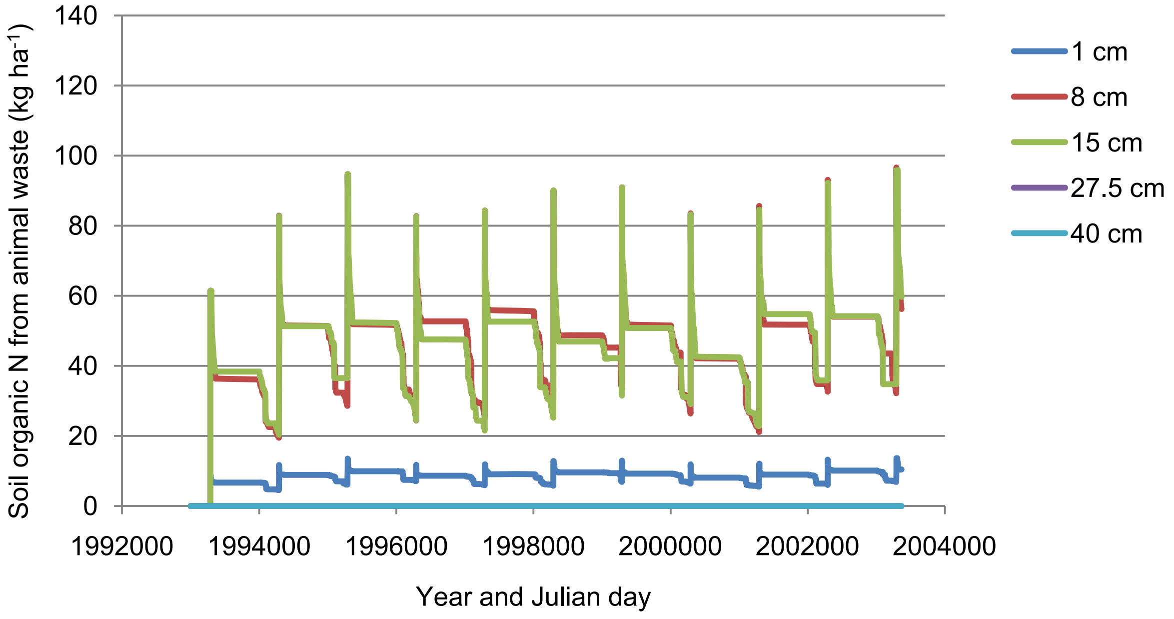

Figure 5.8 Simulated soil organic N from animal waste by soil layer depth for 10-year continuous potato simulation at site DMR using the incorporation manure application method.

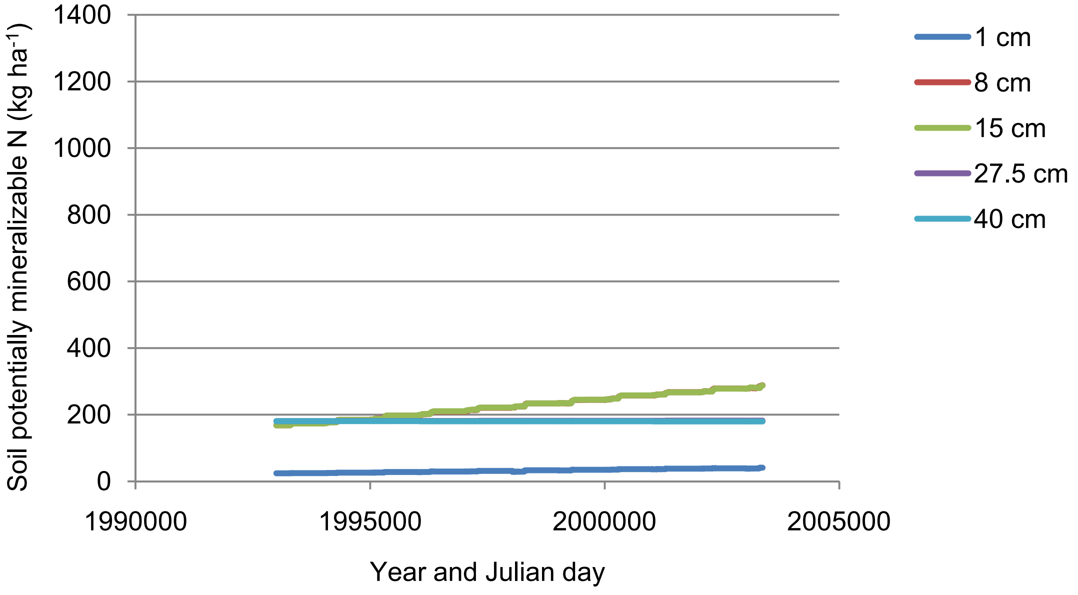

Figure 5.9 Simulated soil organic N from animal waste by soil layer depth for 10-year continuous potato simulation at site DMR using the incorporation manure application method.

5.2.2 Physical field configuration

Although the configuration of the potato hills can be specified in the erosion component of the input parameters to help determine N losses with sediment removal, no specific representation of the plant growth and fertilizer application occurring within those hills is specified in the nutrient or hydrology input parameters. This leads to a two-dimensional (2-D) representation of a 3-D hill-furrow configuration. In reality, the hill-furrow configuration has a great effect on infiltration volume and leaching (Robinson, 1999). Precipitation does not pool on the potato hills but rather tends to run into the furrows and infiltrate there. This in effect reduces the proportion of infiltration volume through the potato hills where the crop is growing and the fertilizer has been band-applied. Since the incorporation method for manure application in GLEAMS results in a uniform distribution of manure in space, it is expected that this representation overestimates contact of infiltration water with soil nutrients concentrated below the hill surface and so overestimates leached N and may in effect underestimate crop uptake.

5.2.3 Water balance

An annual water balance was computed for a 10-year continuous potato simulation with annual manure application for the DMR site and is shown in table 5.9. The monthly water balance components (precipitation, runoff, percolation, and ET) for the simulation are shown in figure 5.10. Runoff volume remained less than 3 cm throughout the simulation period. Percolation volume (average= 12 cm) was responsive to precipitation volume, as expected, but appeared high for silt loam considering that Peralta and Stockle (2002) estimated annual percolation volume at 1.7 m depth in sandy soils planted with potato and irrigated with 54 cm water to be only 5.9 cm . The average simulated seasonal ET (39 cm) appeared lower than the expected values for potato in this high altitude region based on a comparison to 60 cm seasonal ET using a crop coefficient for potatoes grown in a sub-humid region of 0.78 (Kashyap and Panda, 2001) and a grass reference ET measured in the Altiplano of 76.4 cm (Garcia et al., 2004). Average annual soil water remained relatively constant throughout the simulation period (average= 4cm).

Table 5.9 Annual water balance components for continuous 10 year simulation of site DMR. Values rounded from GLEAMS standard hydrology output to nearest cm.

Year	Precipitation (cm)	Runoff (cm)	ET (cm)	Percolation (cm)	Average soil water (cm)
1994	46	0	42	5	4
1995	62	1	42	16	4
1996	63	1	48	16	4
1997	69	1	52	18	5
1998	55	1	40	10	4
1999	36	1	28	8	4
2000	52	0	41	10	4
2001	64	1	50	14	5
2002	44	1	36	6	4
2003	66	2	40	24	4
Average	52	1	39	12	4

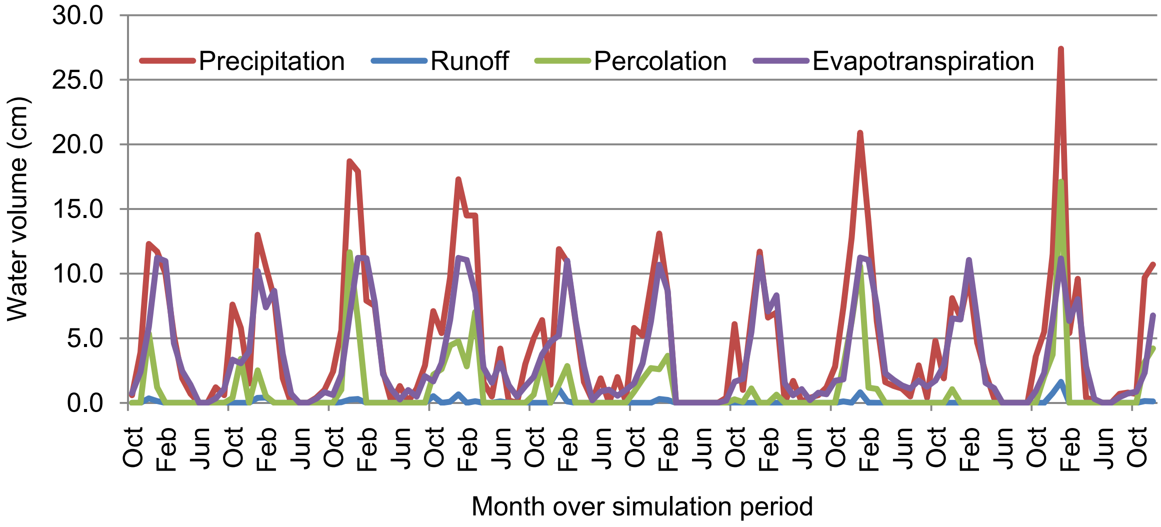

Figure 5.10. Simulated monthly water balance components over 10-year simulation using base input parameters for DMR site.

5.2.4 Soil nitrogen pool trends

The general trends observed for the soil N pools over the 2008-2009 growing period were similar across all the sites. The amounts of N in the respective soil pools over the study period are shown graphically for site TTK to demonstrate the trends observed at all sites. The results from the remaining sites are included in appendix E.

Figure 5.11 shows the simulated soil NO_3^- levels over the validation period. The soil NO_3^- increased shortly after the manure application due to the small NO_3^- addition from the manure application and also due to nitrification, one of the represented mineralization components in GLEAMS (a zero order process only dependent on soil water and temperature factors) (Knisel and Davis, 1999). The NO_3^- levels then decreased sharply, close to the period of crop flowering and rapid N uptake. The NO_3^- levels may have also decreased during this period because this was the peak of the rainy season (December-January) and the period of peak leaching, preventing the soil NO_3^- levels from accumulating. Near-zero levels occurred from day 10 in 2009 until the foliage death at day 74 in 2009.

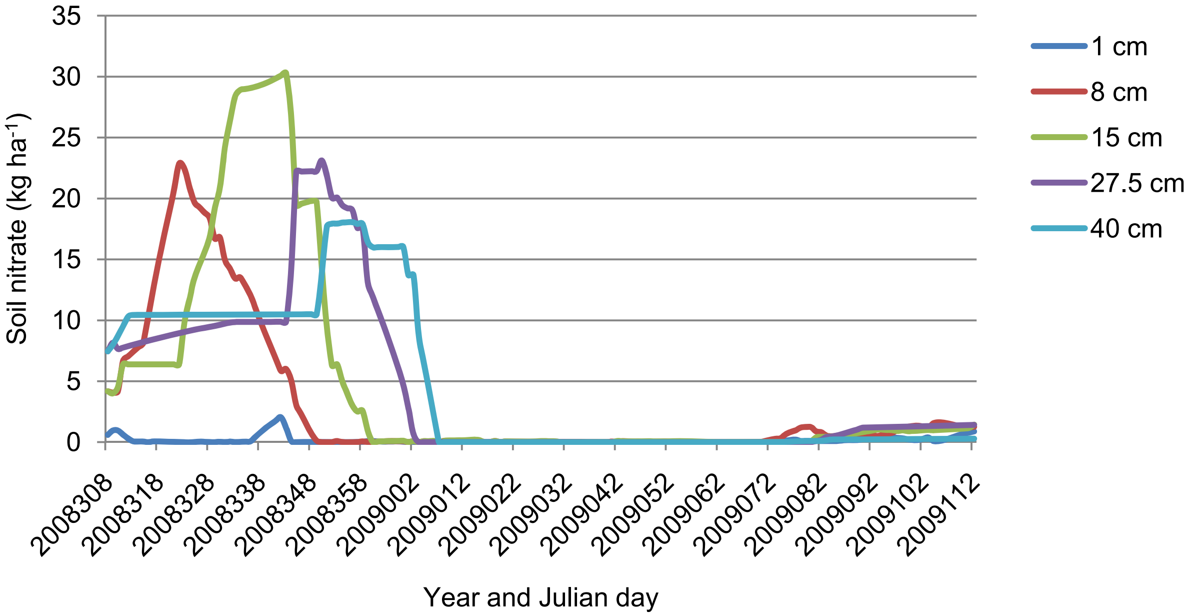

Figure 5.11 Simulated soil NO_3^- over the 2008-2009 season by soil layer for site TTK.

Figure 5.12 shows the simulated soil NH_4^+ levels over the validation period. Like soil NO_3^-, soil NH_4^+ levels rose sharply after the manure incorporation. This was likely due to the NH_4^+ addition from the manure and subsequent ammonification of the organic N in the manure. The level, however, decreased rapidly as the NH_4^+ was likely nitrifying and being consumed by the crop. There appeared to be little accumulation of soil NH_4^+ through continued ammonification for the remainder of the season.

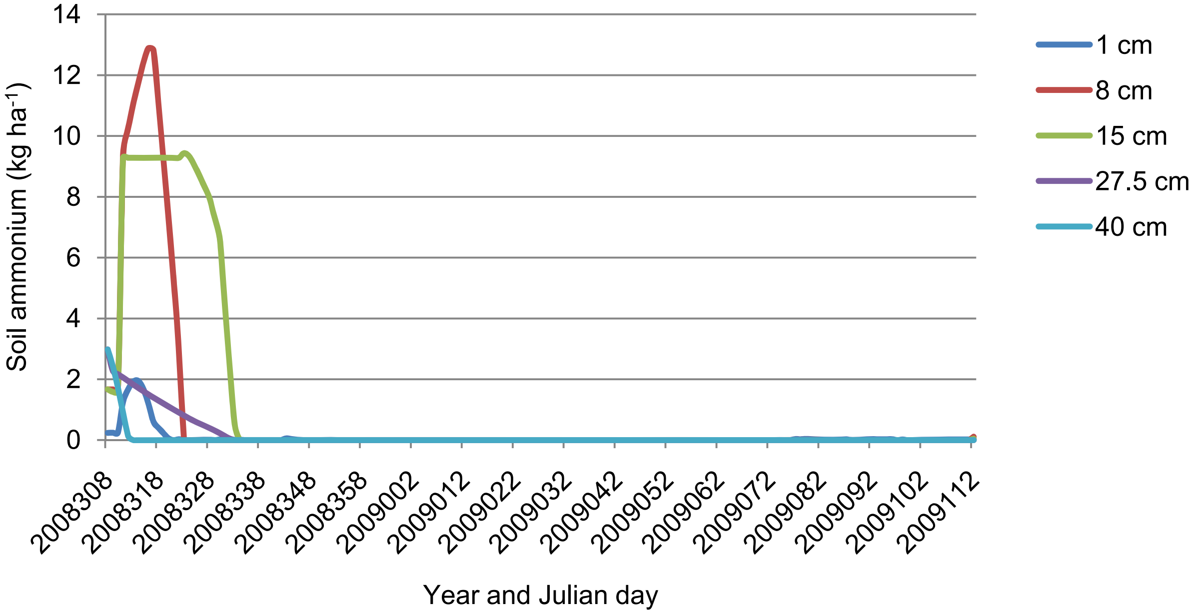

Figure 5.12. Simulated soil NH_4^+ over the 2008-2009 season by soil layer for site TTK.

Figure 5.13 shows the simulated soil organic N levels from crop residue over the validation period. The default initial crop residue amount (40 kg ha^{-1} from roots) is partitioned between the soil layers. After the first tillage operation at fertilization, the organic N from crop residue slowly declined as it was mineralized. The organic N from crop residue rose when the crop was killed at frost, primarily in the soil layers where most of the roots would be found (down to 27.5 cm).

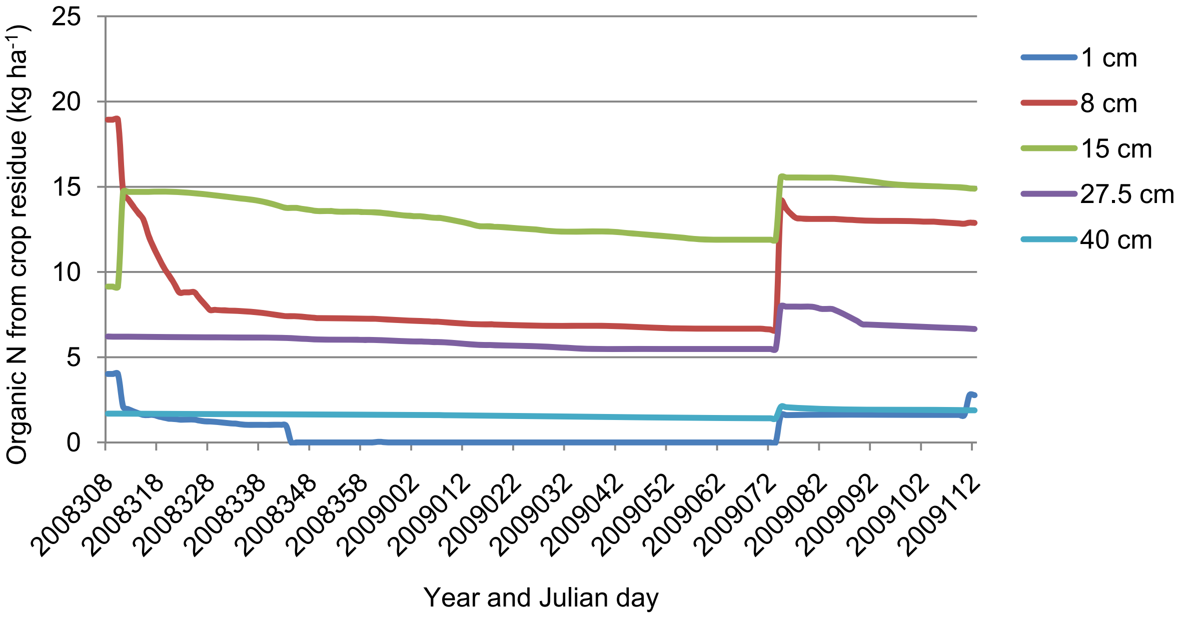

Figure 5.13. Simulated organic N levels from crop residue over the 2008-2009 season by soil layer for site TTK.

Figure 5.14 shows the simulated soil organic N levels from animal waste over the validation period. As expected, these values were zero until manure application. The peak levels of soil organic N from animal waste corresponded to the dry manure application rate multiplied by the organic N content of manure specified in the nutrient input parameter file. Two stages with different rates of decline of organic N from animal waste in the soil are seen, a short initial rapid stage and then a longer gradual stage. The initial rapid stage may correspond to a period when neither the C:N nor the C:P (factor *CNP* determined in GLEAMS from equation 3.9) in the organic material is limiting mineralization. The decomposition factor included in GLEAMS (*RC* for crop residue and *AWRC* for animal waste, equations 3.7 and 3.8 respectively) decreases as decomposition occurs, which would cause the mineralization rate to decrease over time. The organic N from animal waste decreased over the growing season as the manure was partitioned by the model according to Knisel and Davis (1999) into the soil potentially mineralizable N (20%) or mineralized into the soil NH_4^+ pool (80%) where it could be taken up by the crop. Only a portion of the initially available organic N from animal waste was mineralized for each site and the rest of the organic N from animal waste remained in the soil over the course of the validation period.

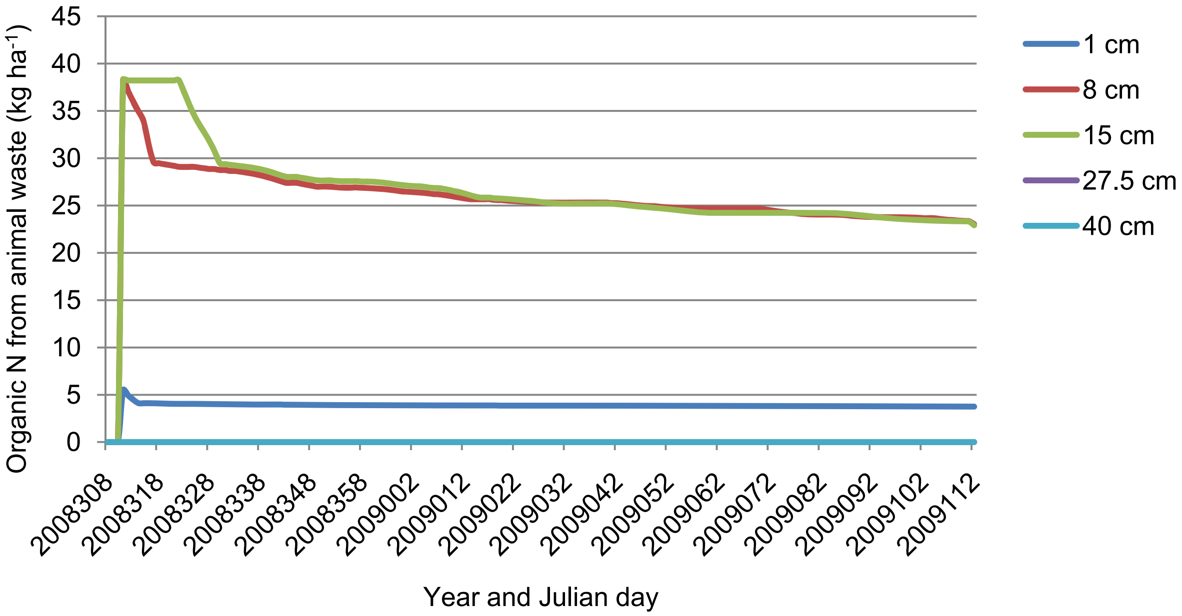

Figure 5.14 Simulated organic N levels from animal waste over the 2008-2009 season by soil layer for site TTK.

Figure 5.15 shows the simulated soil potentially mineralizable N levels over the validation period. The soil potentially mineralizable N levels remained relatively constant over the course of the simulation for all soil horizons. However, there appeared to be a small increase within the 8 cm and 15 cm soil layers shortly after manure incorporation into these layers and then at a much more gradual rate throughout the course of the simulation. This slight increase was probably due to the additions from crop residue and animal waste pools where approximately 20% of the mineralized organic N from these pools is added to the soil potentially mineralizable pool according to the model documentation (Knisel and Davis, 1999). However, it was expected that a gradual overall decrease in soil potentially mineralizable N would be observed as this pool is also mineralized through ammonification and nitrification and is removed from the soil by crop uptake, leaching, or denitrification.

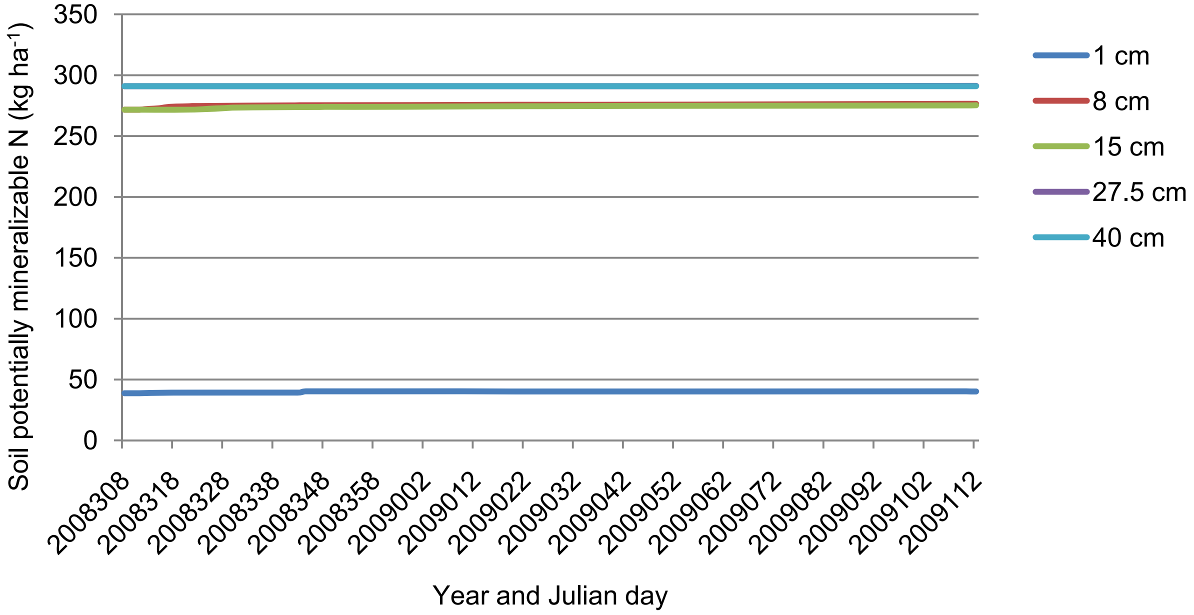

Figure 5.15 Simulated soil potentially mineralizable N levels over the 2008-2009 season by soil layer for site TTK.

Figure 5.16 shows the simulated stable soil organic N levels over the validation period. These levels remained relatively constant for all soil layers except for a slight increase in the 8 cm and 15 cm soil layers at manure incorporation. No significant removal and only slight overall additions over time to this pool were observed in the simulations for all the sites.

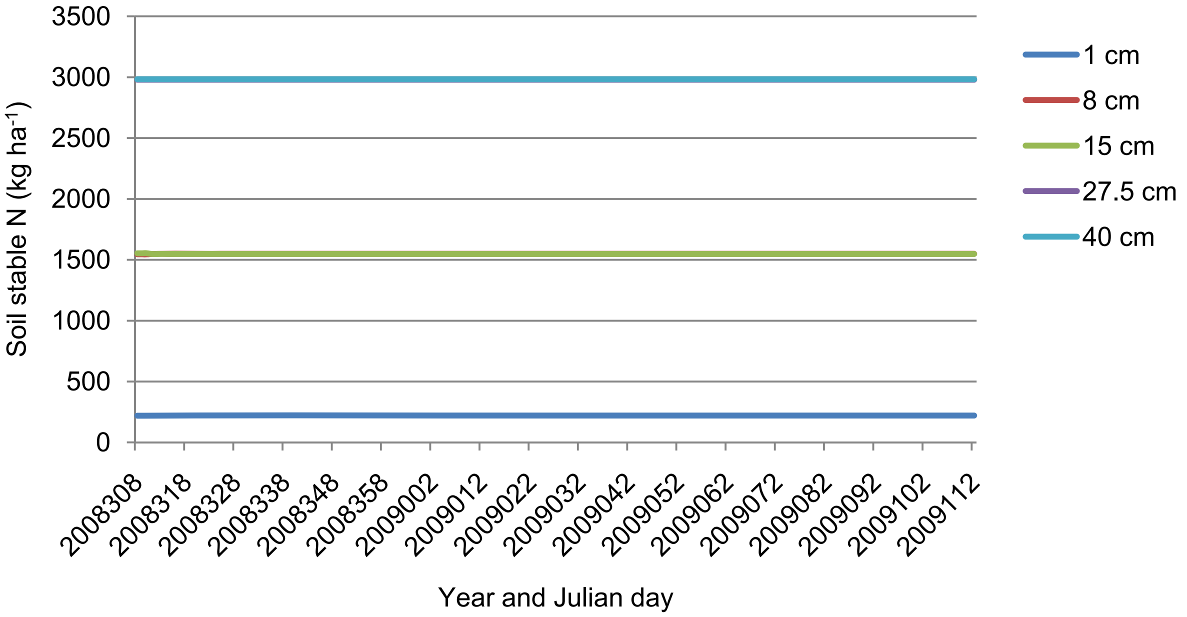

Figure 5.16 Simulated soil stable N levels over the 2008-2009 season by soil layer for site TTK.

5.2.5 Monthly nitrogen transformations

Simulated monthly N transformations over the 2008-2009 growing season are shown for each site in tables 5.10– 5.17. The peak N uptake occurred during December and January for each site. This must have corresponded to the higher levels of simulated NH_4^+ and NO_3^- during these months after manure incorporation. The limited soil NH_4^+ and NO_3^- levels after this period explains why crop uptake was drastically reduced during the month of February for all sites, the month when the tubers would be expected to be in a bulking stage and the crop taking up much more N. Each site's rank from greatest to least total N uptake over the months from October to March matches the rank of the total fertilizer N addition from greatest to least, shown in table 5.7. This indicates that the applied N rate may predominately determine the level of simulated N uptake and other N uptake dependent parameters such as total dry matter production and yield.

The low soil NH_4^+ and soil NO_3^- and consequently low crop uptake from February to March is due to the low amount of mineralization simulated beyond December for sites DMR, CBJ, TTK, SAR, and SAP. The total mineralization amounts from these sites closely matched the sum difference of organic N from crop residue and animal waste between the time of manure incorporation and crop death at frost. This indicated that total simulated mineralization was dominated by these pools and that mineralization from the potentially mineralizable soil N pool was negligible. It must be noted that the mineralization output for the Villa Flores site (tables 5.15- 5.17) appeared to be extremely large and did not correspond to annual nutrient balances also included in the standard GLEAMS nutrient output (demonstrated in appendix E) nor did it seem to affect other parameters such as uptake for VF2, VF4, and VF8. Therefore, it was considered that this printed output value for mineralization in these cases is due to an error.

Denitrification and leaching loss patterns occurred as expected with peak values occurring during months with the heaviest rainfall in the simulation, December and January. In all cases, leaching N losses represented a high proportion of the total N included in the simulated N balance. No field data were available to compare the simulated leaching losses with typical values for the Jatun Mayu watershed area but this information would be useful to help validate this component that is likely affecting crop uptake and could be representing excessively high NO_3^- loadings to groundwater systems.

Volatilization losses occurred only during the month when the manure was incorporated at each site. This simulated loss may be higher than what would be seen in the field using the banding/injection method to apply manure. It likely occurred in the simulations because the applied manure was represented as being incorporated and well-mixed within the surface 15 cm soil layer, allowing more contact with the atmosphere than would be seen with the injection manure application method. The simulated volatilization loss may also have contributed to the low simulated uptake, although it did not represent a high N amount considering the other N partitions overall.

Table 5.10 Simulated monthly N transformations and total from October to March 2008-2009 growing season for site CBJ.

Transformation (kg ha^{-1})	Oct (kg ha^{-1})	Nov (kg ha^{-1})	Dec (kg ha^{-1})	Jan (kg ha^{-1})	Feb (kg ha^{-1})	Mar (kg ha^{-1})	Total (kg ha^{-1})
Uptake	0	12	26	8	2	0	48
Mineralization	0	20	8	4	2	4	38
Leached	0	0	32	0	0	0	32
Denitrification	0	0	1	0	0	0	1
Ammonia volatilized	0	7	0	0	0	0	7

Table 5.11 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site DMR.

Transformation (kg ha^{-1})	Oct (kg ha^{-1})	Nov (kg ha^{-1})	Dec (kg ha^{-1})	Jan (kg ha^{-1})	Feb (kg ha^{-1})	Mar (kg ha^{-1})	Total (kg ha^{-1})
Uptake	2	17	33	18	3	1	74
Mineralization	21	22	11	6	3	6	69
Leached	0	0	46	2	0	0	48
Denitrification	0	1	3	0	0	0	4
Ammonia volatilized	11	0	0	0	0	0	11

Table 5.12 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site TTK.

Transformation (kg ha^{-1})	Oct (kg ha^{-1})	Nov (kg ha^{-1})	Dec (kg ha^{-1})	Jan (kg ha^{-1})	Feb (kg ha^{-1})	Mar (kg ha^{-1})	Total (kg ha^{-1})
Uptake	0	15	28	19	2	0	64
Mineralization	0	24	5	4	2	4	39
Leached	0	0	15	6	0	0	21
Denitrification	0	0	3	0	0	0	3
Ammonia volatilized	0	3	0	0	0	0	3

Table 5.13 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site SAR.

Transformation (kg ha^{-1})	Oct (kg ha^{-1})	Nov (kg ha^{-1})	Dec (kg ha^{-1})	Jan (kg ha^{-1})	Feb (kg ha^{-1})	Mar (kg ha^{-1})	Total (kg ha^{-1})
Uptake	12	17	44	34	4	1	112
Mineralization	27	15	8	6	4	5	65
Leached	0	0	14	8	0	0	22
Denitrification	0	0	0	0	0	0	0
Ammonia volatilized	11	0	0	0	0	0	11

Table 5.14 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site SAP.

Transformation ($kg\ ha^{-1}$)	Oct ($kg\ ha^{-1}$)	Nov ($kg\ ha^{-1}$)	Dec ($kg\ ha^{-1}$)	Jan ($kg\ ha^{-1}$)	Feb ($kg\ ha^{-1}$)	Mar ($kg\ ha^{-1}$)	Total ($kg\ ha^{-1}$)
Uptake	11	16	40	46	4	1	118
Mineralization	32	16	8	6	4	8	74
Leached	0	0	16	13	0	0	29
Denitrification	1	1	5	1	0	0	8
Ammonia volatilized	12	0	0	0	0	0	12

Table 5.15 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site VF2.

Transformation ($kg\ ha^{-1}$)	Oct ($kg\ ha^{-1}$)	Nov ($kg\ ha^{-1}$)	Dec ($kg\ ha^{-1}$)	Jan ($kg\ ha^{-1}$)	Feb ($kg\ ha^{-1}$)	Mar ($kg\ ha^{-1}$)	Total ($kg\ ha^{-1}$)
Uptake	0	9	24	30	3	1	67
Mineralization^{+}	0	142	241	236	211	234	1064
Leached	0	0	21	15	0	0	36
Denitrification	0	0	4	1	0	0	5
Ammonia volatilized	0	5	0	0	0	0	5

$^{+}$ indicates likely printed output error

Table 5.16 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site VF4.

Transformation ($kg\ ha^{-1}$)	Oct ($kg\ ha^{-1}$)	Nov ($kg\ ha^{-1}$)	Dec ($kg\ ha^{-1}$)	Jan ($kg\ ha^{-1}$)	Feb ($kg\ ha^{-1}$)	Mar ($kg\ ha^{-1}$)	Total ($kg\ ha^{-1}$)
Uptake	0	9	24	30	3	1	67
Mineralization^{+}	0	142	240	237	212	234	1065
Leached	0	0	22	15	0	0	37
Denitrification	0	0	4	1	0	0	5
Ammonia volatilized	0	5	0	0	0	0	5

$^{+}$ indicates likely printed output error

Table 5.17 Simulated monthly N transformations and seasonal total over 2008-2009 growing season for site VF8.

Transformation ($kg\ ha^{-1}$)	Oct ($kg\ ha^{-1}$)	Nov ($kg\ ha^{-1}$)	Dec ($kg\ ha^{-1}$)	Jan ($kg\ ha^{-1}$)	Feb ($kg\ ha^{-1}$)	Mar ($kg\ ha^{-1}$)	Total ($kg\ ha^{-1}$)
Uptake	0	9	25	30	3	1	68
Mineralization^{+}	0	142	240	237	212	234	1065
Leached	0	0	22	15	0	0	37
Denitrification	0	0	4	1	0	0	5
Ammonia volatilized	0	5	0	0	0	0	5

$^{+}$ indicates likely printed output error

It was expected that a higher amount of N should have been available from the soil potentially mineralizable N pool. Using a conservative estimate for mineralization rate of 1.5% of the soil TKN amount (Brady and Weil, 2008), it was expected that the soil potentially mineralizable N pool should contribute from 34-68 kg ha^{-1} of crop available N for each site. This could mean that a proportion of the N source for crop uptake is not being represented appropriately by GLEAMS. This could be due to the low constant mineralization rate (CMN=0.0003 kg ha^{-1} day^{-1}) or the temperature factor (TFA) used to determine ammonification from the soil potentially mineralizable N pool in equation 3.2 from the GLEAMS nutrient component documentation (Knisel and Davis, 1999).

The low simulated N uptake, especially in relation to the observed N uptake may also be due to over-estimations by the model for N leaching and volatilization. Additional field data, especially for leaching, would greatly assist in confirming actually N losses due to leaching that may be limiting crop growth and becoming potential sources of ground water pollution.

5.3 Validation

5.3.1 Runoff from Villa Flores

Daily runoff was simulated for VF2, VF4, and VF8. The validation included days with precipitation greater than 0.8 cm from 16 January 2009 to 1 May 2009, which totaled 13 days with which to compare observed and simulated runoff predictions. The results of the observed and simulated values using curve numbers 82, 86, 90, 95, and 99 for the 13 evaluated days are shown in tables 5.18-5.20 for the three plots.

Table 5.18 Plot VF2 precipitation and observed and predicted runoff volume (cm) for SCS curve numbers 82, 86, 90, 95, and 99 for storms greater than 0.80 cm from 16 January 2009 to the end of the study period.

Date	Precipitation (cm)	Runoff					
		Observed (cm)	Simulated (cm)				
			CN=82	CN=86	CN=90	CN=95	CN=99
1/16/2009	1.80	0.03	0.00	0.00	0.03	0.14	0.39
1/19/2009	0.90	0.00	0.00	0.00	0.00	0.01	0.12
1/20/2009	4.10	0.34	0.15	0.28	0.45	0.81	1.25
1/23/2009	1.00	0.19	0.00	0.00	0.00	0.02	0.15
1/27/2009	1.10	0.00	0.00	0.00	0.00	0.03	0.17
2/6/2009	0.90	0.09	0.00	0.00	0.00	0.00	0.10
2/12/2009	1.80	0.08	0.00	0.00	0.01	0.11	0.36
2/18/2009	0.90	0.03	0.00	0.00	0.00	0.01	0.10
2/20/2009	0.85	0.05	0.00	0.00	0.00	0.01	0.09
3/12/2009	1.20	0.06	0.00	0.00	0.00	0.02	0.17
3/22/2009	2.10	0.32	0.00	0.01	0.04	0.19	0.48
3/26/2009	0.97	0.25	0.00	0.00	0.00	0.01	0.12
4/14/2009	1.70	0.12	0.00	0.00	0.01	0.08	0.32

Table 5.19 Plot VF4 precipitation and observed and predicted runoff volume (cm) for SCS curve numbers 82, 86, 90, 95, and 99 for storms greater than 0.80 cm from 16 January 2009 to the end of the study period.

Date	Precipitation (cm)	Runoff					
		Observed (cm)	Simulated (cm)				
			CN=82	CN=86	CN=90	CN=95	CN=99
1/16/2009	1.80	0.02	0.00	0.00	0.03	0.14	0.39
1/19/2009	0.90	0.00	0.00	0.00	0.00	0.01	0.12
1/20/2009	4.10	0.22	0.16	0.28	0.46	0.82	1.25
1/23/2009	1.00	0.16	0.00	0.00	0.00	0.02	0.15
1/27/2009	1.10	0.00	0.00	0.00	0.00	0.03	0.17
2/6/2009	0.90	0.03	0.00	0.00	0.00	0.00	0.10
2/12/2009	1.80	0.04	0.00	0.00	0.01	0.11	0.36
2/18/2009	0.90	0.01	0.00	0.00	0.00	0.01	0.10
2/20/2009	0.85	0.01	0.00	0.00	0.00	0.01	0.09
3/12/2009	1.20	0.01	0.00	0.00	0.00	0.02	0.17
3/22/2009	2.10	0.02	0.00	0.01	0.05	0.19	0.48
3/26/2009	0.97	0.02	0.00	0.00	0.00	0.01	0.12
4/14/2009	1.70	0.02	0.00	0.00	0.01	0.08	0.32

Table 5.20 Plot VF8 precipitation and observed and predicted runoff volume (cm) for SCS curve numbers 82, 86, 90, 95, and 99 for storms greater than 0.80 cm from 16 January 2009 to the end of the study period.

Date	Precipitation	Runoff					
		Observed	Simulated				
	(cm)	(cm)	(cm)				
			CN=82	CN=86	CN=90	CN=95	CN=99
1/16/2009	1.80	0.01	0.00	0.00	0.03	0.14	0.39
1/19/2009	0.90	0.00	0.00	0.00	0.00	0.01	0.12
1/20/2009	4.10	0.44	0.16	0.29	0.47	0.82	1.26
1/23/2009	1.00	0.19	0.00	0.00	0.00	0.02	0.15
1/27/2009	1.10	0.00	0.00	0.00	0.00	0.03	0.17
2/6/2009	0.90	0.19	0.00	0.00	0.00	0.01	0.10
2/12/2009	1.80	0.13	0.00	0.00	0.01	0.11	0.36
2/18/2009	0.90	0.00	0.00	0.00	0.00	0.01	0.10
2/20/2009	0.85	0.03	0.00	0.00	0.00	0.01	0.09
3/12/2009	1.20	0.08	0.00	0.00	0.00	0.02	0.17
3/22/2009	2.10	0.00	0.00	0.01	0.05	0.19	0.48
3/26/2009	0.97	0.15	0.00	0.00	0.00	0.01	0.12
4/14/2009	1.70	0.03	0.00	0.00	0.01	0.08	0.32

Table 5.21 shows the RSR values calculated between the observed and simulated runoff for each of the five tested curve numbers for the 13 observations. The lowest RSR was computed using a curve number of 90 for VF2, 82 for VF4, and 90 for VF8. Both RSR and PBIAS were greater than one, indicating optimal agreement between observed and simulated values was not reached. The PBIAS seemed quite high suggesting poor average agreement between observed and simulated values for daily runoff volume.

Table 5.21 Root mean square error standard deviation ratio (RSR) and percent bias (PBIAS) results between observed and predicted runoff (cm) for each plot at the Villa Flores site.

SCS curve number	RSR			PBIAS		
					(%)	
	VF2	VF4	VF8	VF2	VF4	VF8
82	4.4	2.8	3.5	90	72	87
86	4.1	2.9	3.0	82	50	76
90	4.0	4.5	2.7	65	4	55
95	5.0	9.9	4.3	7	-153	-17
99	9.3	19.8	9.0	-147	-566	-207

The curve number 90 was selected as the calibrated curve number and was used in subsequent simulations for the three plots at Villa Flores. The calibration of the curve number for Villa Flores was considered in choosing a curve number for the other sites. The base curve number of 82 was increased to 86 for the other sites to reflect the under-prediction at Villa Flores with the base curve number of 82. A higher curve number was not used for the remaining sites where curve number was not directly calibrated considering the GLEAMS user manual maximum recommendation for straight row crops on soils in hydrologic soil group C is 88 (Knisel and Davis, 1999).

5.3.2 Soil nutrient levels

The daily simulated soil TKN (mg kg^{-1}) by soil depth was plotted with the observed soil TKN concentrations at potato flowering and potato harvest to graphically compare the data. Figures 5.17-5.24 show the observed and simulated data for each site over the 2008-2009 study period. Continuous lines represent the simulated TKN concentration for the corresponding soil layer. Points represent measured data from the 0-15 cm and 15-30 cm potato hill depths. The model simulated soil TKN was initialized with the soil TKN entered as an input for each site according to the concentration measured from the potato furrow soil sample at flowering. The simulated soil TKN concentration then rose sharply to account for the fertilization that occurred shortly after the simulation began. The simulated TKN concentration had an initial rapid reduction and then decreased at a much more gradual rate until the potato plants were killed by frost. The TKN then increased slightly until harvest occurred. This may have been due to crop residue that was available for mineralization after frost occurred.

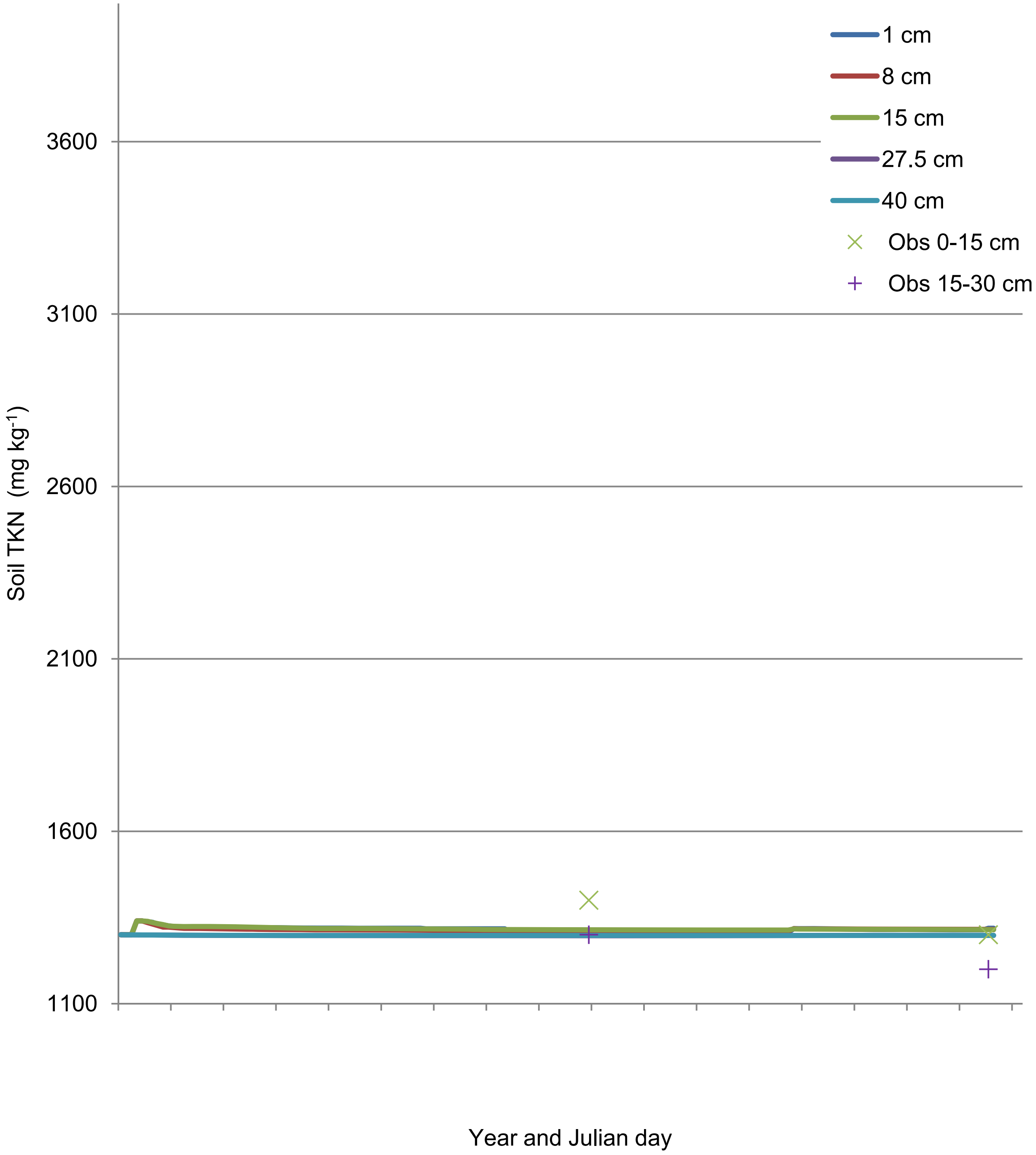

Figure 5.17 Site CBJ simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration at potato flowering and harvest.

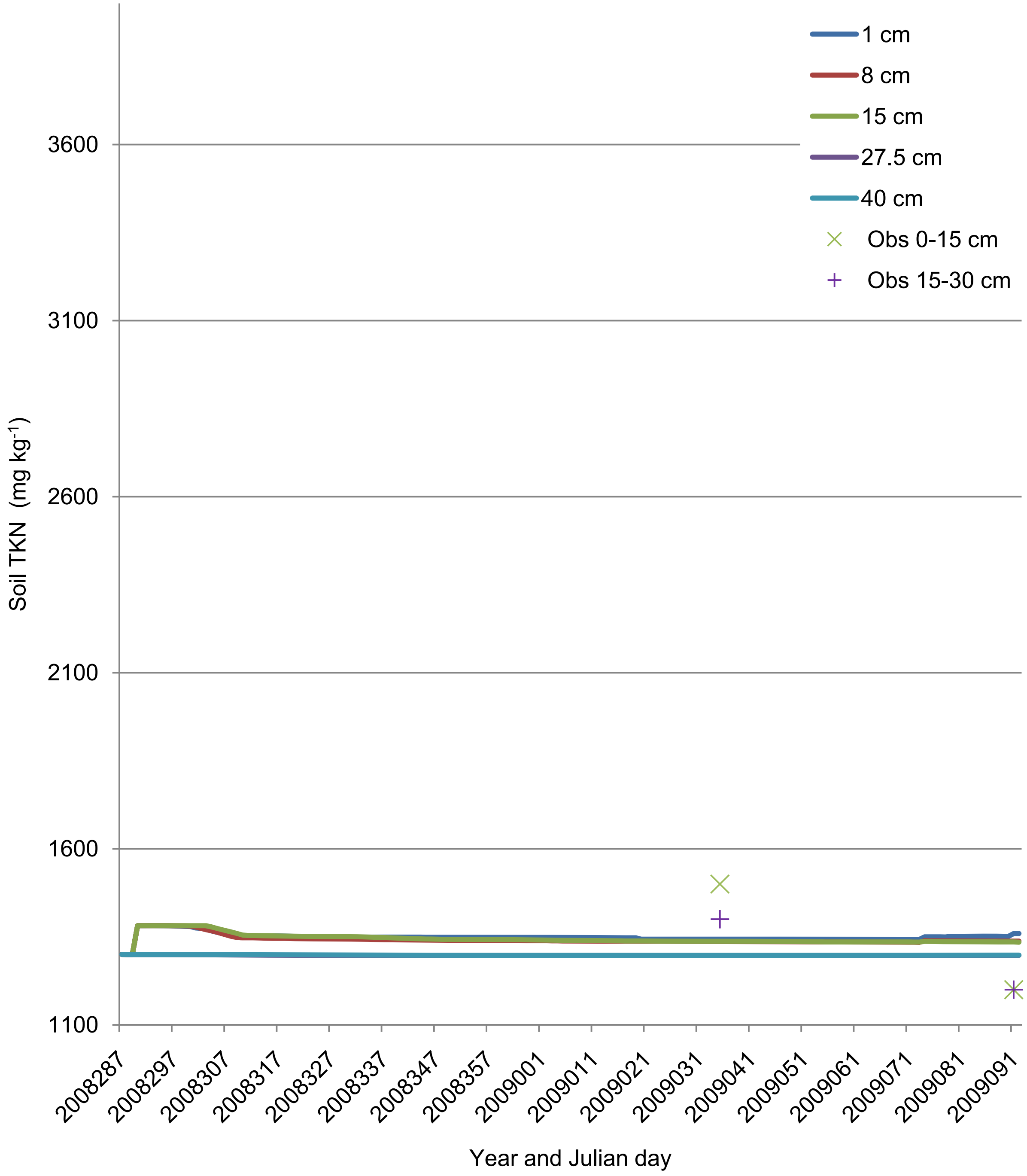

Figure 5.18 Site DMR simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration at potato flowering and harvest.

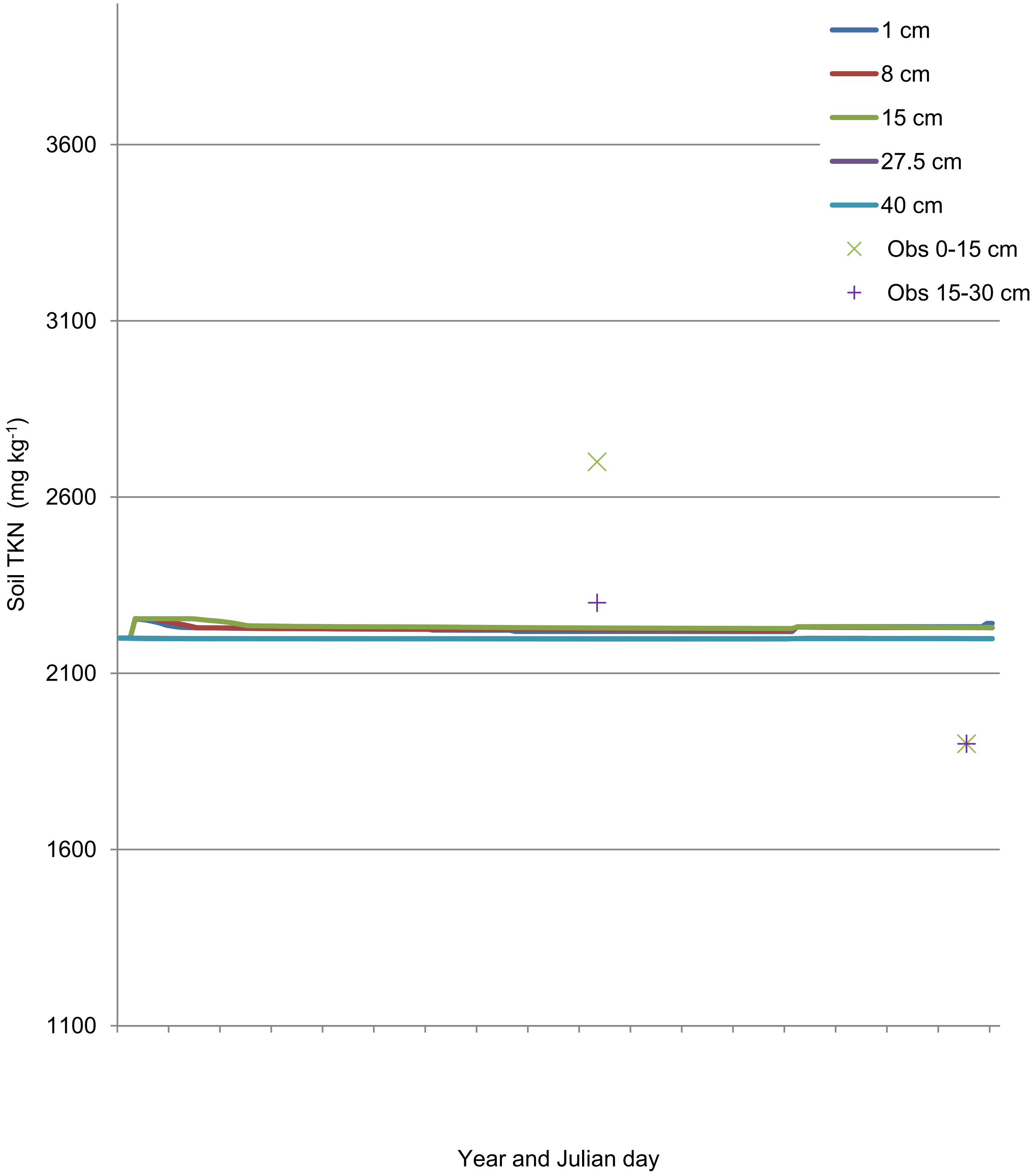

Figure 5.19. Site TTK simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration at potato flowering and harvest.

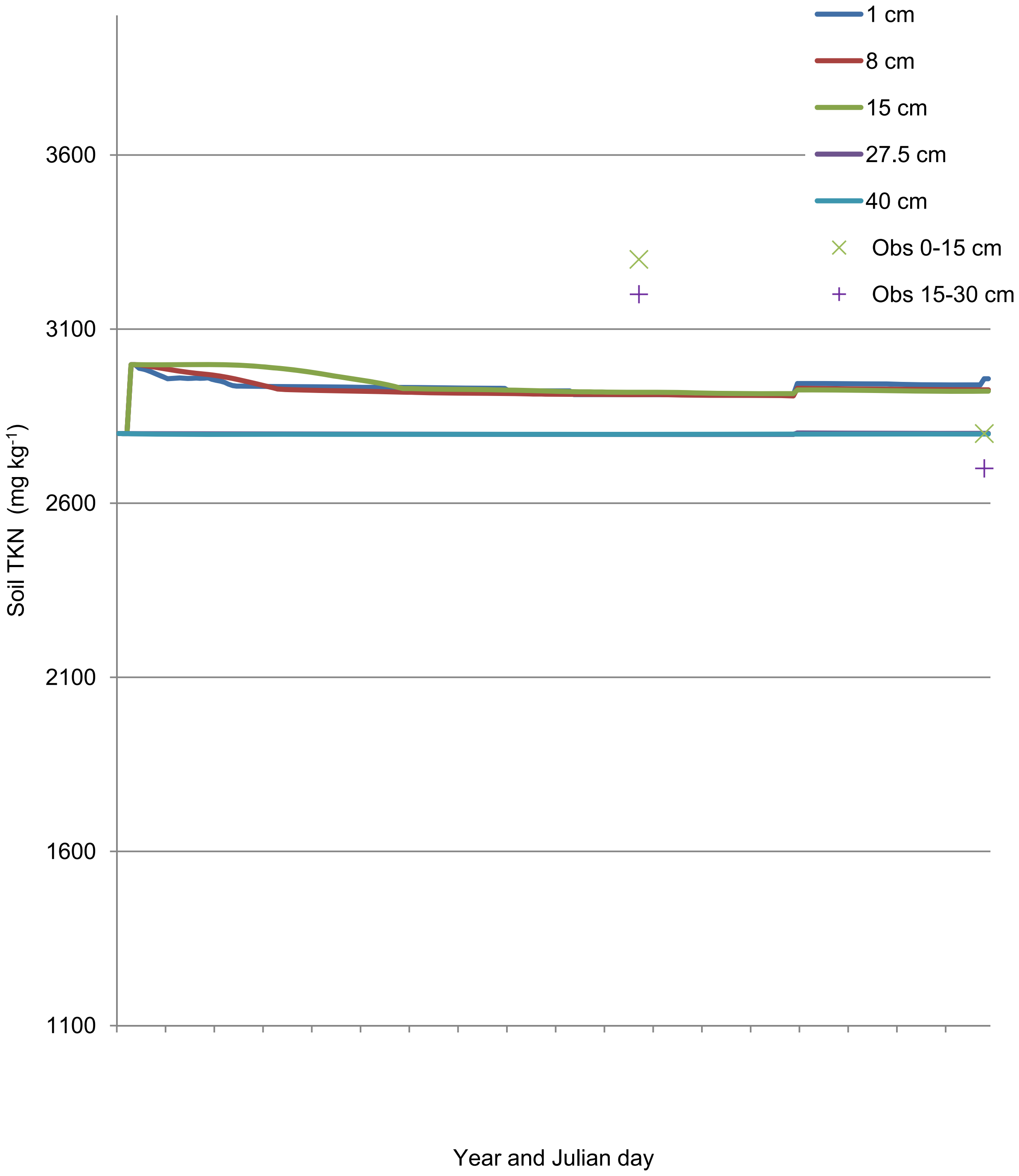

Figure 5.20 Site SAR simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration at potato flowering and harvest.

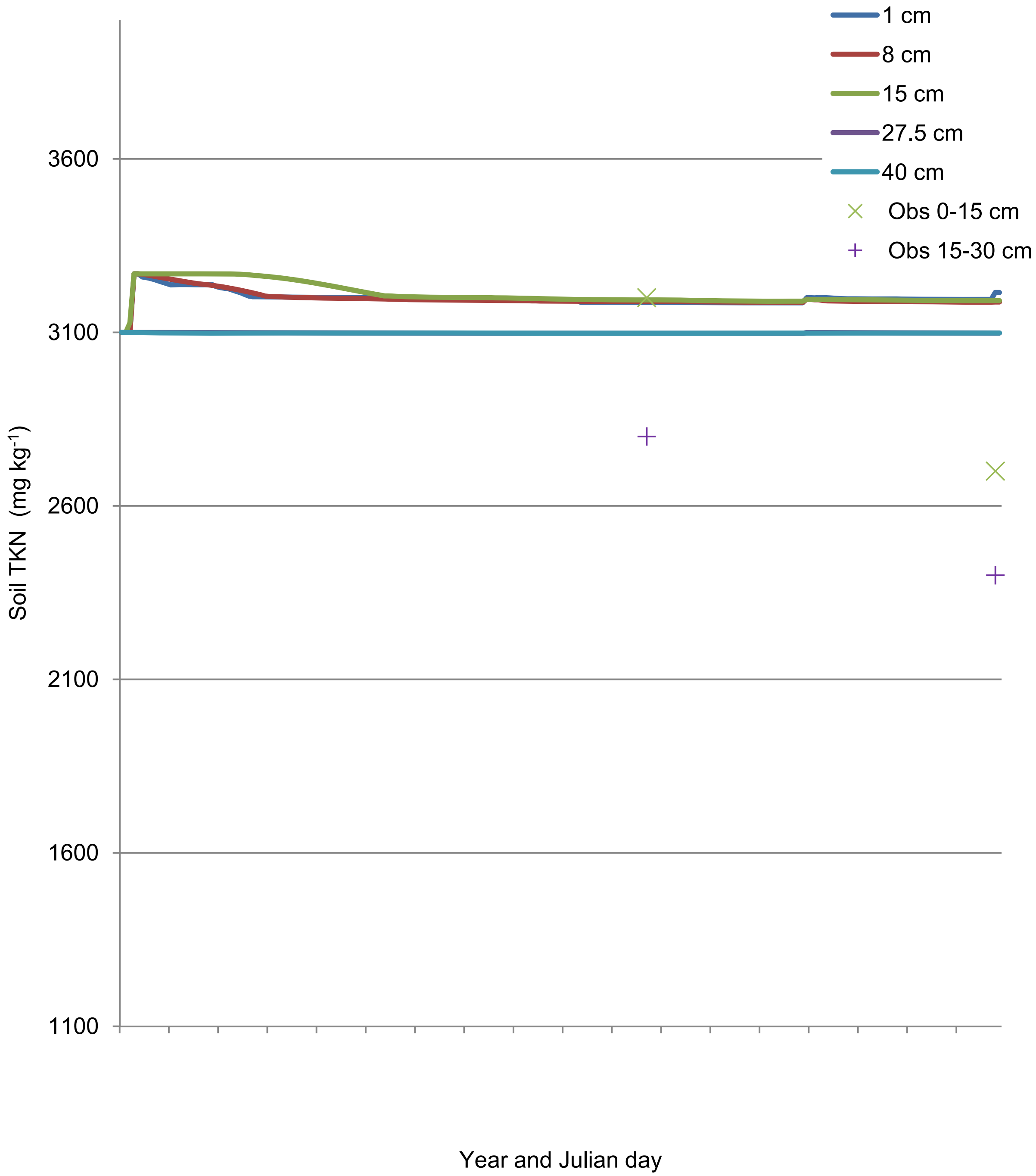

Figure 5.21. Site SAP simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration at potato flowering and harvest.

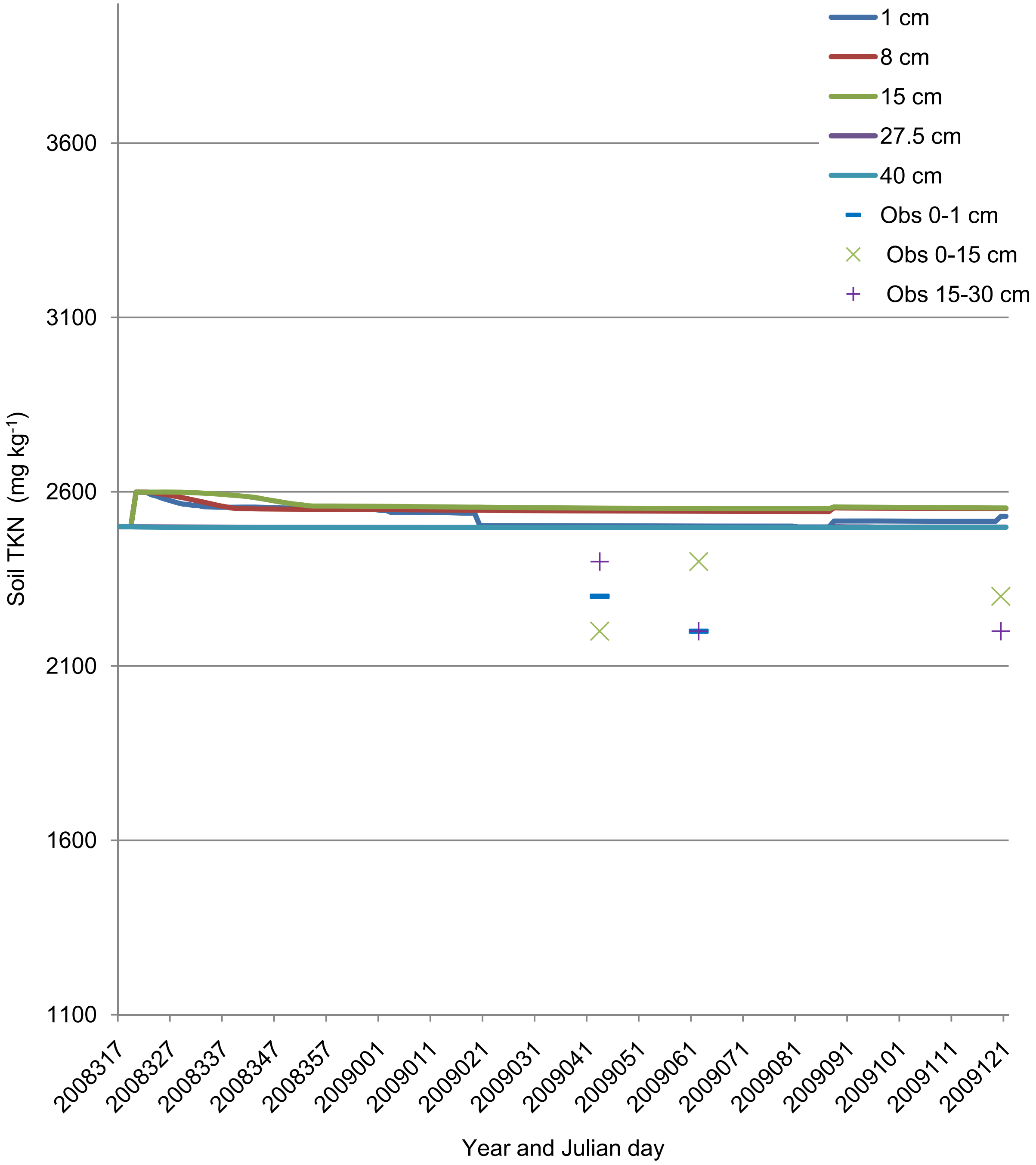

Figure 5.22 Site VF2 simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration prior to potato flowering, at potato flowering, and harvest.

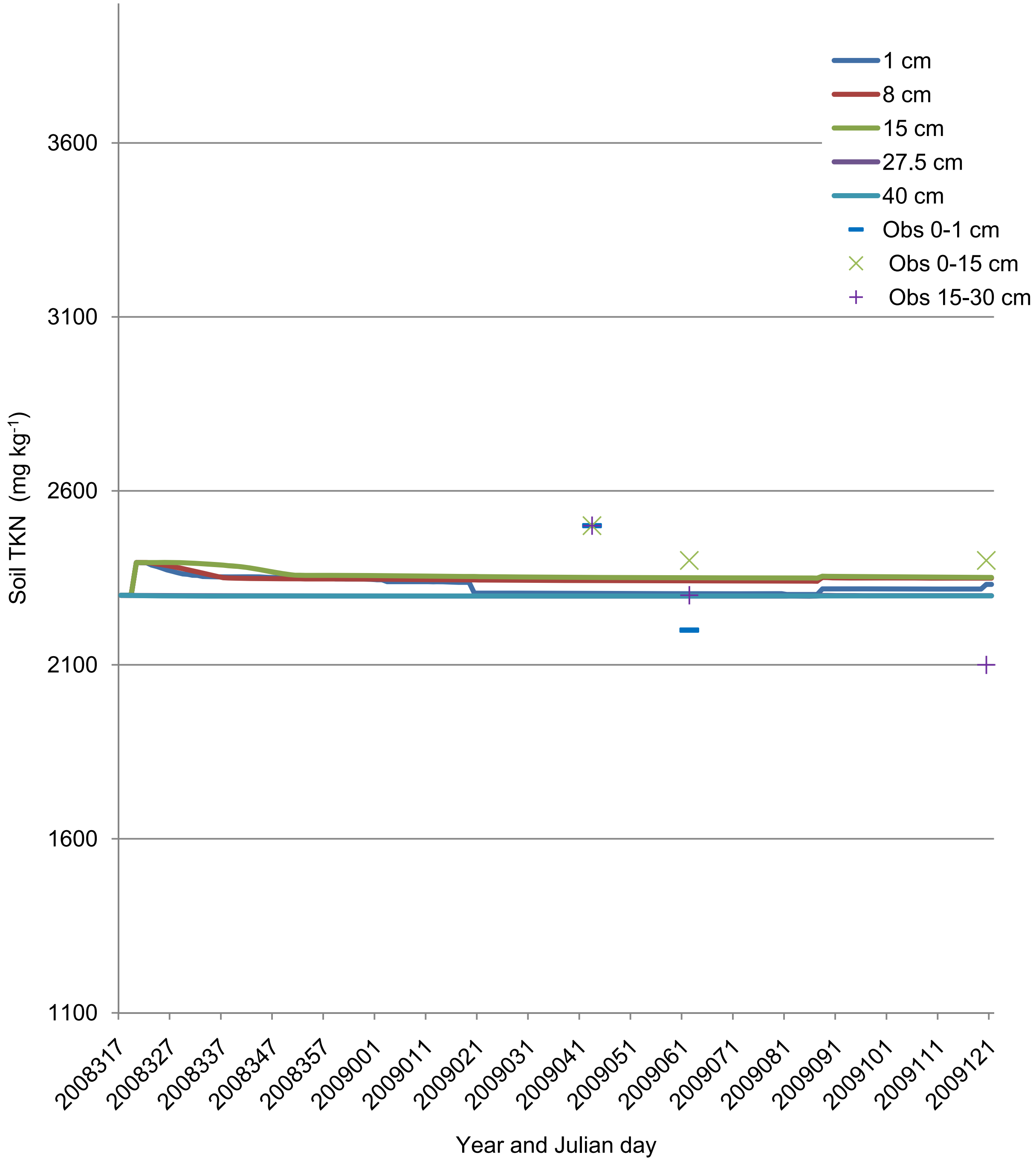

Figure 5.23 Site VF4 simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration prior to potato flowering, at potato flowering, and harvest.

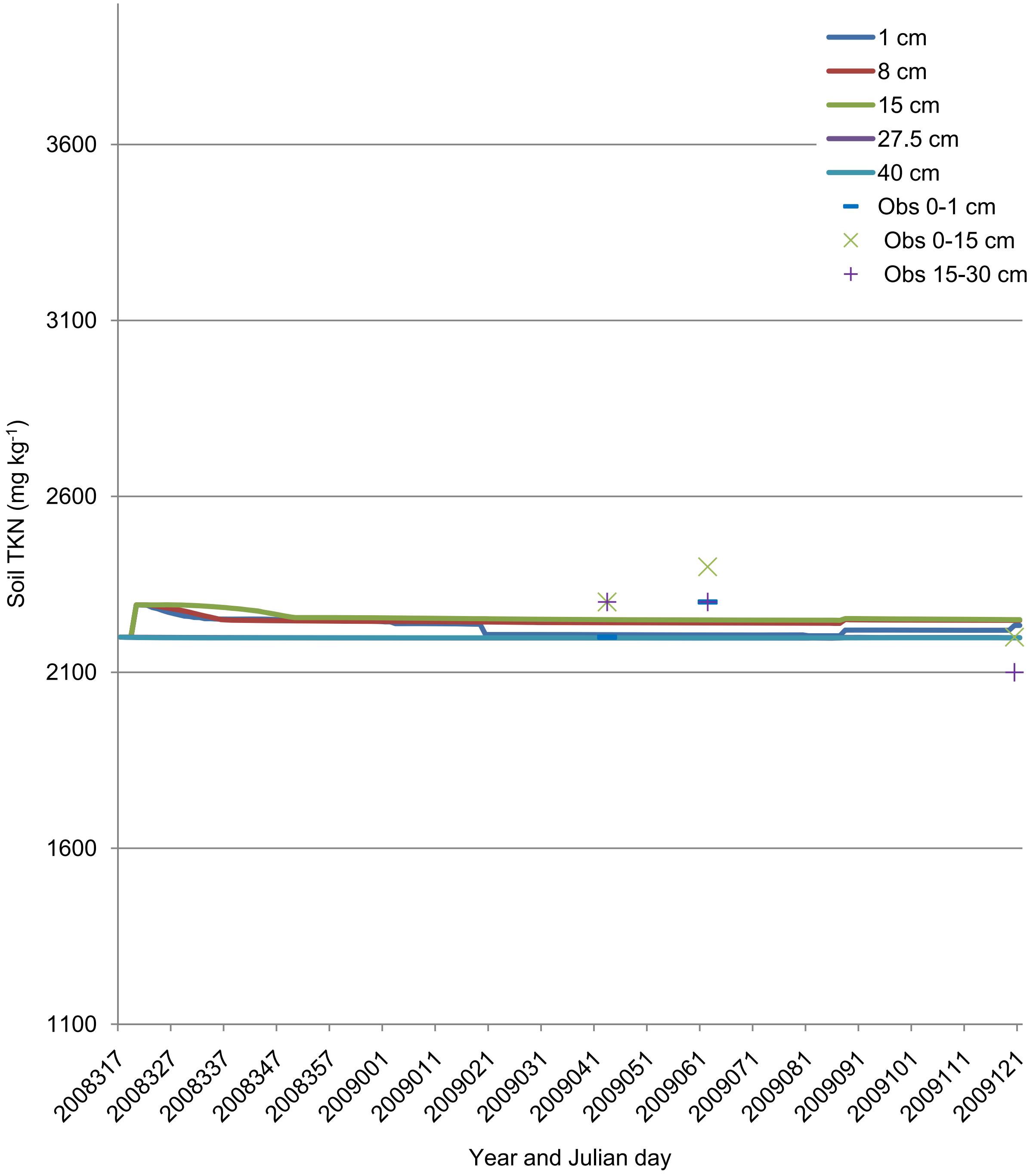

Figure 5.24 Site VF8 simulated daily soil TKN concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed TKN concentration prior to potato flowering, at potato flowering, and harvest.

Table 5.22 shows the observed and simulated TKN values used to compute RSR and PBIAS. The RSR and PBIAS for soil TKN concentration combining data from all sites were 3.0 and -2.2%, respectively.

Table 5.22 Observed and simulated soil TKN by site, crop event, and soil layer and overall computed root mean square error standard deviation ratio (RSR) and percent bias (PBIAS) for the two data sets.

Site	Crop event	Soil horizon	Soil TKN (mg ka^{-1})	
			Obs	Sim
CBJ	Flowering	Horz1	1400	1313
		Horz 2	1300	1297
	Harvest	Horz 1	1300	1316
		Horz 2	1200	1298
DMR	Flowering	Horz1	1500	1337
		Horz 2	1400	1297
	Harvest	Horz 1	1200	1339
		Horz 2	1200	1298
TTK	Flowering	Horz1	2700	2226
		Horz 2	2300	2198
	Harvest	Horz 1	1900	2230
		Horz 2	1900	2199
SAR	Flowering	Horz1	3300	2915
		Horz 2	3200	2797
	Harvest	Horz 1	2800	2926
		Horz 2	2700	2800
SAP	Flowering	Horz1	3200	3191
		Horz 2	2800	3097
	Harvest	Horz 1	2700	3191
		Horz 2	2400	3098
VF2	Pre-flower	Surface	2300	2502
		Horz 1	2200	2546
		Horz 2	2400	2498
	Flowering	Surface	2200	2502
		Horz1	2400	2545
		Horz 2	2200	2497
	Harvest	Horz 1	2300	2551
		Horz 2	2200	2499
VF4	Pre-flower	Surface	2500	2305
		Horz 1	2500	2344
		Horz 2	2500	2298
	Flowering	Surface	2200	2305
		Horz1	2400	2343
		Horz 2	2300	2297
	Harvest	Horz 1	2400	2349
		Horz 2	2100	2299

Table 5.22 (cont.)

VF8	Pre-flower	Surface	2200	2207
		Horz 1	2300	2243
		Horz 2	2300	2198
	Flowering	Surface	2300	2206
		Horz1	2400	2241
		Horz 2	2300	2197
	Harvest	Horz 1	2200	2248
		Horz 2	2100	2199
RSR				3
PBIAS				-2.2%

The simulated TKN concentrations fell within the range created by the observed data between flowering and harvest for all sites except VF2. The general trend observed was that the model under-predicted soil TKN at flowering and over-predicted soil TKN at harvest. All sites except for SAP and VF2 had an observed soil TKN concentration higher than the simulated peak soil N concentration which occurred after fertilization. This may have been in part because the soil TKN measurement taken from the furrow at potato flowering and used to initiate the soil TKN pool was under-estimated, in part due to mineralization and potential subsequent TKN reductions from the surface TKN concentration due to nitrification, NO_3^- leaching, volatilization and runoff between the time when the simulation started at planting and potato flowering when the samples were taken. It also may have been because the applied manure rate or manure total N content was under-estimated.

5.3.3 Crop production and nitrogen uptake

Figures 5.25-5.26 show the observed and simulated crop dry matter production and crop dry yield production, respectively. The model under-predicted crop dry matter production and yield for six of the eight simulations. The greatest discrepancy between observed and simulated crop dry matter production and yield occurred for the CBJ site. The model simulated much higher dry matter production for sites SAR and SAP than the observed values. This may have been due to the high fertilization rates at these sites, including the mineral fertilizer addition from DAP whose N addition did not have to undergo mineralization to become crop available. The predicted yield for each site as a function of predicted dry matter yield varied according to the dry matter ratio (*DMY*) input for each site according to the relative amounts of dry foliage production observed at frost and crop yield (shown in table 5.4). Sites that had low tuber yield in relation to measured foliage had a higher DMY input and so the simulated dry matter production and consequently predicted yield reflected this ratio. The DMR site had the lowest *DMY* (*DMY*=1.27) and so much closer values between total dry matter production and tuber yield production as opposed to the Villa Flores site (*DMY*=1.65) which showed a greater difference between simulated dry matter production and tuber yield.

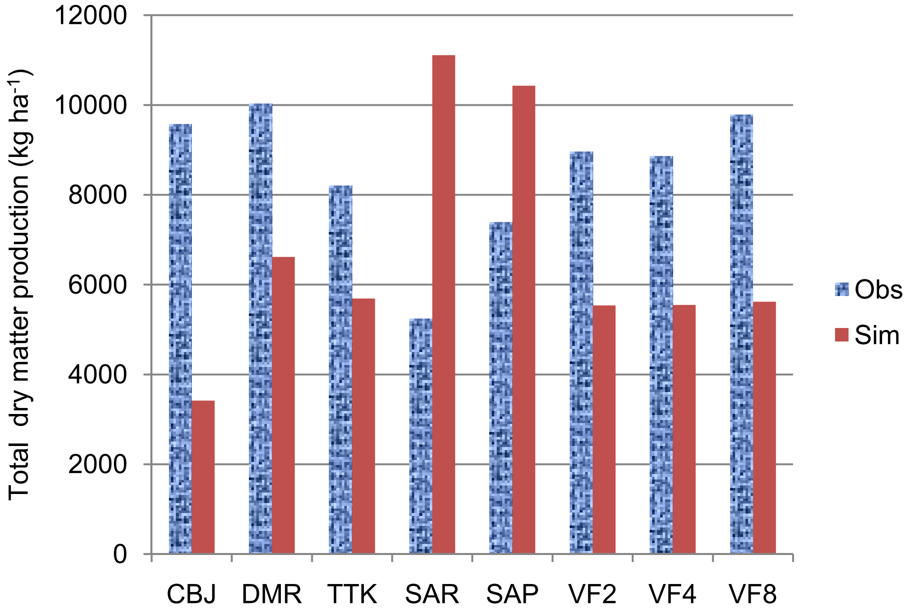

Figure 5.25 Observed and simulated total potato crop dry matter production for each site from 2008-2009 seasonal data.

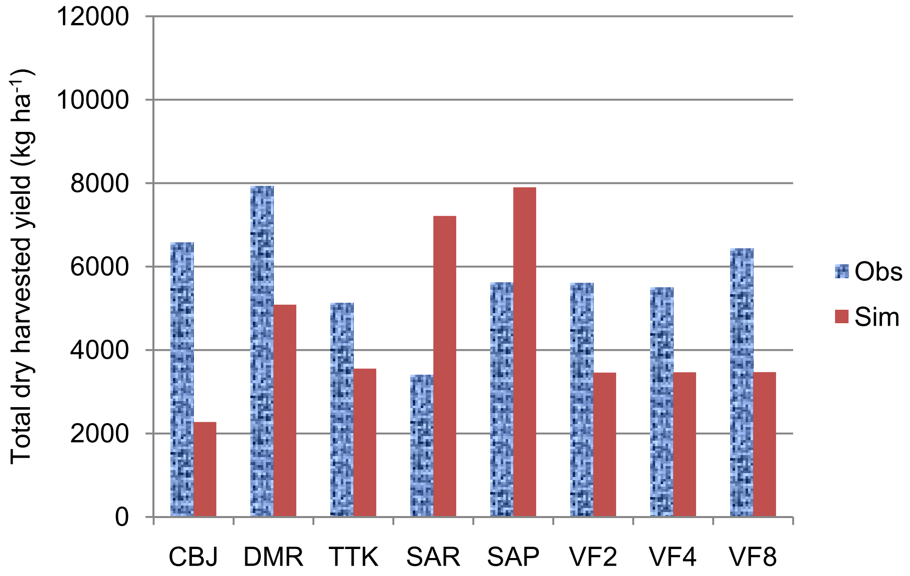

Figure 5.26 Observed and simulated dry harvested tuber yield for each site from the 2008-2009 seasonal data.

Figures 5.27-5.28 show the observed and simulated total crop N uptake and the yield N uptake (both dry basis). The model under-predicted the crop N uptake for seven of the eight simulations. The closest agreement occurred again for the SAR and SAP sites. This indicates that the simulated available N for crop uptake was not as limiting to crop growth at SAR and SAP compared to the other sites, possibly due to the high manure application rate and mineral fertilizer addition. The poor representation of N uptake observed for the other sites where most of the fertilizer N addition was from manure may be due to the model’s inadequacy in simulating N mineralization and thus crop availability.

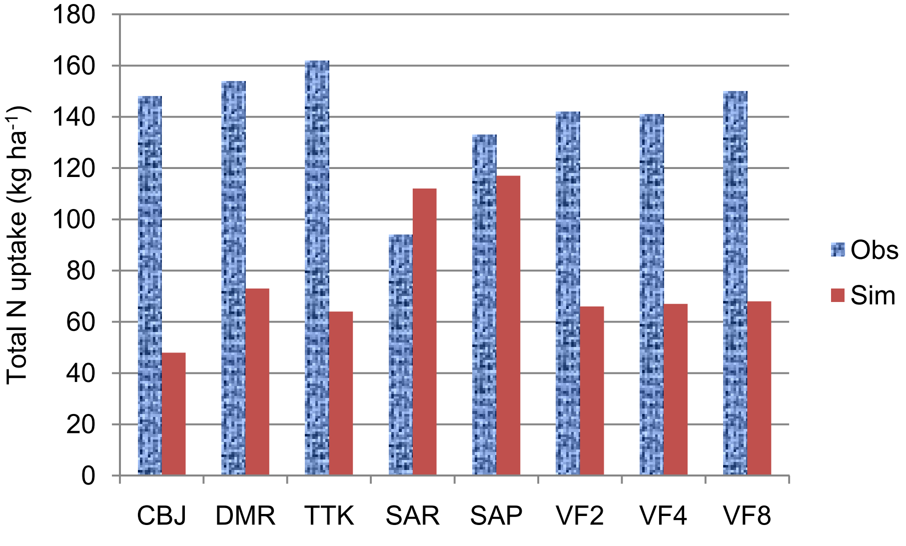

Figure 5.27 Observed and simulated total crop N uptake (dry basis) for all sites from the 2008-2009 seasonal data.

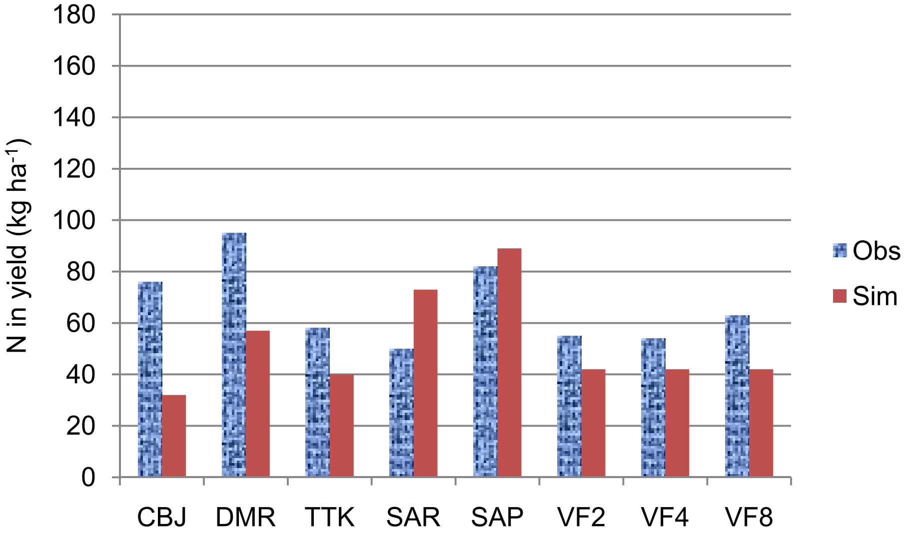

Figure 5.28 Observed and simulated N in tuber yield (dry basis) for all sites from the 2008-2009 seasonal data.

Table 5.23 shows the computed RSR and PBIAS values for total dry matter production, total dry harvested yield, total N uptake, and total N in yield. Observed and simulated agreement for total dry matter and total dry harvested yield were very similar since the simulated yield is directly related to the simulated dry matter through the input parameter *DMY*. Observed and simulated agreement for N in yield was better than for total N uptake. This may have been because the model under predicted the N content in the foliage that contributed to the total N uptake. Both RSR and PBIAS values appear undesirably high (RSR>3 and PBIAS>20%) suggesting that improved simulation of these parameters should be investigated further.

Table 5.23 Observed and simulated crop production and crop N uptake and corresponding RSR and PBIAS.

Site	Total dry matter (kg ha^{-1})		Total dry harvested yield (kg ha^{-1})		Total N uptake (kg ha^{-1})		N in yield (kg ha^{-1})	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
CBJ	9576	3416	6580	2277	148	48	76	32
DMR	10033	6617	7931	5090	154	74	95	57
TTK	8204	5689	5137	3556	162	64	58	40
SAR	5240	11110	3402	7214	94	112	50	73
SAP	7393	10430	5621	7901	133	118	82	89
VF2	8960	5538	5608	3461	142	67	55	42
VF4	8856	5547	5504	3466	141	67	54	42
VF8	9791	5620	6438	3470	150	68	63	42
RSR		7		6		10		4
PBIAS		21%		21%		45%		22%

5.4 Sensitivity analysis

Table 5.24 shows the relative sensitivity of selected model outputs to SCS curve number. Runoff volume and dissolved N in runoff were the output parameters most sensitive to curve number, though in consideration of other N losses, produced a very small proportion of the total N balance from the field. Percolation volume and N in percolation were negatively sensitive to increases in curve number. Nitrogen uptake was moderately sensitive at the lower curve numbers but was extremely sensitive as the curve number reached 95. Inconsistent model output (i.e. change in output increase/ decrease trend with successive increase of curve number) was observed for output parameters such as N percolation, volatilization, denitrification, and N uptake, especially at the highest curve number (99). Careful attention should be paid to model output when using such an extremely high curve number to assure that trends in model output are following expected behavior.

Table 5.24 Model output and relative sensitivity of simulated average annual output simulations to changes in SCS curve number.

Curve number	Runoff volume		Percolation volume		N runoff		N sediment	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
	(cm)		(cm)		(kg ha^{-1})		(kg ha^{-1})	
75	0.0036	7.42	1.1544	-0.63	0.0003	7.59	0.0780	7.63
80	0.0159	11.12	1.1475	-1.07	0.0018	11.78	0.4899	12.16
86$^+$	0.0711	-	1.0680	-	0.0103	-	3.2291	-
90	0.1754	31.57	0.9629	-2.12	0.0347	50.96	3.7166	3.25
95	0.5677	66.78	0.6412	-3.82	3.2726	3025.93	13.5210	30.46
99	1.7416	155.53	0.0980	-6.01	3.2726	2094.88	13.5210	21.08

$^+$ indicates base value.

Table 5.24 (cont.)

Curve number	N percolation		N volatilization		N denitrification		N uptake	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
75	39.3013	-0.31	10.0504	0.00	6.8345	0.08	105.1548	0.11
80	39.5673	-0.67	10.0466	0.00	6.6907	0.45	104.8167	0.24
86$^+$	37.8120	-	10.0497	-	6.9067	-	106.6201	-
90	35.7330	-1.18	10.0497	0.00	6.6832	-0.70	109.3551	0.55
95	6.3557	-7.95	10.0447	0.00	6.4940	-0.57	143.2649	3.28
99	6.3557	-5.50	10.0325	-0.01	4.7078	-2.11	143.2649	2.27

$^+$ indicates base value.

Table 5.25 shows the computed relative sensitivity of selected model outputs to rooting depth. Percolation volume, N in runoff, N in sediment, denitrified N, and N uptake were all moderately sensitive to sensitive to rooting depth. Percolation N was moderately sensitive to sensitive to rooting depth. Runoff volume and volatized N were generally insensitive to rooting depth. Inconsistent model output was observed for output parameters such as percolation volume, N in runoff, N in sediment, volatilization, and denitrification with increased rooting depth.

Table 5.25 Model output and relative sensitivity of simulated average annual output simulations to changes in rooting depth.

Rooting depth	Runoff volume		Percolation volume		N runoff		N sediment	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(cm)	(cm)		(cm)		(kg ha^{-1})		(kg ha^{-1})	
25	0.0702	0.03	1.3328	-0.66	0.0106	-0.08	3.7229	-0.41
35	0.0709	0.02	1.1467	-0.59	0.0105	-0.18	2.4569	1.91
40^{+}	0.0711	-	1.0680	-	0.0103	-	3.2291	-
45	0.0721	0.11	1.0786	0.08	0.0102	-0.06	2.0736	-2.86
55	0.0722	0.04	0.9375	-0.33	0.0110	0.17	2.0786	-0.95

$^{+}$ indicates base value.

Table 5.25 (cont.)

Rooting depth	N percolation		N volatilization		N denitrification		N uptake	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
cm	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
25	54.6614	-1.19	10.0496	0.00	6.7857	0.05	86.3171	0.51
35	42.3944	-0.97	10.0497	0.00	7.3081	-0.46	100.1459	0.49
40^{+}	37.8120	-	10.0497	-	6.9067	-	106.6201	-
45	33.4141	-0.93	10.0498	0.00	6.5287	-0.44	111.6140	0.37
55	26.4090	-0.80	10.0498	0.00	7.0085	0.04	118.7755	0.30

$^{+}$ indicates base value.

Table 5.26 shows the computed relative sensitivity of selected model outputs to soil porosity. Runoff volume, percolation volume, N in runoff, and N uptake were all moderately sensitive to changes in soil porosity. N in sediment and N denitrification were moderately sensitive to sensitive to changes in soil porosity. N uptake was extremely sensitive to soil porosity. Inconsistent model output was observed for N in runoff, N in sediment, and N in percolation with increases to soil porosity.

Table 5.26 Model output and relative sensitivity of simulated average annual output simulations to changes in soil porosity.

Porosity	Runoff volume		Percolation volume		N runoff		N sediment	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(cm^3cm^{-3})	(cm)		(cm)		(kg ha^{-1})		(kg ha^{-1})	
0.45	0.0805	-0.88	1.0597	0.05	0.0119	-1.01	2.2069	2.10
0.53$^+$	0.0711	-	1.0680	-	0.0103	-	3.2291	-
0.65	0.0631	-0.49	1.0876	0.08	0.0102	-0.04	1.9242	-1.78
0.70	0.0610	-0.44	1.0916	0.07	0.0115	0.35	1.9134	-1.27

$^+$ indicates base value.

Table 5.26 (cont.)

Porosity	N percolation		N volatilization		N denitrification		N uptake	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(cm^3cm^{-3})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0.45	35.4718	0.41	10.0447	0.00	8.2612	-1.30	108.9286	7.17
0.53$^+$	37.8120	-	10.0497	-	6.9067	-	106.6201	-
0.65	39.8927	0.24	10.0558	0.00	6.1962	-0.45	102.8318	-3.91
0.70	38.9226	0.09	10.0592	0.00	6.1753	-0.33	102.1768	-2.61

$^+$ indicates base value.

Table 5.27 shows the computed relative sensitivity of selected model outputs to dry potential yield. N in runoff was sensitive to extremely sensitive to changes in potential yield. N percolation, N denitrification, and N uptake were sensitive to potential yield when it was low (4000 kg ha^{-1}). All other tested N loss output parameters were insensitive to changes in potential yield. Inconsistent model output was observed for N in sediment with increases in potential yield.

Table 5.27 Model output and relative sensitivity of simulated average annual output simulations to changes in dry potential yield.

Potential yield	N runoff		N sediment		N percolation	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
4000	0.0269	-2.90	3.2414	-0.01	66.8385	-1.35
7000	0.0131	-1.23	3.2301	0.00	43.8539	-0.66
9000^{+}	0.0103	-	3.2291	-	38.2337	-
12000	0.0075	-0.83	3.2768	0.04	32.6709	-0.44
16000	0.0071	-0.39	3.4127	0.07	27.1089	-0.37

$^{+}$ indicates base value.

Table 5.27 (cont.)

Potential yield	N volatilization		N denitrification		N uptake	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
4000	10.0498	0.00	9.3755	-0.64	69.1548	0.63
7000	10.0498	0.00	7.5479	-0.42	98.9388	0.32
9000^{+}	10.0497	-	6.9067	-	106.6201	-
12000	10.0497	0.00	6.1559	-0.33	113.0673	0.18
16000	10.0496	0.00	5.4844	-0.26	119.6833	0.16

$^{+}$ indicates base value.

Table 5.28 shows the computed relative sensitivity of selected model outputs to chicken litter application rate. N in runoff, percolation N, and denitrification N were sensitive to extremely sensitive to changes in the manure application rate. Volatilization N and N uptake were also sensitive to manure application. Manure application rate was the only parameter of those included in the sensitivity analysis to which N volatilization was sensitive.

Table 5.28 Model output and relative sensitivity of simulated average annual output simulations to changes in dry chicken litter application.

Manure rate	N runoff		N sediment		N percolation	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
2	0.0061	0.58	3.2147	0.01	5.1391	1.23
6.7^{+}	0.0103	-	3.2291	-	38.2337	-
10	0.0229	2.49	3.4220	0.12	80.8902	2.27
16	0.0569	3.26	3.7266	0.11	170.7023	2.50

$^{+}$ indicates base value.

Table 5.28 (cont.)

Manure rate	N volatilization		N denitrification		N uptake	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
2	3.1855	0.97	1.1826	1.18	44.8690	0.83
6.7^{+}	10.0497	-	6.9067	-	106.6201	-
10	16.0458	1.21	14.2302	2.15	138.0765	0.60
16	25.6909	1.12	30.3830	2.45	156.4383	0.34

$^{+}$ indicates base value.

Table 5.29 shows the computed relative sensitivity of selected model outputs to initial soil organic matter. All the selected output parameters were insensitive to changes in initial soil organic matter. It was expected that N uptake, N in yield, and N mineralization would be more sensitive to the initial soil organic matter as mineralizing organic matter from the soil should increase available N for crop uptake. The insensitivity of crop production and uptake to this parameter may be an indicator of the model's inability to adequately represent N mineralization processes from the soil N pool.

Table 5.29 Model output and relative sensitivity of simulated seasonal yield and N parameters to changes in initial soil organic matter (OM).

OM	N uptake		Yield		N in yield	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(%)	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0.50	74	0.00	5090	0.00	57	0.00
1.00	74	0.00	5090	0.00	57	0.00
2.10^{+}	74	-	5090	-	57	-
3.00	74	0.00	5090	0.00	57	0.00
5.00	74	0.00	5090	0.00	57	0.00

$^{+}$ indicates base value.

Table 5.29 (cont.)

OM	N Mineralized		N Leached		N Denitrified		N Volatilized	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(%)	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0.50	81	0.00	49	0.00	4	0.00	11	0.00
1.00	81	0.00	49	0.00	4	0.00	11	0.00
2.10^{+}	81	-	49	-	4	-	11	-
3.00	81	0.00	49	0.00	4	0.00	11	0.00
5.00	81	0.00	49	0.00	4	0.00	11	0.00

$^{+}$ indicates base value.

Table 5.30 shows the computed relative sensitivity of selected model outputs to initial soil TKN. All the selected output parameters were insensitive to changes in initial soil TKN. It was expected that N uptake, N in yield, and N mineralization would be more sensitive to the initial soil TKN. The insensitivity to this parameter may also be an indicator of the model’s inability to adequately represent N mineralization processes from the soil N pool.

Table 5.30 Model output and relative sensitivity of simulated seasonal yield and N parameters to changes in initial soil TKN.

Initial TKN	N uptake		Yield		N in yield	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(%)	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0.05	74	0.00	5090	0.00	57	0.00
0.13^{+}	74	-	5090	-	57	-
0.20	74	0.00	5090	0.00	57	0.00
0.40	74	0.00	5090	0.00	57	0.00
0.70	74	0.00	5090	0.00	57	0.00

$^{+}$ indicates base value.

Table 5.30 (cont.)

Initial TKN	N Mineralized		N Leached		N Denitrified		N Volatilized	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(%)	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
0.05	81	0.00	49	0.00	4	0.00	11	0.00
0.13^{+}	81	-	49	-	4	-	11	-
0.20	81	0.00	49	0.00	4	0.00	11	0.00
0.40	81	0.00	49	0.00	4	0.00	11	0.00
0.70	81	0.00	49	0.00	4	0.00	11	0.00

$^{+}$ indicates base value.

Table 5.31 shows the computed relative sensitivity of selected model outputs to initial soil NO_3^-. All the output parameters were moderately sensitive to increases in soil NO_3^- except N volatilization. N percolation was the most sensitive output parameter to increases in initial soil NO_3^-.

Table 5.31 Model output and relative sensitivity of simulated seasonal yield and N parameters to changes in initial soil NO_3^- .

Initial NO_3^-	N uptake		Yield		N in yield	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(mg kg^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
1	69	0.08	4677	0.10	53	0.09
5$^+$	74	-	5090	-	57	-
10	80	0.08	5767	0.13	62	0.09
20	91	0.08	6984	0.12	70	0.08
100	140	0.05	8162	0.03	108	0.05

$^+$ indicates base value.

Table 5.31 (cont.)

Initial NO_3^-	N Mineralized		N Leached		N Denitrified		N Volatilized	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(mg kg^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
1	81	0.00	34	0.38	4	0.00	11	0.00
5$^+$	81	-	49	-	4	-	11	-
10	80	-0.01	67	0.37	5	0.25	11	0.00
20	80	0.00	103	0.37	7	0.25	11	0.00
100	80	0.00	433	0.41	26	0.29	11	0.00

$^+$ indicates base value.

Table 5.32 shows the computed relative sensitivity of selected model outputs to initial potentially mineralizable soil N. Overall, only N denitrification was moderately sensitive to initial potentially mineralizable soil N. It was not expected that output parameters such as N uptake, yield, and N in yield would decrease (albeit slightly) with increases to the soil potentially mineralizable N pool. This also may indicate the model's inability to represent N mineralization since it was expected that increased amounts of potentially mineralizable N in the soil would increase the N mineralization and become more available for crop uptake.

Table 5.32 Model output and relative sensitivity of simulated seasonal yield and N parameters to changes in initial soil potentially mineralizable nitrogen (POTMN).

POTMN	N uptake		Yield		N in yield	
	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
100	74	0.00	5179	-0.02	57	0.00
200	74	0.00	5100	0.00	57	0.00
361^{+}	74	-	5090	-	57	-
500	74	0.00	5090	0.00	57	0.00
700	73	-0.01	5090	0.00	56	-0.02

$^{+}$ indicates base value.

Table 5.32 (cont.)

POTMN	N Mineralized		N Leached		N Denitrified		N Volatilized	
	Output	Rel sens	Output	Rel sens	Output	Rel sens	Output	Rel sens
(kg ha^{-1})	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
100	80	0.02	50	-0.03	3	0.35	11	0.00
200	81	0.00	50	-0.05	3	0.56	11	0.00
361^{+}	81	-	49	-	4	-	11	-
500	82	0.03	48	-0.05	5	0.65	11	0.00
700	82	0.01	48	-0.02	6	0.53	11	0.00

$^{+}$ indicates base value.

Figure 5.29 shows the model response to increases in base temperature for N losses using annual averages from a 10-year simulation for the DMR site. Nitrogen uptake increased only slightly when the temperatures were increased from the base scenario. This may indicate that N mineralization and crop uptake may still be limited even in high temperatures, reflecting the insensitivity of the calculated ammonification amounts to the temperature factor for ammonification (*TFA*, equation 3.4) used by the model to determine ammonification amounts from soil organic N, organic N in crop residue, and organic N in animal waste (equations 3.2, 3.7, and 3.8).

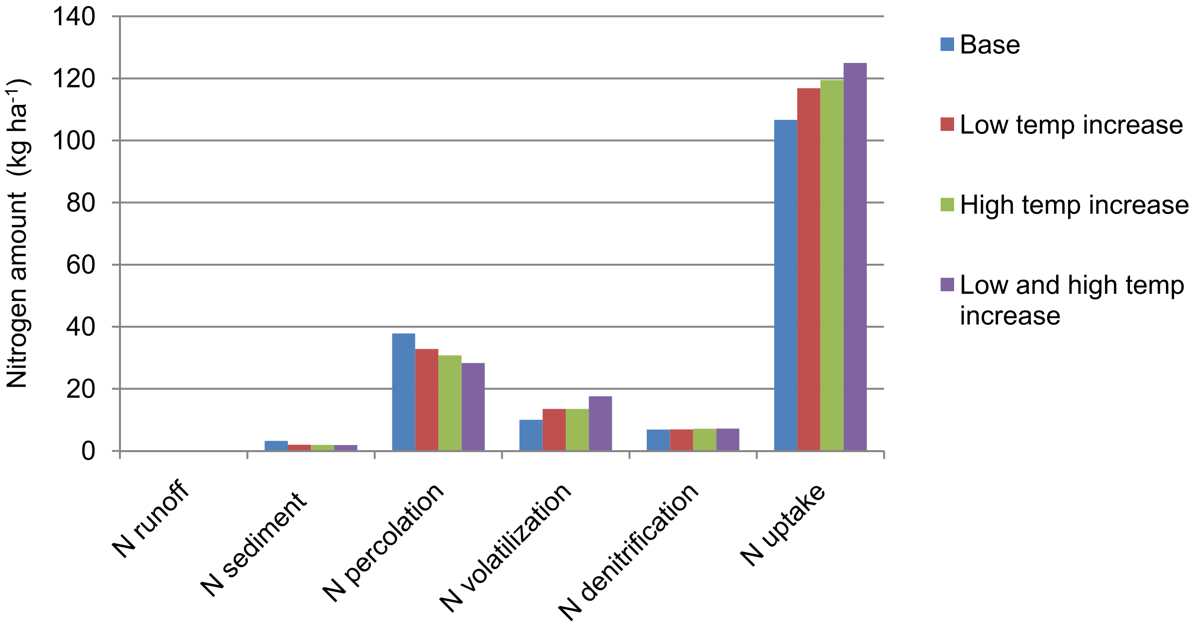

Figure 5.29 Model response to increases in base temperature values by 10°C.

In general, relative sensitivity of model outputs was greatest for hydrology input parameters, especially SCS curve number. Changes to the hydrology components demonstrated much more inconsistent output with regards to the sequential changes in model inputs than shown for changes to nutrient input components. N in sediment was the output parameter that had the highest occurrence of inconsistent trends with sequential changes to input parameters. It was determined that an exceptionally large simulated N sediment yield (15.97 kg ha^{-1}) was produced one year for the base simulations that skewed the average annual base output for this parameter. The insensitivity of crop production, crop N uptake, and N loss outputs to initial soil nutrient levels such as organic matter content, TKN concentration, and potentially mineralizable N does not seem representative of real world crop systems. The insensitivity is a reflection of the low mineralization rate used for the soil potentially mineralizable N pool. The low sensitivity of crop N uptake output to increases in temperature reflects the ammonification temperature factor used by the model for organic N mineralization.

Chapter 6. Summary, conclusion, and recommendations

The objective of this study was to assess the suitability of the GLEAMS model as a tool for evaluating fertilization and cropping system practices in the Jatun Mayu watershed area and to make recommendations for its continued development as an analysis tool. The model was evaluated by assessing the appropriateness of the model representation and behavior; through validation with observed data for runoff, soil TKN concentration, crop yield, and crop N uptake; and through sensitivity analysis.

6.1 Model representation and behavior

Certain representations of the potato fields by the GLEAMS model are not entirely appropriate for the sites in this study, such as the 2-D representation of the potato hill-furrow configuration and the model's inability to represent weed growth with the crop. Although these factors play a significant role in determining total N losses from the fields or final crop production for farms in central Bolivia, improvements in the representation for these characteristics may be beyond the scope of GLEAMS, due to the complexity of representing 3-D plant-soil systems and the dynamic interaction of N competition between weeds and the potato crop. Representation of banded manure application by specifying manure application as injection did not correctly partition the organic N addition from animal waste and so the selected application method chosen was incorporation to a 15 cm depth. This representation, however, may overestimate manure contents at the surface level and thus overestimate N losses through volatilization, leaching, and runoff.

In GLEAMS, N mineralization occurs from three soil N pools: soil organic N, animal waste organic N, and crop residue organic N. Crop dry matter production and N uptake are functions of user-specified coefficients in an exponential N uptake relationship that is dependent on accumulated LAI over the growing season and can be limited by water and N deficiencies. The model predicted negligible mineralization from the soil potentially mineralizable N pool which does not adequately reflect the actual mineralization that likely occurs in these systems. The low mineralization rate from this pool is due to an under-predicted mineralization constant (*CMN*) or a temperature factor (*TFA*) that limits mineralization at the temperatures observed at these sites. It is important that mineralization from the soil potentially mineralizable N pool is better represented because this is a primary nutrient input in the cropping systems in this region. Some farmers do not apply sufficient manure or fertilizer to correspond to the crop demand and so the mineralized N from the soil organic N pool is an important source of N for the crop.

6.2 Validation

Site specific data were collected from five potato plots independently managed by local farmers and one experimental site. The data were collected both to develop input parameter sets to run GLEAMS and to collect data with which to validate model output. Remaining input parameters were determined from farmer interviews, field observations, and guidance from the GLEAMS user manuals or published literature. Calibration of SCS curve number was completed so that of the tested curve numbers, the curve number with the lowest overall RSR between observed and simulated runoff volume was selected. This final calibrated curve number of 90 (RSR values of 4.0, 4.5, and 2.7 for VF2, VF4, and VF8, respectively) was used for subsequent simulations of the Villa Flores site. The PBIAS between the observed and predicted runoff volumes for the curve number 90 were 65%, 4%, and 55% for VF2, VF4, and VF8, respectively. As a limited data set was used to validate this component, the representation of runoff dynamics in these systems and their representation in GLEAMS should be evaluated further to possibly improve the model simulations. The knowledge gained by calibrating curve number at Villa Flores influenced the decision to increase the curve number to 86 from the base curve number of 82 for simulations of other sites.

The RSR and PBIAS between the observed and simulated soil TKN concentrations were 3.0 and -2.2%, respectively. These statistics represent reasonable simulation ability of GLEAMS for soil nutrient concentrations. Graphically, it could be seen that the simulated values generally follow the same declining soil TKN concentration trend over the growing season as observed from the field data. However, if the model process for mineralization from the soil potentially mineralizable N pool was modified, this would decrease simulated soil TKN levels over time which would better match the observed data.

The RSR and PBIAS between the observed and simulated crop total dry matter production were 7 and 21%. The RSR and PBIAS between the observed and simulated crop total dry harvestable yield production were 6 and 21%. The RSR and PBIAS between the observed and simulated crop total N uptake were 10 and 21%. The RSR and PBIAS between the observed and simulated yield N uptake were 4 and 22%. The simulated crop dry matter production and N uptake were under-predicted in all cases where manure was the only applied fertilizer source. The agreement between the observed and simulated values could be improved by better representation of mineralization from the soil potentially mineralizable N pool as reduced crop N uptake appears to be limited by lack of available N from this soil N component.

6.3 Sensitivity analysis

The sensitivity analysis demonstrated that model outputs for N transformations and losses have much higher relative sensitivities to changes to hydrology input parameters than nutrient input parameters. Model output did not always follow a consistent trend with sequential changes in input parameter and any user should be aware of this, especially when using extreme input values in the hydrology component. The seasonal model outputs of N losses and N uptake were not sensitive to initial soil organic matter, soil TKN, or soil potentially mineralizable N, which is not representative of crop systems with low applied N, as observed from some of the sites studied. This is another indication of the model’s under-representation of mineralization, especially from the soil potentially mineralizable N pool.

6.4 Conclusion and recommendations

The overall conclusion from this study is that improved representation of the mineralization component from the soil potentially mineralizable N pool should be completed and verified prior to using the GLEAMS model to compare farm management scenarios for central Bolivia. The organic N pool plays a very significant role in potato crop production systems in central Bolivia where there is little use of inorganic fertilizer thus crop yields are highly dependent on mineralization from applied manures and soil organic N. The following recommendations are made for improvement and further development of GLEAMS as an analysis tool for crop production and N losses to the environment from potato fields in central Bolivia:

- Improve the representation of N mineralization from soil potentially mineralizable N pool. The initial approach should be to assess appropriate values for the mineralization rate constant (*CMN*) and evaluate the exponential equation that defines the temperature factor (*TFA*).
- Validate percolation volume and NO_3^- leached with field data from the area. The high NO_3^- leaching losses simulated in this study represent a high proportion of the total N budget and so should be confirmed before using the model to predict other output parameters highly dependent on percolation volume (i.e., crop N uptake and N losses to the environment).
- Review the model code to determine why the injection manure application method improperly partitions the soil organic N from animal waste immediately to the soil potentially mineralizable N pool. If the injection method were functioning correctly, it would better represent the banded manure application practiced by the farmers in central Bolivia, and the affected N dynamics of the potato fields.
- Verify model output for general expected trends and partitioning to expected soil N pools. Blatant errors in printed output have been observed for certain simulation scenarios, but a general pattern or cause has not been established.

GLEAMS has the potential to simulate a broad range of climate, environmental, and management factors over time through its support for complex representation of agricultural systems. Once the recommendations presented here are met, not only will the GLEAMS model better represent the scenarios seen in central Bolivia, but increased understanding of the agricultural systems observed will assist in building knowledge necessary to improve crop yields sustainably for the communities located there.

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Appendix A. Centro de Investigacion Agricola Tropical (CIAT) laboratory methods

RESUMEN DE METODOS ANALITICOS DE SUELOS

LABORATORIO CIAT (C. Herrera y M. Paz, 2005)

Soil analysis

Ph : método del ph-metro .- lectura directa en una solución suelo: agua; 1:5 (rutina)

Fósforo Disponible: método de Olsen Modificado.- se usa NaCO3 0,5M como extractor en presencia de molibdato de amonio, tartrato de antimonio, ácido sulfúrico y ácido ascórbico, se lee directamente en fotocolorimetro a 882 nm

Materia Orgánica: Por el método de Walkley y Black, se lee en colorímetro directamente el sobrenadante de la digestión húmeda de suelo con ácido sulfúrico concentrado, dicromato de sodio y agua destilada.

Nitrógeno Total: método de microkeldajhl.-titulación con un ácido de baja concentración, de un extracto de suelo-ácido sulfúrico, sulfato de litio y peroxido de hidrogeno en presencia de Na OH 5N y H3BO3 1%, la lectura resultante es el resultado directo de N Total (%.

Textura : método de Bouyoucos modificado.-con una lectura de Hidrómetro en la solución suelo: hexametafosfato de sodio, agua destilada después de 6 horas se cuantifica arcilla (%) y por tamizado obtenemos arena, el limo se calcula por diferencia.

Retención de Humedad (C.C. 0.33 bar;P.M.P. 15 bares): en equipo de platos, ollas de presión, compresora y manómetros.

Plant and manure analysis

Nitrogeno Total (%): metodo microkeldajhl modificado; se digestiona la muestra con acido sulfurico, y en el extractante que resulta se titula la muestra con un acido de baja normalidad, de la lectura se calcula el nitrogeno.

Fosforo Total (%) : metodo Truog; la muestra se digestiona de la misma manera que para nitrogeno pero en el extracto se aplica el metodo del azul de molibdato y se lee en fotocolorimetria.

Potasio Total (%) : metodo de calcinacion; la muestra se incinera y de la ceniza resultante se cuantifican los minerales, entre ellos el potasio usando el fotometro de llama.

Appendix B. GLEAMS input documentation

B.1 Hydrology

HBDATE- Beginning simulation date

The beginning day and year for the model evaluation simulations to compare with observed data began one day before planting for each site (October-November depending on the site).

FLGPEN- Evapotranspiration formula flag

The Penman-Monteith method was selected since it was more descriptive than the Priestly-Taylor method for the stages when the soil was bare or had little crop canopy and because it includes an aerodynamic term which better describes ET patterns in the Andes (Garcia et al., 2004).

IBACK()- Selected variable output

The outputs that were selected to compare with measured data for model evaluation were TKN concentration by soil layer (code 958) and total PO_4 concentration by soil layer (code 961). The model predictions for seasonal total yield and N and P in yield were taken from the standard nutrient output produced when running the N component in GLEAMS. The simulations of the Villa Flores site for validation also had additional outputs of daily runoff (code 2). Additional soil N amounts (kg ha^{-1}) outputs including NO_3^- (950), NH_4^+ (955), TKN (957), organic N from crop residue (965), and organic N from animal waste (966), soil active N (potentially mineralizable N) (975), and stable N (976) where produced.

DAREA- Total drainage area

The total drainage area (ha) was calculated from each field perimeter recorded with a GPS unit tracking function.

RC- Effective saturated hydraulic conductivity

The effective saturated hydraulic conductivity (cm hr^{-1}) directly below the root zone was estimated at 0.5 cm hr^{-1} according to recommendations by the University Mayor de San Simon soils laboratory.

BST- Plant available water in soil at simulation start

The fraction of plant available water in the soil at the simulation start was selected as 10% of the plant available water (i.e., 10% of the water content difference between field capacity and permanent wilting point for each soil). This water content was selected since the simulation start was just before planting which occurred at the end of the dry season when the soil water content was assumed to be very low.

CONA- Soil evaporation parameter

The soil evaporation parameter dependent on texture was selected according to the value listed for each textural class (silt loam, CONA=4.5) in Table H-3 in the GLEAMS hydrology user manual (Knisel and Davis, 1999)

CN2- Curve number

The hydrologic soil group (C) was determined primarily according to soil texture (silt loam for all sites for the upper soil horizon with no observed underlying drainage impediments). The base SCS curve number for hydrologic soil condition II was selected as the median value for soil hydrologic group C for a good (non-compacted) surface with contoured row crops (CN = 82). The Villa Flores calibration of curve number using runoff data resulted in a higher curve number than the base to be used in the validation model runs (curve number = 90 for Villa Flores and curve number = 86 for all other sites).

CHS- Hydraulic slope of field

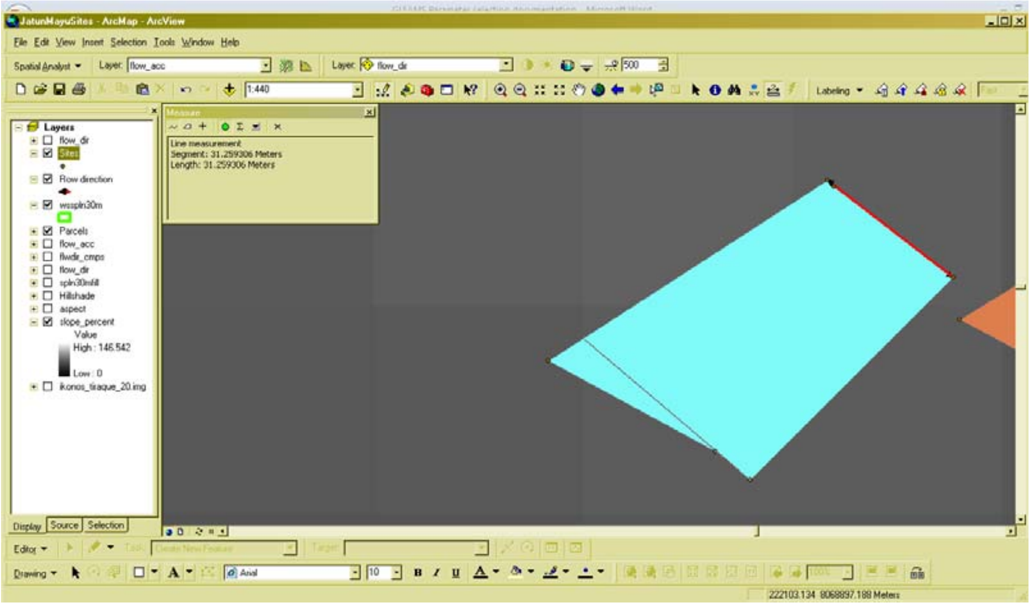
The hydraulic slope of the field was

$$CHS = \frac{ELEV_{mx} - ELEV_{mn}}{LFP} \quad \text{(B.1)}$$

Where CHS = hydraulic slope of field
$ELEV_{mx}$= maximum elevation (m)
$ELEV_{mn}$= minimum elevation (m)
LFP= longest flow path (m).

Maximum difference in elevation was the elevation at the most remote point in the field minus the elevation at the outlet point. The longest flow path was the flow distance from the most remote point to the outlet. Because the potatoes were hilled along the contour in all of the sites, the maximum difference in elevation considered the difference between the uphill portion of the row and the outlet at the opposite end of the row. The flow was assumed to go from the top of the potato hill into the furrow and flow downhill until the outlet at the field edge, and so the row length was considered the maximum flow path. Figure B.1 shows an example of the two points used to calculate difference in elevation and the arrow to represent the longest flow path down the row in a field on a slope. The elevation for each corner of the field was determined from a GPS unit. The longest flow path was measured as the two points furthest from each other on either side of the field in the direction of the row. The measurement was done in a GIS and an example is shown in figure B.2

Figure B.1 Example of the points used to determine the elevation difference and the length of the longest flow path (arrow shown down the potato row) to calculate *CHS*.



Line measurement
Segment: 31.259306 Meters
Length: 31.259306 Meters

Figure B.2 Example of distance tool used to measure *LFP* in a GIS. The parcel was delineated from points taken with a GPS unit and the row direction shown with the red arrow was the same direction used to measure the *LFP* in the parcel.

WLW- Watershed length width ratio

The watershed length:width ratio was calculated according to the GLEAMS hydrology user manual (pg 27, Knisel and Davis, 1999) for ridge-furrow systems as

$$WLW = \frac{LFP^2}{DA\ x\ 10{,}000} \tag{B.2}$$

Where *WLW*= watershed length:width
DA = overland drainage area (ha).

The longest flow path was the same row length used above for *CHS*. The flow path drainage area was the row spacing (top of hill to next top of hill) by the row length. Figure B.3 shows an example of the row spacing measurement and the flow path length used to calculate the flow path drainage area needed for WLW. Both the *CHS* and WLW parameters were not updateable in GLEAMS and were chosen to represent the field when the potato hills were present since this represented the majority of the simulated time period.

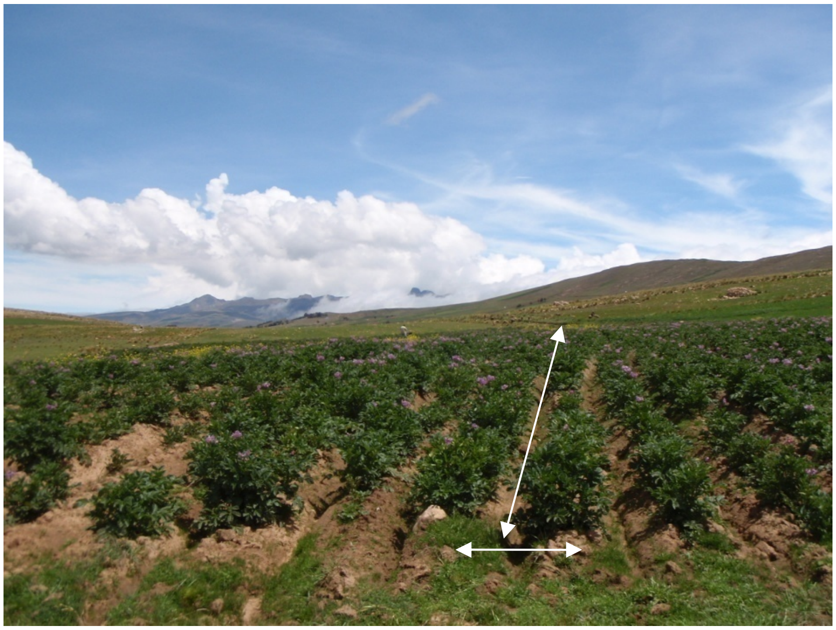


Figure B.3 An example of the measurements used to calculate the *WLW* ratio. The long arrow represents the row length used to define *LFP* and the horizontal arrow represents the row spacing used to *DA*.

RD- Rooting depth

The GLEAMS hydrology user manual (pg 28, Knisel and Davis, 1999) describes the RD as the depth to the bottom of the horizon where most common roots are found and above that where many fine roots were found. The effective rooting depth (cm) observed at the field sites was 40 cm.

ELEV- Mean outlet elevation and LAT- Mean outlet latitude

The mean elevation (masl) and latitude (degrees) of the field outlet were determined using a marked GPS point for the lowest corner end row for each site.

ISOIL- Soil sorption phosphorus

The soil sorption condition was selected as slightly weathered (code 2) for all sites and soil layers in the study because local agronomists described the soil as neither calcareous nor highly weathered.

NOSOHZ- Number of soil horizons and BOTHOR()- Depth to bottom of horizon

The number of soil horizons simulated in the model was selected as two to correspond with the soil sampling depth levels (0-15 cm for top portion of hill and 15-30 cm for bottom). The soil depth to the bottom of each soil horizon (BOTHOR) was a modified depth of the sampling depth. The GLEAMS defined soil horizons and depths were horizon 1 (0-15 cm) and horizon 2 (15-30 cm). Simulated horizon 1 output was compared to sampled data from the 0-15 cm portion of the hill and horizon 2 to the 15 - 30 cm portion of the hill, according to figure B.4.

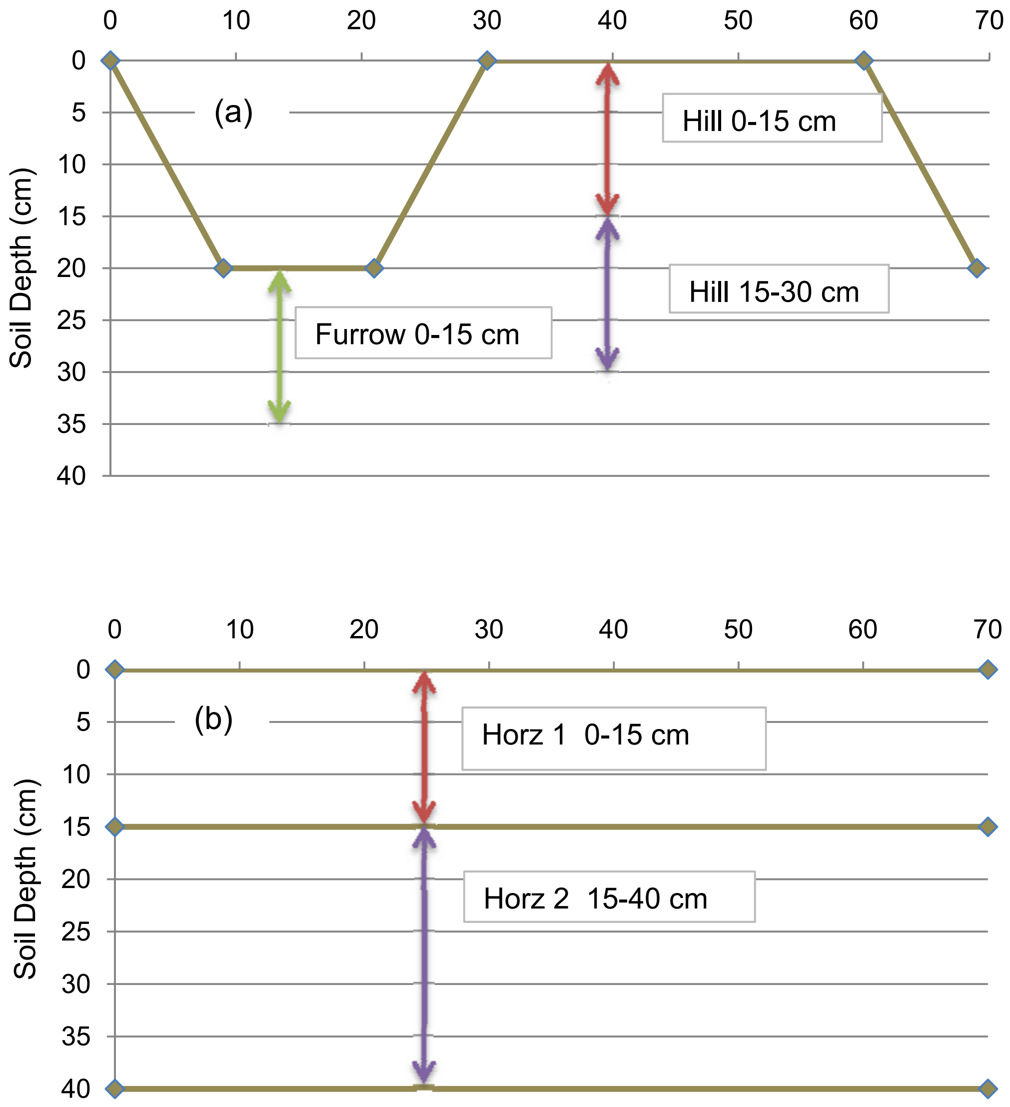


Figure B.4 The soil sampled layers (a) and the GLEAMS represented layers (b) for the potato systems.

POR()- Soil porosity

The soil porosity (cm^3 cm^{-3}) for each horizon was inferred from the bulk density measurements for each soil layer, assuming that the average soil particle density in the soil was 2.65 g cm^{-3}, from the following equation,

$$POR = 1 - \frac{BD}{2.65} \tag{B.3}$$

Where POR=porosity (cm^3 cm^{-3})
BD= bulk density (g cm^{-3}).

FC() – Field capacity and BR15()- Wilting point

The field capacity and wilting point fractions (cm cm^{-1}) for each soil layer were according to the values from the soil analysis. The soil analysis reported gravimetric percent moisture content at 0.33 bars and 15 bars for field capacity and wilting point, respectively. The percentage was multiplied by the soil bulk density to get the volumetric content (cm cm^{-1}) according to the hydrology user manual (pg 30, Knisel and Davis, 1999). It was realized that for two sites (CBJ and SAP) their base wilting points prevented the model from simulating mineralization of organic N from the manure application. This undesirable representation was avoided by using the wilting point at DMR for CBJ and at SAR for SAP.

SATK() – Saturated hydraulic conductivity

The saturated hydraulic conductivity (cm hr^{-1}) for each soil layer was estimated as the same as RC (0.5 cm hr^{-1}).

OM() – Organic matter % and pH()- pH

The initial values for organic matter content and pH when the simulation began at planting (just prior fertilization) were estimated based on the soil analysis values for the 0-15 cm furrow for each plot sampled at the flowering stage. Since the fertilizer was band applied into the potato hill and this is where the potato growth occurred, the furrow portion of the field was assumed to have similar soil chemical properties as the field prior to planting which is why the properties from this location were used for the initial values.

BSAT() - Base saturation %

The BSAT for all layers at all sites was estimated as 69% according to measurements taken at the Toralapa Research Station, Cochabamba, Bolivia (Devaux et al., 1997).

CLAY() - Clay percent % and SILT()- Silt %,

CLAY and SILT percentages were according to percentages reported from the soil analysis.

TEMPX() -Mean monthly maximum temperature, TEMPN()- Mean monthly minimum temperature, and RAD()-mean monthly solar radiation

Temperature (deg C) and solar radiation data (MJ m^{-2} d^{-1}) from a weather station at the Toralapa Station were used for model evaluations for sites in the middle zone (CBJ and DMR). Temperature data were taken from a weather station in Sankayani Alto for the sites in the upper zone (TTK, SAR, SAP, and Villa Flores). Solar radiation data from the Toralapa Research Station were used for the sites in the upper zone.

WIND() and DEWPT()- Mean monthly wind speed and dew point temperature

Wind speed and dew point were estimated from suggestions from Allen et al. (1998). This was 172.8 km d^{-1} average wind speed. The dew point estimation was the same as the minimum mean monthly temperature as suggested for humid/sub-humid locations.

HBYR- Hydrology simulation year start

The hydrology simulation year start was selected as the same as the simulation start 2008 for the model evaluation.

HEYR- Hydrology simulation year end

The hydrology simulation year end was selected as 2009 for model evaluation to correspond to the end of the growing season for the period of data collection.

IROT- Years in rotation cycle

The number of years in the rotation cycle was selected as two for the potato season. Two years were selected since the planting occurred at the end of one calendar year and the harvesting in the first half of the second year.

ICROP- Crop code

The crop code selected for the model evaluation simulations was user defined (code 79) for potato so that the leaf area index reported in literature for the Andean Waycha potato variety (Condori et al., 2008), could be utilized, which differed from the model's internal database for Irish potato.

DPLANT- Planting date and DHRVST- Harvest date

Absolute dates for planting and harvesting were taken from farmer interviews or field observations. Each site had frost damage which killed most of the potato foliage or as typical practice, had the foliage cut 1-4 weeks prior to harvest to allow the potato skin to cure. In these cases, the DHRVST entered in the model was the frost damage or foliage cut date since this was the date when the crop ceased to grow, perform transpiration, and uptake nutrients. The dates were converted and entered as Julian days in the specific rotation year. Planting was typically in October-November of rotation year 1 and frost damage/foliage cut was typically in February-March of rotation year 2. The day of frost or foliage cutting was set as DHRVST in GLEAMS rather than a truncation date, DTRUNC, because it was not desired that GLEAMS continued simulating crop “growth” and leaf area index (LAI) accumulation up until the actual day of crop harvest.

CCRD- Crop rooting depth, CRPHTX- Maximum crop height

Root lengths were measured for each site, though accurate measurements of the root lengths were difficult because the roots were thin and tended to break. The range of max root lengths between the sites was 25-40 cm and so the root length entered for each site was 30 cm. The maximum crop height was 0.60 m.

NOLAI- Number of LAI points, USRFRC- Fraction of growing season for defined LAI, USRLAI- LAI at specified fraction of growing season

The user-defined crop code of 79 for potato required the definition of leaf area index (LAI, m^2 m^{-2}) throughout the growing season. Ten points were used to define the LAI based on a study on Andean tubers including the Waycha variety grown at all sites (Condori et al., 2008). The LAI values and fraction of growing season entered in GLEAMS were adjusted from the values reported in Condori et al. (2008) to account for the growth halt due to frost when there was still significant LAI. Point number, fraction of growing season, and measured LAI entered in GLEAMS are shown in table B.1. Figure B.5 shows the LAI graphically as reported by Condori et al. (2008) as well as the default LAI for the GLEAMS internal database for Irish potatoes.

Table B.1 Number of LAI points, fraction of growing season, and measured LAI (m^2 m^{-2}) derived from Condori et al. (2008) and input in GLEAMS for the Andean potato variety Waycha grown at all the study sites.

Point number	Fraction of growing season	LAI
1	0.00	0.00
2	0.36	0.35
3	0.43	0.70
4	0.50	1.35
5	0.57	2.00
6	0.64	3.00
7	0.71	3.50
8	0.79	3.90
9	0.86	3.90
10	1.00	2.35

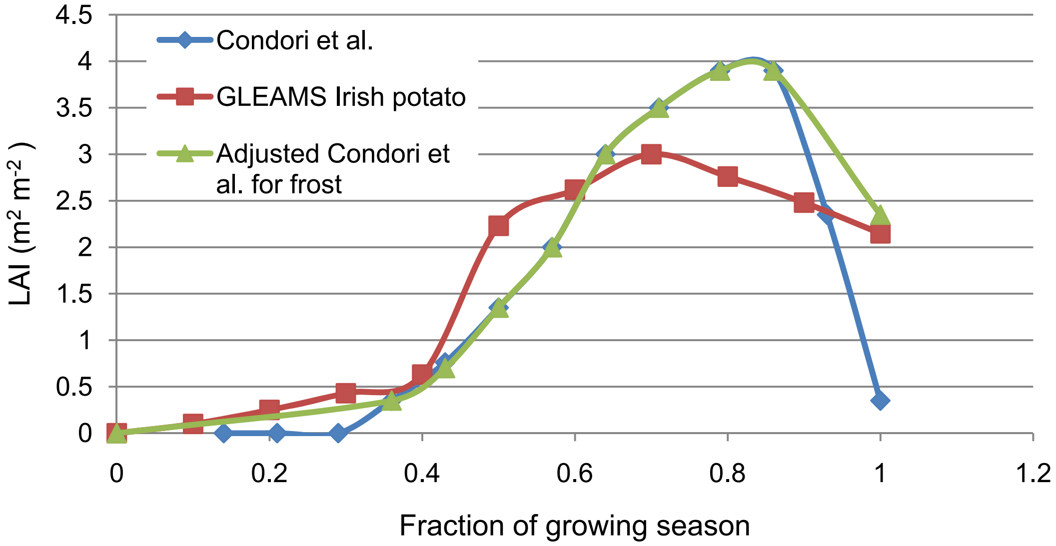


Figure B.5 LAI (m^2 m^{-2}) over growing season as reported in Condori et al. (2008) for the Andean potato variety Waycha , the GLEAMS default values for Irish potatoes, and the adjusted Condori et al. (2008) for frost used in the simulations.

Perennial crops, forest cover, irrigation, and annual updates of mean monthly weather data were not considered for the model evaluation or subsequent simulations. Tables B.2 and B.3 summarize most of the hydrology input parameters entered for each site.

Table B.2 Hydrology input parameters for sites CBJ, DMR, and TTK.

Parameter	Description	Site		
		CBJ	DMR	TTK
HBDATE	start date	2008313	2008288	2008309
HYDOUT	code for level of output	0	0	0
FLGPEN	code ET method	1	1	1
FLGNUT	code for nutrients	1	1	1
FLGPST	code for pesticides	0	0	0
FLGGEN	code min/max temp gen.	0	0	0
FLGMET	code english/metric	1	1	1
FLGTMP	code read mean daily temp	0	0	0
BCKEND	code selection of output variables	1	1	1
FOREST	code ag/forestry	0	0	0
IBACK()	output variable selection	958, 961	958, 961	958, 961
DAREA	drainage area	0.5843	0.4142	0.2532
RC	effective sat. of soil hz below root zone	0.5	0.5	0.5
BST	initial plant available water	0.1	0.1	0.1
CONA	soil evap parameters	4.5	4.5	4.5

Table B.2 (cont.)

Parameter	Description	Site		
		CBJ	DMR	TTK
CN2	SCS CN for MCII	86	86	86
CHS	hydraulic slope of field	0.037	0.022	0.013
WLW	ratio of field length:width	88.52	69.23	114.93
RD	effective rooting depth	40	40	40
ELEV	mean elevation of outlet	3554	3575	3784
LAT	latitude (deg)	-17.48	-17.48	-17.45
ISOIL	soil P sorption	2	2	2
NOSOHZ	number of soil horz	2	2	2
	horz- depth to bottom			
BOTHOR(I)	1	15	15	15
	2	40	40	40
	horz- porosity for each horz			
POR()	1	0.56	0.53	0.55
	2	0.56	0.53	0.55
	horz- field capacity			
FC()	1	0.18	0.18	0.29
	2	0.18	0.18	0.29
	horz- wilting point			
BR15()	1	0.09	0.07	0.15
	2	0.09	0.07	0.15
	horz- saturated hydraulic conductivity			
SATK()	1	0.5	0.5	0.5
	2	0.5	0.5	0.5
	horz- organic matter			
OM()	1	2.0	2.1	2.0
	2	2.0	2.1	2.0
	horz percent clay			
CLAY()	1	20	21	20
	2	20	21	20
	horz-percent silt			
SILT()	1	50	57	61
	2	50	57	61
	horz-pH			
pH()	1	6.1	5.3	5.2
	2	6.1	5.3	5.2
	horz-base saturation			
BSAT()	1	69	69	69
	2	69	69	69
HBYR	beginning year of hyd sim	2008	2008	2008
HEYR	ending year of hyd sim	2009	2009	2009

Table B.2 (cont.)

Parameter	Description	Site		
		CBJ	DMR	TTK
IROT	number of years in rotation	2	2	2
ICROP	code crop	79	79	79
DPLANT	date of planting crop	1314	1289	1310
DHRVST	date of harvest	2074	2074	2074
CCRD	crop rooting depth	30	30	30
ICROP	if crop is not in database and must enter LAI	79	79	79
NOLAI	number of points to describe LAI	10	10	10

Table B.3 Hydrology input parameters for sites SAR, SAP, and Villa Flores.

Parameter	Description	Site				
		SAR	SAP	Villa Flores		
				VF2	VF4	VF8
HBDATE	start date	2008274	2008274	2008318		
HYDOUT	code for level of output	0	0	0		
FLGPEN	code ET method	1	1	1		
FLGNUT	code for nutrients	1	1	1		
FLGPST	code for pesticides	0	0	0		
FLGGEN	code min/max temp gen.	0	0	0		
FLGMET	code english/metric	1	1	1		
FLGTMP	code read mean daily temp	0	0	0		
BCKEND	code selection of output variables	1	1	1		
FOREST	code ag/forestry	0	0	0		
IBACK()	output variable selection	958, 961	958, 961	2, 958,961		
DAREA	drainage area	0.2244	0.146	0.001		
RC	effective sat. of soil hz below root zone	0.5	0.5	0.5		
BST	initial plant available water	0.1	0.1	0.1		
CONA	soil evap parameters	4.5	4.5	4.5		
CN2	SCS CN for MCII	86	86	86		
CHS	hydraulic slope of field	0.048	0.032	0.0002		
WLW	ratio of field length:width	58.33	46.01	3.34		
RD	effective rooting depth	40	40	40		
ELEV	mean elevation of outlet	4036	4026	3971		
LAT	latitude (deg)	-17.45	-17.45	-17.43		
ISOIL	soil P sorption	2	2	2		
NOSOHZ	number of soil horz	2	2	2		
	horz- depth to bottom					
BOTHOR(I)	1	15	15	15		
	3	40	40	40		

Table B.3 (cont.)

Parameter	Description	Site				
		SAR	SAP	Villa Flores		
				VF2	VF4	VF8
	horz- porosity for each horz					
POR()	1	0.68	0.63	0.63	0.61	0.60
	2	0.68	0.63	0.63	0.61	0.60
	horz- field capacity					
FC()	1	0.26	0.26	0.24		
	2	0.26	0.26	0.24		
	horz- wilting point					
BR15()	1	0.12	0.13	0.10		
	2	0.12	0.13	0.10		
	horz- saturated hydraulic conductivity					
SATK()	1	0.5	0.5	0.5		
	2	0.5	0.5	0.5		
	horz- organic matter					
OM()	1	2.5	2.7	2.3	2.2	2.0
	2	2.5	2.7	2.3	2.2	2.0
	horz-percent clay					
CLAY()	1	15	15	15		
	2	15	15	15		
	horz-percent silt					
SILT()	1	61	58	52		
	2	61	58	52		
	horz-pH					
pH()	1	5.5	5.1	5.4	5.6	5.3
	2	5.5	5.1	5.4	5.6	5.3
	horz-base saturation					
BSAT()	1	69	69	69		
	2	69	69	69		
HBYR	beginning year of hyd sim	2008	2008	2008		
HEYR	ending year of hyd sim	2009	2009	2009		
IROT	number of years in rotation	2	2	2		
ICROP	code crop	79	79	79		
DPLANT	date of planting crop	1275	1275	1319		
DHRVST	date of harvest	2074	2074	2088		
CCRD	crop rooting depth	30	30	30		
ICROP	if crop is not in database and must enter LAI	79	79	79		
NOLAI	number of points to describe LAI	10	10	10		

B.2 Erosion

FLGSEQ- Erosion sub-module sequence

Overland-channel flow characteristics (code 3) were chosen to describe the runoff flow from all sites. The overland flow refers to water running off the potato hill and down the side slopes into the center of the furrow. The channel refers to the furrow that runs between the hills and exits the side of the parcel into the surrounding field or grass border. Figure B.6 depicts examples from three sites for overland-channel characterization.

Figure B.6 Examples from three sites (from left to right, CBJ, SAP, TTK) of the potato hill, furrow, and outlet configuration that was represented as overland-channel flow.

SSCLY- Clay surface specific area

The clay surface specific area ($m^2 g^{-1}$) was selected as 30 for kaolinite clays according to recommendations from the University Mayor de San Simon soils laboratory in Cochabamba.

NPTSO- Points on overland flow slope profile

Five points were selected to describe the overland flow profile. These points were selected to characterize the flow profile from the top of the potato hill to the middle of the furrow. The location of the points was modeled after an example in the GLEAMS erosion user manual for a strawberry hill-furrow system (pg 74, Knisel and Davis, 1999). An example of the overland flow profile from the edge of the potato hills to the center of the furrow channel is show in Figure B.7. The flow profile began at the center of the potato hill and the first segment extended from there to the edge of the hill. Since there was an abruptly changing slope there, two points were used to describe the slope changing from almost flat to steep. Likewise, at the bottom of the hill where it hit the channel, the slope abruptly changed again and so two points with two slopes were used here as well. The overland profile ended with a point at the center of the furrow.

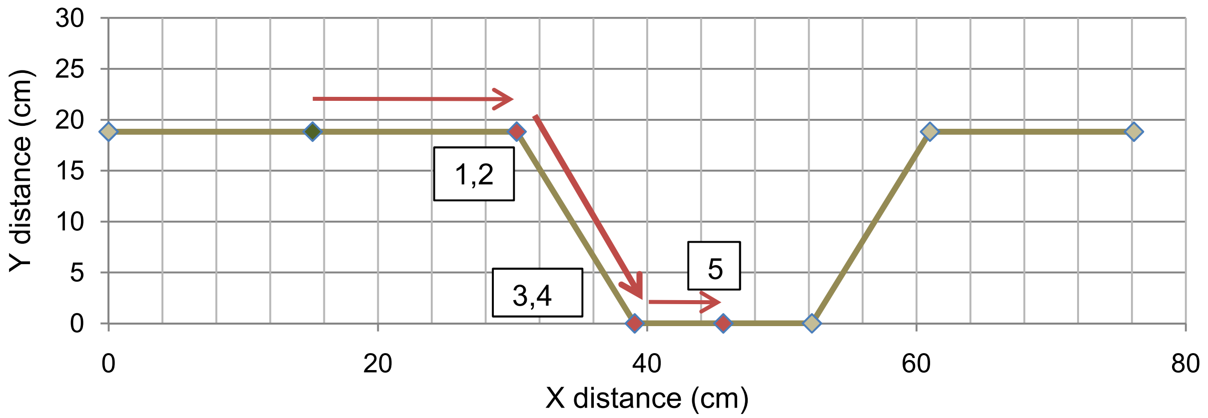


Figure B.7 Points defined for overland slope profile.

DAOVR- Drainage area representing overland flow profile

The drainage area (ha) representing the overland flow profile was calculated as the row spacing times the row length, according to the recommendation in the GLEAMS erosion user manual for ridge-furrow systems (pg 73, Knisel and Davis, 1999). This is the same method used to determine the denominator to calculate WLW in the hydrology parameter file.

XOV()- Distance up to point where slope is given and SLOV()- Slope at that point

The distances (m) in the overland flow profile were the cumulative lengths of the segments between the 5 points from the profile start in the center of the potato hill to the profile end in the center of the furrow. The slope was the change in height over the change in horizontal distance for that point. GLEAMS cannot accept a zero slope and so a negligible slope of 0.002 was entered for near flat areas (such as on the hill top surface and bottom furrow surface). The profile distances were taken from an average of multiple measurements within each site or an average from measured sites for those parcels that were not directly measured. Figure B.8 shows the measurements used to determine the overland flow profile and channel dimensions with the following abbreviations,

s = flat portion if the top potato hill surface,
w = width of the furrow bottom
h = potato hill height
x = side slope horizontal distance.

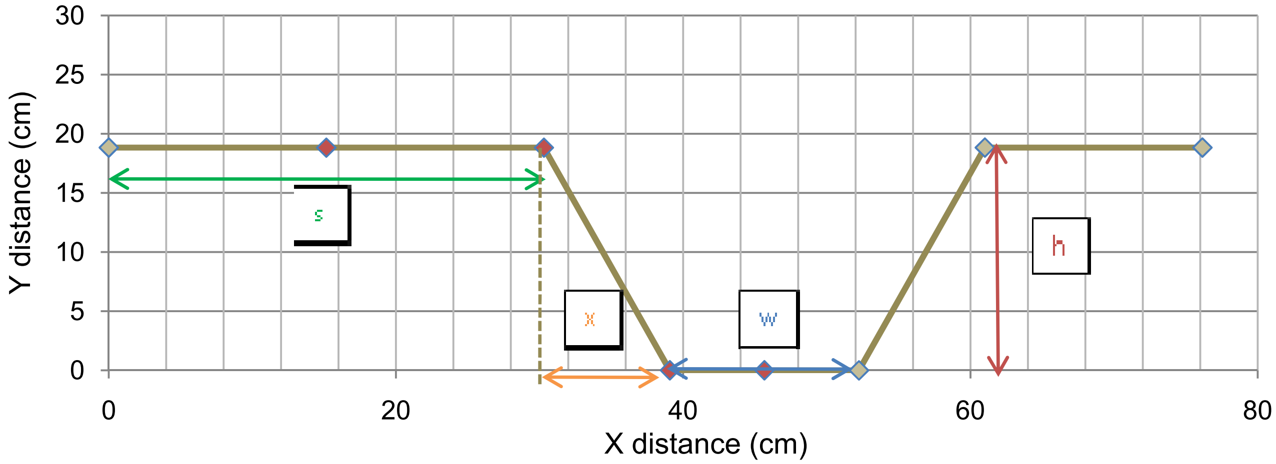


Figure B.8 Relative segment lengths used to determine cumulative length of the overland flow profile for the potato hills from the center of the hill to the center of the furrow.

An example of cumulative horizontal distance (m) and corresponding slope for each point on the overland slope profile is shown in table B.4.

Table B.4 Overland profile points, relative distances from middle of top of potato hill to the center of the furrow, and representative slopes used in erosion component of GLEAMS.

Overland flow profile point	Relative distance, m (XOV)	Slope relationship, m/m (SLOV)
1	s/2	negligible
2	s/2	h/x
3	s/2 + x	h/x
4	s/2 + x	negligible
5	s/2 + x + w/2	negligible

NXK- Number of soil segments with different soil erodibility factors and
XSOIL()- Relative distance for each segment

The entire soil profile was considered to have the same soil erodibility factor, K, and so the number of segments was 1 and the relative distance from the top of the profile to the bottom was 1.0.

KSOIL()- Overland flow segment soil erodibility factor

The soil erodibility factor was calculated from the equation in the GLEAMS erosion user manual (based on the Universal Soil Loss Equation) as,

$$KSOIL = \frac{2.1TF^{1.14}(10^{-4})(12-OM)+3.25(SF-2)+2.5(PF-3)}{100} \quad \text{(B.4)}$$

Where *KSOIL*= soil erodibility factor
TF= texture factor = (% silt + % very fine sand)(100-% clay)
OM= organic matter content (%)
SF=soil structure code
PF=soil permeability class.

The texture factor was determined from the texture reported in the soil analysis for the top layer of the hill (horizon 1) where very fine sand was considered to be 50% of the sand percentage for the textural class. The soil structure was considered blocky (code 4) according to soil surveys completed in the watershed (CIDETI, 1994) and the permeability was considered moderate (code 3).

NSC- Channel segments with different slopes

The simulated channels routed through the furrows were considered to have a uniform slope from the highest uphill point to the outlet and were represented with one segment.

CTLO- Channel outlet conditions

Uniform flow was considered to control depth at the end of the channel and the furrow channel was considered to have the same Manning's n as the outlet channel for all sites, so code 3 was selected.

DACHL- Total drainage area at lower end of channel

This area (ha) was considered to be the total row spaced area at the end of the row, which was the same area used for DAOVR (row spacing times row length).

DACHU- Total drainage area at upper end of channel

This area (ha) was zero since there was no additional drainage area considered above the channel that was not already accounted for in the overland flow profile.

Z- Field channel side slope

The field channel side slope (horizontal:vertical, erosion user manual pg 77, Knisel and Davis, 1999) was calculated as the x length above in figure B.8 divided by the potato hill height, h.

XLSP- Distance of channel segment and SSLP- Slope of channel segment

The distance of the channel segment (m) was selected as the row length for each site. The slope of the channel segment (m m^{-1}) was calculated as the difference in elevation between the uphill portion of the row and the outlet over the row length. This was the method used to calculate CHS for the hydrology parameter file.

CLTZ- Outlet channel side slope

The outlet channel side slope was considered to be the same as channel side slope Z since the furrows that represented the channel extended to the edge of the field where runoff was discharged.

CTLN- Manning's n for outlet control structure

The rows in the potato fields typically led into the neighboring area which was rough grass and weed covered. The Manning's n at the outlet was therefore selected as 0.30 according to the value for very dense grass in Table E-3 in the GLEAMS erosion user manual (Knisel and Davis, 1999). The exception was Villa Flores where the outlet was a metal spout. The Manning's n here was selected as 0.012.

CTLSL- Slope at outlet control structure

The slope (m m^{-1}) at the outlet control structure was considered to be the same as the channel slope SSLP in the row since the rows ran along the contour of the hills and discharged at the same slope into the surrounding field.

NYEARS- Number of years in rotation

This is the same number as IROT in hydrology parameter file (2 years).

CDATE- Date when parameters take place

The Julian day for erosion parameter updates for tillage or differences in crop cover were included for the overland profile and channel changes over the crop rotation. Seven dates were included for the potato rotation to represent the following changes in the field over the rotation:

Initialization→Planting→Hill formation→Hill cover 50-75%→ Hill cover 75-80%→Hill cover 10-50%→Harvest

Actual Julian days depended on the farming practices of each site and were entered according to farm interviews when available and estimated when not. GLEAMS required an initialization of parameters on Julian day 001 and so this was the first date entered with conditions for tilled surface to begin the potato rotation. The harvest date was considered to be the actual day of harvest when the hills were destroyed and the soil mixed (as opposed to considering harvest as the day crop growth ceased as for DHRVST in the hydrology parameter file). An entry for the hill cover 10-50% was included after hill cover 75-80% to consider the period after frost or foliage cutting when the crop canopy cover was reduced before actual crop harvest.

NXF- Number of overland flow segments to update

The 3 main segments defined for the overland flow profile (hill surface, side slope, and furrow) had changing parameters that affected erosion during the crop rotation and so these 3 were selected to be updated.

XFACT()- Relative distance for each updated slope segment

The relative distance for each segment was determined by dividing the portion horizontal distance from the total profile horizontal distance. For the three segments chosen above, the relative distances were

Up to first profile segment point at edge of hill → $\frac{0.5s}{0.5s+x+0.5w}$

Up to second segment point at base of hill → $\frac{0.5s+x}{0.5s+x+0.5w}$

Up to third segment point in center of furrow → $\frac{0.5s+x+0.5w}{0.5s+x+0.5w} \rightarrow 1.$

Where the lengths for s, x, and w are described in figure B.8 above.

CFACT()- Crop factor for overland flow segment, PFACT()- Contouring factor for overland flow segment, NFACT()- Manning's n for overland flow segment

Each overland flow segment defined in NXF for each CDATE required definition of crop factor soil loss fraction (CFACT), contour factor (PFACT), and surface Manning's n (NFACT). The CFACT according to crop stage mainly affected the first segment for the potato hill surface since this is where most of the vegetation growth occurred. CFACT values were taken from line 160 in Table E-6 in the erosion user manual (Knisel and Davis, 1999). An estimation for CFACT based on the potato values was used for the side slope and furrow for those sites that had significant weed coverage.

The contouring factors for the hill and furrow segments were taken from Table E-4 in the GLEAMS erosion user manual (Knisel and Davis, 1999). The slope percentage and flow length path prior to hill formation represented the field as a whole and was estimated from a calculation in a GIS based on a 30 m resolution digital elevation model for the watershed. The PFACT prior to hill formation and after harvest was determined from the overall field slope percentage and field downhill length. When the field length was longer than that listed for the respective slope percentage in Table E-4, a PFACT of 1.0 was assigned according to the suggestion in the GLEAMS erosion user manual (pg 83, Knisel and Davis, 1999). After hill formation, the PFACT became 0.60 or 0.50 because the hills formed along the contour determined the slope of the flow path. The side slope segment had a PFACT of 1.0 after hill formation and until harvest according to the user manual suggestion for hill side slopes.

The Manning's n values for the overland profile segments were selected from Table E-5 in the GLEAMS erosion user manual (Knisel and Davis, 1999). It was considered that the potato hill and furrow surfaces had a Manning's n value sequence comparable to shallow rough surface depressions, and sparse grass to account for both the bare surface at the beginning of the growing season and then some roughness added by potato plant foliage and weeds later in the season for sites Cebada Jichana, Dami Rancho, and Totora Kocha. Sites Sankayani Alto Puruma and Sankayani Alto Papa had high amounts of surface residue from the native vegetation and were considered to have a Manning's n that corresponded to 2.24 t ha^{-1} and 1.12 t ha^{-1} of wheat straw mulch, respectively. Villa Flores had negligible weeds and surface residue and so the Manning's n here corresponded to rough surface depressions continuously for the simulation.

NXC- Number of channel segments to update

The furrow that made the channel from the overland flow to the field outlet was considered uniform and so was represented with one segment.

XCHAN()- Relative distance of channel

Since only one representative segment for the channel was used, the relative distance was 1.0.

NCHAN()- Manning's n for channel segment, DCHAN()- Depth to non-erodible layer, WCHAN()- Top width of channel segment

The channel Manning's n, depth to non-erodible layer, and channel top width had to be defined for the same CDATEs as for the overland flow profile above. The Manning's n condition sequence for the channel was similar to the conditions defined for the overland flow profile. Values for channel Manning's n were taken from Table E-3 in the GLEAMS erosion user manual (Knisel and Davis, 1999).

The depth to non-erodible layer (m) was considered the depth of the furrow soil layer from which sampling was difficult or 5 cm below the furrow sampling depth. This was 0.40 m from the soil surface prior to hill and furrow formation and 0.05 afterwards until harvest when the furrow and thus channel was exposed.

The channel width (m) was considered to be the furrow width (w) in figure B.8 between hill/furrow formation and harvest. After this period when the hills were nonexistent in the field, the channel width was updated to 10 m, which signaled that the model should consider what was the channel as overland flow. This is according to the GLEAMS erosion user manual (pg 86, Knisel and Davis, 1999).

Tables B.5 and B.6 show most erosion input parameters for all sites.

Table B.5 Erosion input parameters for sites CBJ, DMR, and TTK.

Parameter	Description	Site		
		CBJ	DMR	TTK
BYEAR	year beg sim	2008	2008	2008
EYEAR	year end sim	2009	2009	2009
EROOUT	code output	2	2	2
FLGSEQ	code erosion/sed submodels	3	3	3
METFLG	code metrification	1	1	1
SSCLY	clay surface area	30	30	30
NPTSO	num pts for overland flow profile slope	5	5	5
DAOVR	drainage area for overland flow profile	0.0033	0.0029	0.0052

Table B.5 (cont.)

Parameter	Description	Site		
		CBJ	DMR	TTK
XOV()	dist upper dist of to where slp is given			
	1	0.15	0.15	0.16
	2	0.15	0.15	0.16
	3	0.24	0.26	0.31
	4	0.24	0.26	0.31
	5	0.31	0.33	0.34
SLOV()	slope of overland flow at XOV			
	1	0.002	0.002	0.002
	2	2.15	1.74	1.35
	3	2.15	1.74	1.35
	4	0.002	0.002	0.002
	5	0.002	0.002	0.002
NXK	num of slp segs with dif soil erodibility factors	1	1	1
XSOIL()	rel horizontal dist from top of slope to bottom of seg	1	1	1
KSOIL()	soil erodibility factor for each segment	0.43	0.44	0.44
NSC	num of channel segs with dif slps	1	1	1
CTLO	chan outlet flow conditions that affect flw depth	2	2	2
DACHL	total drainage area at lower end of channel	0.003	0.003	0.005
DACHU	total drainage area at upper end of channel	0	0	0
Z	side slope of field channel X-sec	0.46	0.58	0.74
XLSP()	dist from upper end of channel to bottom of seg	54	45	77
SSLP()	slp of seg directly above	0.0370	0.0222	0.0130
CTLZ	side slp of X-sec at outlet	0.46	0.58	0.74
CTLN	manning's n for outlet control channel	0.3	0.3	0.3
CTLSL	slp of outlet control channel	0.0370	0.0222	0.0130
NYEARS	number of years in rotation (same as HYD IROT)	2	2	2
NXF	num of overland flow profile segs with changes in of updateable parameters	3	3	3
XFACT()	relative horz distance from top of ofp to bottom of seg I			
	1	0.497	0.466	0.484
	2	0.784	0.800	0.920
	3	1	1	1
NXC	num of channel profile segs with dif chan parameters	1	1	1
XCHAN()	relative horz distance from top of chan to bottom of seg	1	1	1

Table B.6 Erosion input parameters for sites SAR, SAP, and Villa Flores.

Parameter	Description	Site		
		SAR	SAP	Villa Fores
				VF2, VF4. VF8
BYEAR	year beg sim	2008	2008	2008
EYEAR	year end sim	2009	2009	2009
EROOUT	code output	2	2	2
FLGSEQ	code erosion/sed submodels	3	3	3
METFLG	code metrification	1	1	1
SSCLY	clay surface area	30	30	30
NPTSO	num pts for overland flow profile slope	5	5	5
DAOVR	drainage area for overland flow profile	0.0030	0.0021	0.0001
XOV()	dist upper dist of to where slp is given			
	1	0.17	0.17	0.13
	2	0.17	0.17	0.13
	3	0.31	0.29	0.25
	4	0.31	0.29	0.25
	5	0.36	0.34	0.30
SLOV()	slope of overland flow at XOV			
	1	0.002	0.002	0.002
	2	1.51	1.40	1.33
	3	1.51	1.40	1.33
	4	0.002	0.002	0.002
	5	0.002	0.002	0.002
NXK	num of slp segs with dif soil erodibility factors	1	1	1
XSOIL()	rel horizontal dist from top of slope to bottom of seg	1	1	1
KSOIL()	soil erodibility factor for each segment	0.41	0.41	0.46
NSC	num of channel segs with dif slps	1	1	1
CTLO	chan outlet flow conditions that affect flw depth	2	2	1
DACHL	total drainage area at lower end of channel	0.003	0.002	0.0001198
DACHU	total drainage area at upper end of channel	0	0	0
Z	side slope of field channel X-sec	0.66	0.71	0.75
XLSP()	dist from upper end of channel to bottom of seg	42	31	2
SSLP()	slp of seg directly above	0.0476	0.0323	0.0002
CTLZ	side slp of X-sec at outlet	0.66	0.71	0.75
CTLN	manning's n for outlet control channel	0.3	0.3	0.012
CTLSL	slp of outlet control channel	0.0476	0.0323	0.0002
NYEARS	number of years in rotation (same as HYD IROT)	2	2	2
NXF	num of overland flow profile segs with changes in of updateable parameters	3	3	3

Table B.6 (cont.)

Parameter	Description	Site		
		SAR	SAP	Villa Fores
				VF2, VF4. VF8
	relative horz distance from top of ofp to bottom of seg I			
XFACT()	1	0.484	0.492	0.431
	2	0.861	0.859	0.820
	3	1	1	1
NXC	num of channel profile segs with dif chan parameters	1	1	1
XCHAN()	relative horz distance from top of chan to bottom of seg	1	1	1

B.3 Nutrients

NBYR- Beginning simulation year and NEYR- End year simulation

These were the same as the years for the weather record used in the hydrology parameter file for HBYR and HEYR.

FLGROT- Number of years in rotation cycle

This was the same value as IROT in the hydrology parameter file.

RESDW- Crop residue on surface at start of simulation

The planting at most sites was into a clean tilled surface and so RESDW was considered zero for these sites. The exceptions were Sankayani Alto Puruma and Sankayani Alto Papa which were in first and second year (respectively) potato cultivation after native vegetation and so had some residue at the start of the simulation. The residue was estimated at 2290 and 993 kg ha^{-1} respectively according to measurements of surface residue taken after potato harvest from this site.

RCN- Rainfall N concentration

The rainfall N concentration was estimated at 0.4 mg kg-1 based on estimates from Godoy et al. (2003) and de Koning et al. (1997).

TN()- Total N in soil layer

The initial soil N (%) in each soil layer was from the soil analysis for the furrow layer. It represented total Kjeldahl N (organic, ammonia, and ammonium nitrogen).

CNIT()- Nitrate concentration in soil layer

The soil NO_3^- concentration (mg kg-1) was not available and so the model default of 5 mg kg-1 per layer was used, which is close to the nitrate concentration of 3.1 mg kg-1 found by Sarmiento and Bottner (2002).

POTMN()- Potential mineralizable N

The potential mineralizable N (kg ha^{-1}) was approximated at 14.9% of total N (TN). This percentage was selected because it was the average percentages listed for the soil orders in table N-1 in the GLEAMS user manual from the study area (Alfisol, Entisol, Inceptisol, and Mollisol) (Knisel and Davis, 1999).

ORGNW()- Organic nitrogen from animal manure in plow layer

This value represented carryover of organic N from previous years’ manure application prior to simulation as a percent of the soil in the plow layer. Since manure was only used at planting for potato after two or three years fallow and then an unfertilized small grain, ORGNW was considered 0 for all sites.

TP()- Total phosphorus in soil layer

The total phosphorus (%) in each soil layer was estimated internally from the model and so the input was left blank.

CLAB()- Labile phosphorus

The initial labile phosphorus (mg kg-1) was estimated from the soil analysis for the furrow layer .The method used to report phosphorus was Olsen-P, a quantification of available phosphorus in neutral to calcareous soils. A standardization formula provided in the GLEAMS nutrient user manual (pg 142, Knisel and Davis, 1999) was used to determine the correct input for *CLAB* for slightly weathered soils,

$$CLAB = 1.07(OP) + 4.1 \tag{B.5}$$

Where *CLAB*= labile P GLEAMS entry (mg kg-1)
OP= Olsen P from soil analysis (mg kg-1).

ORGPW()- Organic P from animal manure in plow layer

Like for ORGNPW(), this was considered 0 since no residual manure was assumed to be in the plow layer at the start of simulation.

PDATE- Date that nutrient parameters take effect

The beginning of the simulation for the model was considered the start day for the nutrient parameters to take effect, HBDATE from the hydrology parameter file.

NF- Number of fertilizer applications

The fertilizer application (organic or combined organic-inorganic) was according to farmer interviews. All applications occurred at planting.

NTIL- Number of tillage operations

The tillage operations in the nutrient component refer to operations that affect surface residue and surface applied manure. The number of tillage operations simulated for the nutrient component was two (planting/fertilizer application and harvest).

DHRVST- Harvest date

The harvest date was according to the date of frost damage or foliage cutting and was the same as DHRVST for the hydrology parameter file.

ICROP- Crop code

The crop code (code 79) selected was the same ICROP selected in the hydrology parameter file.

PY- Dry potential yield

The potential dry yield (kg ha^{-1}) was set as 9000 kg ha^{-1} based on a potential yield for Waycha variety potatoes at the Toralapa Research Station reported by Condori et al.

(2008). They reported a fresh potential yield of 35,000 kg tubers ha^{-1} and the dry matter content was estimated as 26%.

DMY- Dry matter ratio

The DMY for each site was the ratio of the total dry matter to the removed yield dry matter and was calculated as

$$DMY_{potato} = \frac{DPW_{potato}}{Y_{tuber}} \qquad \text{(B.6)}$$

Where *DMY*= dry matter ratio
CY =total dry crop yield (kg ha^{-1}) which is equal to the following,

$$CY = Y_{tuber} + Y_{forage} \qquad \text{(B.7)}$$

Where Y_{tuber} = dry tuber yield (kg ha^{-1})
$Y_{foliage}$ = dry potato foliage (kg ha^{-1}).

The foliage was measured as all surface foliage cut from a defined area, dried, and weighed.

CNR- Carbon:Nitrogen crop ratio

The CNR used was from the GLEAMS internal data base for the Irish potatoes.

RNP- Nitrogen:Phosphorus crop ratio

The RNP N:P ratio for the crop was determined from the plant nutrient analysis and the following equations,

$$RNP_{potato} = \frac{Y_{forage}(N_{forage}) + Y_{tuber}(N_{tuber})}{Y_{forage}(P_{forage}) + Y_{tuber}(P_{tuber})} \qquad \text{(B.8)}$$

Where *RNP*= crop N:P
N= N content for respective crop part
P = P content for respective crop part.

C1- Coefficient and C2- Exponent for exponential nitrogen uptake function

The C1 coefficient that describes the scale of the exponential function for N uptake for potato was taken from estimated from an average of the final total measured plant N contents for all the sites at the end of the growing season (1.67) as demonstrated in figure B.9. C2, the shape of the function, was taken from the GLEAMS internal database for potatoes (-0.48).

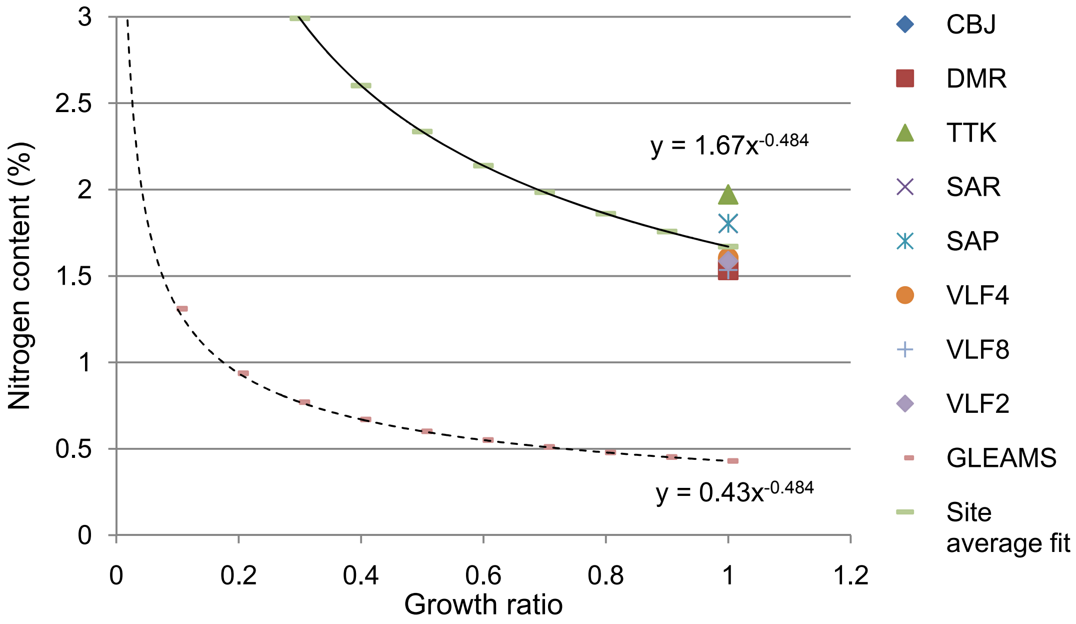


Figure B.9 N extraction curves developed from field data for each sites final plant N (dry basis) content (solid line) and included in GLEAMS internal database for Irish potatoes (dashed line).

DF- Fertilizer application date

The fertilizer application date was determined from the farmer interviews and coincided with potato planting.

METHAP- Fertilizer application method

The fertilizer application method was desired to be injection (code 2) for fertilizer applications applied in bands at planting and immediately covered with soil. However preliminary model simulation using this method partitioned all the organic N supplied by manure applications immediately into the soil potentially mineralizable pool and did not show subsequent mineralization. In light of this the method of application was changed to follow directions in the GLEAMS user manual (pg 150, Knisel and Davis, 1999) for incorporation of manure to a 15 cm soil depth.

MTYPE- Fertilizer type

The fertilizer type was selected as user defined (code 15). The default values for the manure types in the internal GLEAMS database are specified for fresh manure without bedding or storage, whereas the manure applied in the Jatun Mayu region is typically manure that is mixed with some bedding and stored uncovered outdoors for several months before application. Since the user defined option was selected, additional information on the nutrient content of the manure needed to be provided.

ATN- Manure total N, APORGN- Manure organic N, ANH- Manure ammonia, APHOS- Manure total phosphorus, APORGP- Manure organic phosphorus, AOM- Manure organic matter, and WASTYP- Waste type

The nutrient content of the manure (all values %) supplied for the user defined manure option for MTYPE were from combined information from local manure sample analysis and those reported in FAO and SNAG (1995). The manure analysis provided total N and total P contents. The ammonium N was estimated as 20% the total N reported in the sample analysis according to recommendations by Lory and Fulhage (1999) for poultry broiler litter. Organic N and organic P contents were the difference between the total from the manure analysis and the mineral forms. Table B.7 shows the manure nutrient parameters used in the GLEAMS simulations.

Table B.7 Manure nutrient content parameters entered for respective manure source.

Manure	ATN	APORGN	ANH	APHOS	APORGP	AOM
Chicken	2.7	2.1	0.5	1.98	1.52	44.7
Cow	1.5	1.0	0.5	0.50	0.30	37.2

The waste type was considered to be solid (code 1).

RATE- Fertilizer application rate

The dry manure or fertilizer application rate (t ha^{-1}) was determined through farmer interviews, which typically provided a volume of wet manure or fertilizer applied to their field. For manure application, this value was multiplied by the bulk density of the applied material and dry matter fraction determined from manure sample analysis according to the following equation,

$$RATE_{farmer} = \left(\frac{Vol}{DAREA}\right)(BD_{manure} x (1 - MC)) \quad \text{(B.9)}$$

where *Vol* = volume of manure applied by the farmer ($m^{3)}$
DAREA= area of the field which received the manure application (ha)
BD = measured bulk density of the manure (t m^{-3})
MC = measured moisture content fraction of the manure.

DEPIN- Depth of incorporation

The incorporation depth for the fertilizer was specified as 0 cm from the surface according to recommendations in the user manual for specifying incorporated manure (pg 150, Knisel and Davis, 1999).

NTDAY- Tillage day

The tillage days for the operations listed in NTIL (planting/fertilizer application and harvest) were obtained from farmer interviews and entered as one day after planting and fertilization. The harvest day for tillage considerations was considered the actual day of harvest and not the day crop growth ceased, as considered for DHRVST in the hydrology parameter file because this was the day when the potato hills were destroyed through soil mixing and some plant residue incorporated and mixed.

LTIL- Tillage implement

The tillage implements used by the farmers are not all included in the GLEAMS internal database and so the representative implement was chosen based on similar properties to those used by the farmers in the watershed. The selected implements are shown in table B.8 below.

Table B.8 Tillage implements selected from GLEAMS internal database to represent farmer used implements for the studied sites.

Tillage event	Time of year	Traditional implement	GLEAMS representative implement	GLEAMS tillage implement code
Planting and manure application	October-November	Ox-drawn tool	User specified	23 (incorporation efficiency= 1.0; mixing efficiency=1.0)
Harvest	March-April	Hand tool	Digger-potato	8

DTIL- Tillage depth

The tillage depth (cm) was considered to be 15 cm according to farmer interviews and field observations. The tillage depth specified here allowed the incorporated manure to be applied and evenly mixed to the 15 cm depth.

Tables B.9 and B.10 show most of the nutrient input parameters for all sites.

Table B.9 Nutrient input parameters for sites CBJ, DMR, and TTK.

Parameter	Description	Site		
		CBJ	DMR	TTK
NBYR	beginning yr of plant rotation	2008	2008	2008
NEYR	ending year of plant nut sim	2009	2009	2009
NUTOUT	code for nut output	1	1	1
FLGROT	num of years in rotation cycle	2	2	2
FLGBAL	code for output for N and P at end of each yr	1	1	1
RESDW	Crop residue on surface at start of sim	0	0	0
RCN	N conc in rainfall	0.4	0.4	0.4

Table B.9 (cont.)

Parameter		Description	Site		
			CBJ	DMR	TTK
		horz-total N			
	TN()	1	0.13	0.13	0.22
		2	0.13	0.13	0.22
	CNIT()	nitrate-N conc in all horz	5	5	5
		horz-potentially mineralizable N			
	POTMN()	1	342	361	582
		2	342	361	582
	ORGNW	organic N from animal waste in plow horizon	0	0	0
		horz-labile P			
	CLAB()	1	9.45	11.59	13.73
		2	9.45	11.59	13.73
	ORGPW	organic P from animal waste in plow horz	0	0	0
	PDATE	date that following parameters are valid	1313	1288	1309
	NF	number of fert/manure applications	2	1	1
	NTIL	number of tillage ops	2	2	2
	DHRVST	crop harvest date	2074	2074	2074
	ICROP	id number for crop	79	79	79
	LEG	code for legume	0	0	0
	PY	dry potential yield (biomass removal)	9000	9000	9000
	DMY	dry matter ratio	1.46	1.27	1.60
	CNR	C:N ratio of crop	60	60	60
	RNP	N:P for crop	8.03	9.23	10.88
	C1	coefficient of exp relationship to est N content of crop	1.67	1.67	1.67
	C2	exponent in exp rel to est N content of crop	-0.48	-0.48	-0.48
	DF	date of fert application	1314	1289	1310
	MFERT	code for inorganic/organic fert	1	1	1
	METHAP	code application method	0	0	0
	MTYPE	code animal waste type	15	15	15
Inorganic fertilizer	FNH	inorganic fert ammonia	-	-	-
	FP	inorganic fert P	-	-	-
	DEPIN	depth of injection	-	-	-

Table B.9 (cont.)

Parameter		Description	Site		
			CBJ	DMR	TTK
Chicken litter	RATE	app rate for dry animal waste, chicken litter	1.57	6.27	3.94
	DEPIN	depth of waste incorporation	0	0	0
	ATN	total N % in manure	2.66	2.66	2.66
	APORGN	organic N % in manure	2.13	2.13	2.13
	ANH	ammonia % in manure	0.53	0.53	0.53
	APHOS	P % in manure	1.98	1.98	1.98
	APORGP	organic P % in manure	1.52	1.52	1.52
	AOM	organic matter % in manure	44.7	44.7	44.7
	WASTYP	waste type (solid, liq, slurry)	1	1	1
Cattle manure	RATE	app rate for dry animal waste, cattle manure	2.44	-	-
	DEPIN	depth of waste incorporation	0	-	-
	ATN	total N % in manure	1.48	-	-
	APORGN	organic N % in manure	1.02	-	-
	ANH	ammonia % in manure	0.46	-	-
	APHOS	P % in manure	0.48	-	-
	APORGP	organic P % in manure	0.31	-	-
	AOM	organic matter % in manure	37.2	-	-
	WASTYP	waste type (solid, liq, slurry)	1	-	-
		tillage day			
	NTDAY		1314	1289	1310
			2111	2091	2111
		tillage implement			
	LTIL	planting	23	23	23
		harvest	8	8	8
	DTIL	tillage depth	15	15	15

Table B.10 Nutrient input parameters for sites SAR, SAP, and Villa Flores

Parameter	Description	Site				
		SAR	SAP	Villa Fores		
				VF2	VF4	VF8
NBYR	beginning yr of plant rotation	2008	2008		2008	
NEYR	ending year of plant nut sim	2009	2009		2009	
NUTOUT	code for nut output	1	1		1	
FLGROT	num of years in rotation cycle	2	2		2	
FLGBAL	code for output for N and P at end of each yr	1	1		1	
RESDW	Crop residue on surface at start of sim	2290	973		0	
RCN	N conc in rainfall	0.4	0.4		0.4	
	horz-total N					
TN()	1	0.28	0.31	0.25	0.23	0.22
	2	0.28	0.31	0.25	0.23	0.22
CNIT()	nitrate-N conc in horz I	5	5		5	
	potentially mineralizable N in horz I					
POTMN()	1	537	675	545	534	521
	2	537	675	545	534	521
ORGNW	organic N from animal waste in plow horizon	0	0		0	
	horz-labile P					
CLAB()	1	9.45	19.08	34.06	15.87	10.52
	2	9.45	19.08	34.06	15.87	10.52
ORGPW	organic P from animal waste in plow horz	0	0		0	
PDATE	date that following parameters are valid	1274	1274		1318	
NF	number of fert/manure applications	2	2		1	
NTIL	number of tillage ops	2	2		2	
DHRVST	crop harvest date	2074	2074		2088	
ICROP	id number for crop	79	79		79	
LEG	code for legume	0	0		0	
PY	dry potential yield (biomass removal)	9000	9000		9000	
DMY	dry matter ratio	1.54	1.32		1.65	
CNR	C:N ratio of crop	60	60		60	
RNP	N:P for crop	6.95	7.85		6.65	
C1	coefficient of exp relationship to est N content of crop	1.67	1.67		1.67	
C2	exponent in exp rel to est N content of crop	-0.48	-0.48		-0.48	
DF	date of fert application	1275	1275		1319	
MFERT	code for inorganic/organic fert	0/1	0/1		1	
METHAP	code application method	2/0	2/0		0	
MTYPE	code animal waste type	15	15		15	

Table B.10 (cont.)

Parameter		Description	Site				
			SAR	SAP	Villa Flores		
					VF2	VF4	VF8
Inorganic fertilizer	FNH	inorganic fert ammonia	19	19	-		
	FP	inorganic fert P	50	50	-		
	DEPIN	depth of injection	15	15	-		
Chicken litter	RATE	app rate for dry animal waste, chicken litter	7.29	8.41	5.78		
	DEPIN	depth of waste incorporation	0	0	0		
	ATN	total N % in manure	2.66	2.66	2.66		
	APORGN	organic N % in manure	2.13	2.13	2.13		
	ANH	ammonia % in manure	0.53	0.53	0.53		
	APHOS	P % in manure	1.98	1.98	1.98		
	APORGP	organic P % in manure	1.52	1.52	1.52		
	AOM	organic matter % in manure	44.7	44.7	44.7		
	WASTYP	waste type (solid, liq, slurry)	1	1	1		
Cattle manure	RATE	app rate for dry animal waste, cattle manure	-	-	-		
	DEPIN	depth of waste incorporation	-	-	-		
	ATN	total N % in manure	-	-	-		
	APORGN	organic N % in manure	-	-	-		
	ANH	ammonia % in manure	-	-	-		
	APHOS	P % in manure	-	-	-		
	APORGP	organic P % in manure	-	-	-		
	AOM	organic matter % in manure	-	-	-		
	WASTYP	waste type (solid, liq, slurry)	-	-	-		
		tillage day					
	NTDAY		1275	1275	1319		
			2120	2120	2120		
		tillage implement					
	LTIL		23	23	23		
			8	8	8		
	DTIL	tillage depth	15	15	15		

Appendix C. GLEAMS input parameter files

C.1 Precipitation data

C.1.1 Toralapa Station precipitation data

The Toralapa Station precipitation (cm) data were used in the model runs for sites CBJ and DMR.

```
Toral 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         1
apa   2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         2
Precp 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         3
study 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         4
2008  2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         5
2009  2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         6
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         7
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         8
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         9
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        11
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        12
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2008 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00        27
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.09 0.00        28
***** 2008 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00        29
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.10 0.00 0.00        30
***** 2008 0.80 0.00 0.00 1.10 0.00 0.10 0.00 0.20 0.00 0.00        31
***** 2008 0.00 0.30 0.00 0.00 0.00 0.00 1.10 0.40 0.00 0.00        32
***** 2008 0.40 0.00 0.00 0.00 0.90 0.30 0.10 0.00 0.20 0.30        33
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00        34
***** 2008 0.00 0.00 0.00 0.00 0.40 2.10 0.00 0.00 1.20 0.00        35
***** 2008 0.80 0.80 0.40 0.40 0.10 1.40 1.40 1.10 0.10 1.90        36
***** 2008 1.40 0.00 0.10 0.00 0.10 0.00 0.00 0.00 0.00 0.00        37
***** 2009 0.00 1.60 0.00 2.30 0.30 0.00 0.00 1.20 0.60 0.20        1
***** 2009 0.00 0.00 0.10 0.00 0.00 0.00 1.70 1.00 1.70 2.80        2
***** 2009 0.00 0.10 0.10 0.10 0.40 0.10 0.00 0.00 0.20 0.20        3
***** 2009 0.00 0.00 0.00 0.00 0.10 0.00 0.20 0.00 0.00 0.00        4
***** 2009 0.30 0.60 1.10 0.10 0.00 0.10 0.40 0.00 0.60 0.10        5
***** 2009 0.00 0.60 0.10 0.80 0.20 0.10 0.30 0.00 0.00 0.20        6
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        7
***** 2009 0.60 0.90 0.20 0.00 0.00 0.00 0.20 0.10 0.10 0.30        8
***** 2009 1.10 1.70 0.30 0.10 0.00 0.20 0.10 0.10 0.40 0.10        9
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.70        10
***** 2009 0.20 0.10 0.00 0.00 1.20 0.10 0.00 0.10 0.00 0.00        11
```

```
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        12
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        29
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        30
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        31
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        33
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        34
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        36
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00                            37
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C.1.2 Sankayani Alto precipitation data

The Sankayani Alto precipitation (cm) data were used in the model runs for sites TTK, SAR, and SAP.

```
Sanka 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         1
yani  2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         2
Precp 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         3
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         4
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         5
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         6
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         7
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         8
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         9
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        11
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        12
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
```

```
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2008 0.00 0.00 0.03 0.00 0.00 0.00 0.00 0.10 0.00 0.00        27
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.86 0.00 0.00        28
***** 2008 0.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00        29
***** 2008 0.03 0.00 0.08 0.00 0.00 0.58 0.28 0.05 0.00 0.20        30
***** 2008 0.00 0.00 0.53 0.00 0.00 0.00 0.25 0.00 0.00 0.00        31
***** 2008 0.25 0.00 0.00 0.00 0.00 0.63 0.03 0.00 0.00 0.05        32
***** 2008 0.00 0.00 0.79 0.15 0.13 0.03 0.00 0.00 0.33 0.00        33
***** 2008 0.31 0.03 0.10 0.00 0.05 0.00 0.00 0.00 0.00 0.00        34
***** 2008 0.00 0.00 0.20 1.14 1.21 0.00 0.00 0.18 0.00 1.10        35
***** 2008 1.17 1.04 0.00 0.48 0.20 0.15 0.63 0.10 2.05 0.58        36
***** 2008 0.08 0.00 0.00 0.10 0.06 0.00 0.00 0.00 0.00 0.00        37
***** 2009 1.88 0.10 2.40 0.08 0.00 0.00 0.86 0.05 0.00 0.00        1
***** 2009 0.00 0.60 0.00 0.00 0.05 1.65 0.96 0.05 2.55 0.03        2
***** 2009 0.13 0.10 0.08 0.66 0.23 0.00 0.00 0.03 0.03 0.00        3
***** 2009 0.00 0.00 0.00 0.00 0.03 0.18 0.00 0.00 0.00 0.38        4
***** 2009 0.51 1.77 0.15 0.00 0.25 0.18 0.00 0.48 0.18 0.53        5
***** 2009 0.76 0.00 0.00 0.00 0.08 0.55 0.25 0.20 0.18 0.05        6
***** 2009 0.00 0.10 0.00 0.23 0.00 0.00 0.00 0.00 0.00 0.30        7
***** 2009 0.53 0.48 0.00 0.00 0.00 0.08 0.03 0.76 0.08 0.73        8
***** 2009 1.39 0.46 1.85 0.71 0.03 0.00 0.03 0.25 0.05 0.00        9
***** 2009 0.03 0.00 0.00 0.00 0.00 0.00 0.15 0.00 0.30 0.20        10
***** 2009 0.00 0.00 0.00 1.22 0.05 0.00 0.00 0.00 0.00 0.00        11
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        12
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        29
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        30
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        31
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        33
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        34
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        36
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00                            37
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C.1.3 Sankayani Alto- Villa Flores precipitation data

The Sankayani Alto- Villa Flores precipitation (cm) data were used in the model runs for the Villa Flores site (VF2, VF4, and VF8). They include the Sankayani Alto data until 15 January 2009. After this, rain gage data were recorded manually until the end of the growing season (30 April 2009).

```
Sanka 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          1
yani- 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          2
Villa 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          3
Flore 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          4
Prcip 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          5
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          6
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          7
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          8
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00          9
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         10
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         11
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         12
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         13
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         14
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         15
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         16
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         17
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         18
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         19
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         20
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         21
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         22
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         23
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         24
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         25
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         26
***** 2008 0.00 0.00 0.03 0.00 0.00 0.00 0.00 0.10 0.00 0.00         27
***** 2008 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.86 0.00 0.00         28
***** 2008 0.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00         29
***** 2008 0.03 0.00 0.08 0.00 0.00 0.58 0.28 0.05 0.00 0.20         30
***** 2008 0.00 0.00 0.53 0.00 0.00 0.00 0.25 0.00 0.00 0.00         31
***** 2008 0.25 0.00 0.00 0.00 0.00 0.63 0.03 0.00 0.00 0.05         32
***** 2008 0.00 0.00 0.79 0.15 0.13 0.03 0.00 0.00 0.33 0.00         33
***** 2008 0.31 0.03 0.10 0.00 0.05 0.00 0.00 0.00 0.00 0.00         34
***** 2008 0.00 0.00 0.20 1.14 1.21 0.00 0.00 0.18 0.00 1.12         35
***** 2008 1.17 1.04 0.00 0.48 0.20 0.15 0.63 0.10 2.05 0.58         36
***** 2008 0.08 0.00 0.00 0.10 0.03 0.00 0.00 0.00 0.00 0.00         37
***** 2009 1.88 0.10 2.40 0.08 0.00 0.00 0.86 0.05 0.00 0.00         1
***** 2009 0.00 0.61 0.00 0.00 0.05 1.80 0.00 0.00 0.90 4.10         2
***** 2009 0.00 0.00 1.00 0.00 0.00 0.00 1.10 0.00 0.08 0.00         3
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.90 0.00 0.00 0.00         4
***** 2009 0.46 0.30 1.80 0.10 0.10 0.25 0.00 0.10 0.90 0.40         5
***** 2009 0.85 0.00 0.00 0.00 0.13 0.00 0.00 0.30 0.00 0.00         6
***** 2009 0.00 0.04 0.00 0.31 0.00 0.00 0.00 0.00 0.00 0.00         7
***** 2009 1.20 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.65 0.50         8
***** 2009 2.10 0.00 0.00 0.00 0.97 0.00 0.00 0.20 0.00 0.00         9
***** 2009 0.25 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         10
***** 2009 0.00 0.00 0.00 1.70 0.30 0.00 0.00 0.00 0.00 0.00         11
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         12
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         13
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***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        29
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        30
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        31
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        33
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        34
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        36
***** 2009 0.00 0.00 0.00 0.00 0.00 0.00                            37
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C.1.4 Toralapa Station long term precipitation data

The Toralapa Station long term precipitation data were used to run the 10 year simulations used in the sensitivity analysis for the site Dami Rancho (DMR).

```
Toral 1993 0.90 0.60 0.50 3.10 1.10 0.50 0.00 0.20 3.50 0.00         1
apa   1993 0.00 0.00 0.20 0.10 1.70 0.00 0.30 2.10 0.90 0.00         2
Precp 1993 0.80 0.40 0.00 0.30 4.30 0.90 0.50 0.00 0.50 0.50         3
***** 1993 0.10 0.00 0.30 0.20 0.80 0.70 0.00 0.40 0.10 0.00         4
***** 1993 0.00 0.00 0.70 0.40 0.10 0.00 0.10 0.90 0.00 0.00         5
***** 1993 0.20 0.00 0.00 0.00 0.40 0.00 1.20 0.60 0.30 0.00         6
***** 1993 1.50 0.00 0.20 0.60 0.10 0.00 0.00 0.00 0.00 0.00         7
***** 1993 0.00 0.00 0.00 0.20 0.00 0.00 0.20 0.00 0.20 0.10         8
***** 1993 0.00 0.10 0.20 0.00 0.10 0.10 0.20 0.70 0.10 1.70         9
***** 1993 0.10 0.00 0.50 0.00 0.00 0.10 0.10 0.00 0.10 0.00        10
***** 1993 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10        11
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10        12
***** 1993 0.00 0.00 0.30 0.10 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00        17
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.70 0.00 0.00        19
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 1993 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 1993 0.00 0.00 0.20 1.60 0.90 0.00 0.00 0.00 0.00 0.70        23
***** 1993 0.00 0.10 0.40 4.10 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00        25
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***** 1993 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00        26
***** 1993 0.00 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00        27
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 1.20 0.00 0.30 0.00        28
***** 1993 0.00 0.10 0.00 0.00 0.00 0.60 0.20 0.00 0.00 0.00        29
***** 1993 0.00 0.00 0.00 0.00 0.30 0.00 0.00 0.00 0.00 0.00        30
***** 1993 0.00 0.00 0.00 0.30 0.80 0.10 0.10 0.00 0.00 0.00        31
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.50 0.00 0.00 1.50        32
***** 1993 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00        33
***** 1993 0.50 0.10 0.00 0.20 0.30 0.00 0.00 0.00 0.00 0.00        34
***** 1993 0.00 0.50 0.00 0.00 1.60 0.10 0.10 0.00 1.70 2.60        35
***** 1993 0.90 2.90 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00        36
***** 1993 0.00 0.00 0.00 0.70 0.70 0.00                           37
***** 1994 0.00 0.00 3.10 0.80 0.00 0.10 0.00 0.10 0.90 0.10         1
***** 1994 0.00 0.00 0.00 0.00 0.80 0.70 0.00 1.90 0.70 0.90         2
***** 1994 0.50 0.20 0.00 0.00 0.00 0.80 0.00 0.00 0.00 0.00         3
***** 1994 0.10 0.00 0.00 1.30 0.00 0.30 0.70 1.50 0.00 0.10         4
***** 1994 1.00 0.50 0.30 0.00 1.80 0.00 0.00 0.40 0.90 0.00         5
***** 1994 0.00 0.00 0.10 0.60 0.00 0.00 0.50 0.00 0.00 0.00         6
***** 1994 1.40 0.00 0.00 0.00 0.00 0.00 0.00 0.50 0.10 0.00         7
***** 1994 0.20 0.00 0.00 0.00 0.00 1.00 0.40 0.10 0.00 0.00         8
***** 1994 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 1.40 0.00         9
***** 1994 0.00 0.30 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 1994 0.00 0.10 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00        11
***** 1994 0.00 0.00 0.00 1.10 0.00 0.00 0.00 0.00 0.20 0.00        12
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.70        13
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 1.20        23
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00        26
***** 1994 0.00 0.00 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00        27
***** 1994 0.00 0.00 0.30 1.00 2.00 0.00 0.00 1.00 0.40 1.20        28
***** 1994 0.10 0.00 0.00 0.00 0.10 0.00 0.00 0.40 0.00 0.00        29
***** 1994 0.30 0.00 0.00 0.00 0.40 0.00 0.00 0.00 0.10 0.00        30
***** 1994 0.00 0.20 0.40 0.00 0.00 0.00 0.00 0.00 0.00 0.00        31
***** 1994 0.30 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 1994 1.00 0.90 0.40 0.50 1.30 1.00 0.20 0.00 0.00 0.00        33
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        34
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 1994 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        36
***** 1994 0.00 0.20 0.20 0.10 1.00 1.90                           37
***** 1995 0.20 0.00 0.50 0.10 0.70 0.20 0.10 0.00 0.00 0.00         1
***** 1995 0.90 0.00 0.30 3.10 0.00 0.10 3.00 2.20 0.10 0.00         2
***** 1995 0.10 0.00 0.20 0.00 0.00 0.00 0.00 0.20 0.50 0.40         3
***** 1995 0.10 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.10         4
***** 1995 0.10 0.00 0.80 0.80 0.10 0.10 0.40 1.10 0.20 1.10         5
***** 1995 3.60 0.00 0.00 0.00 1.10 0.00 0.70 0.10 0.00 0.70         6
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 1.00 0.00 0.00 0.00         7
***** 1995 0.60 0.60 0.00 0.00 0.10 0.00 0.30 0.00 0.50 0.40         8
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***** 1995 0.00 0.10 0.60 0.00 0.90 0.40 0.10 1.70 0.00 0.10         9
***** 1995 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.20 0.00 0.50        11
***** 1995 0.00 0.20 0.30 0.00 0.00 0.00 0.00 0.00 0.00 0.50        12
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.40 0.00 0.00        23
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 1995 0.00 0.00 0.00 0.50 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 1995 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.30 0.00 0.00        27
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 1995 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        29
***** 1995 0.00 0.20 0.50 0.00 0.00 0.00 0.00 0.00 1.00 0.00        30
***** 1995 0.70 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00        31
***** 1995 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 1995 0.40 0.00 0.00 0.00 1.30 2.20 0.00 0.00 0.60 0.00        33
***** 1995 0.10 0.00 0.20 0.50 0.00 0.00 2.40 0.90 0.00 0.00        34
***** 1995 0.70 0.50 0.20 0.00 0.90 1.20 0.00 0.00 0.20 0.00        35
***** 1995 0.00 0.00 0.00 0.80 0.30 0.30 0.30 0.40 1.90 1.70        36
***** 1995 1.00 2.70 1.40 0.00 0.90 0.00                            37
***** 1996 0.30 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.10 0.00         1
***** 1996 3.30 0.10 1.90 0.10 0.70 0.60 1.90 0.70 1.50 0.10         2
***** 1996 0.00 1.70 1.00 0.00 0.10 0.10 0.50 0.10 0.00 0.00         3
***** 1996 3.00 0.00 0.30 0.00 0.00 0.00 0.10 1.50 0.00 0.10         4
***** 1996 1.60 0.10 0.00 0.00 0.00 0.80 0.00 0.40 0.00 0.00         5
***** 1996 0.00 1.00 0.10 0.10 0.00 0.00 0.10 1.20 0.00 0.50         6
***** 1996 0.10 0.20 1.40 0.70 0.30 0.50 0.10 0.00 0.00 0.00         7
***** 1996 0.00 0.20 0.00 0.00 0.00 0.80 0.00 0.00 0.00 0.00         8
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***** 1996 0.10 0.00 0.00 0.00 0.00 0.00 0.20 0.00 0.10 0.00        11
***** 1996 0.00 0.00 0.00 0.00 0.00 1.60 0.00 0.00 0.00 0.00        12
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 1996 0.90 0.40 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 1996 0.00 1.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.50        26
***** 1996 0.00 0.00 0.00 0.00 0.40 0.10 0.60 0.10 0.00 0.00        27
***** 1996 0.00 0.00 0.00 0.00 0.00 0.00 0.00 1.20 0.00 0.00        28
***** 1996 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00        29
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***** 1996 0.40 0.30 0.10 3.80 0.00 0.00 0.00 0.00 0.10 0.10        32
***** 1996 0.60 0.00 0.00 0.50 0.40 0.20 0.50 0.00 0.00 0.00        33
***** 1996 0.40 0.00 0.00 0.40 0.00 0.10 0.30 0.00 0.00 0.00        34
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***** 1996 0.00 0.00 0.00 0.00 0.00 0.20 0.20 0.00 0.10 0.90        36
***** 1996 1.60 1.20 2.40 0.90 0.60 0.00                            37
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***** 1997 0.00 1.60 0.10 0.40 0.40 0.50 0.40 0.50 0.40 0.10         5
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***** 1997 0.10 1.00 0.80 1.40 0.80 0.10 0.50 0.10 0.50 1.50         7
***** 1997 2.20 1.20 0.30 0.80 0.70 0.30 0.00 0.70 0.00 0.10         8
***** 1997 0.00 0.00 2.60 0.20 1.90 0.90 0.20 0.00 0.00 0.00         9
***** 1997 0.00 0.00 0.00 0.00 0.20 0.10 0.10 0.00 0.00 0.50        10
***** 1997 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.20 0.30        11
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        12
***** 1997 0.90 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 1997 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00        14
***** 1997 0.00 0.00 0.40 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
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***** 1997 0.00 0.00 0.00 0.00 0.00 3.10 0.00 0.00 0.00 0.00        17
***** 1997 0.00 0.00 0.00 1.10 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.20        22
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 1997 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 1997 0.00 0.70 0.00 0.00 0.00 0.00 0.00 0.00 1.70 0.20        27
***** 1997 0.00 0.00 0.40 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 1997 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.20 0.00 1.00        29
***** 1997 0.10 0.00 0.00 0.00 0.00 0.00 0.30 0.00 0.00 0.00        30
***** 1997 0.00 0.00 0.00 0.60 1.60 0.00 0.90 0.10 0.00 0.00        31
***** 1997 0.00 0.00 0.00 0.10 0.20 0.10 0.00 0.30 0.90 0.00        32
***** 1997 0.60 0.80 0.00 0.00 0.80 0.00 0.00 0.80 0.00 0.00        33
***** 1997 1.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.40 0.00        34
***** 1997 0.00 0.00 0.30 0.20 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 1997 0.10 0.00 0.00 0.00 0.20 0.10 0.10 0.00 0.00 0.00        36
***** 1997 0.00 0.10 0.40 0.10 0.20 0.00                            37
***** 1998 0.00 0.10 0.00 0.00 0.00 1.60 0.10 1.60 0.50 0.10         1
***** 1998 0.70 0.10 0.00 0.00 0.00 0.00 0.00 0.50 0.50 0.00         2
***** 1998 0.00 0.00 1.20 0.00 0.00 0.10 0.00 0.10 0.20 0.00         3
***** 1998 0.10 0.10 0.00 0.00 0.00 0.60 0.00 0.10 2.40 0.00         4
***** 1998 5.20 0.00 0.00 0.00 0.00 1.90 0.20 0.00 0.00 0.00         5
***** 1998 0.10 1.70 1.90 0.00 0.00 0.00 0.20 2.90 1.20 0.00         6
***** 1998 0.00 0.10 0.00 0.00 0.00 0.10 0.10 0.00 0.50 0.00         7
***** 1998 0.00 0.00 0.00 1.90 0.10 0.90 0.00 0.10 0.00 0.00         8
***** 1998 0.00 0.00 0.00 0.30 0.10 0.00 0.00 0.00 0.00 0.80         9
***** 1998 0.00 1.20 0.10 0.00 0.00 0.80 0.00 0.00 0.00 0.00        10
***** 1998 0.00 0.00 0.00 0.40 0.00 0.00 0.00 0.00 0.00 0.00        11
***** 1998 0.00 0.10 0.00 0.00 0.60 0.00 0.00 0.00 0.00 0.00        12
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***** 1998 0.00 0.00 0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        14
***** 1998 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 1998 0.00 0.00 0.00 0.00 1.20 0.70 0.00 0.00 0.00 0.00        18
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
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***** 1998 0.00 0.00 0.00 0.00 0.00 0.40 0.00 0.00 0.00 0.00        23
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***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 1.60 0.00        25
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 1998 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 1998 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
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***** 1998 0.00 0.00 0.00 0.00 0.00 0.10 0.60 0.00 0.10 0.50        30
***** 1998 0.70 1.80 0.90 0.70 0.00 0.00 0.00 0.10 0.00 0.00        31
***** 1998 0.00 0.00 0.00 0.00 0.40 0.00 0.00 0.00 0.00 0.00        32
***** 1998 0.80 1.40 0.00 0.00 0.00 0.10 0.30 0.10 0.20 0.10        33
***** 1998 0.00 0.00 0.10 0.00 0.00 0.20 0.00 0.00 0.00 0.00        34
***** 1998 0.00 1.00 0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00        35
***** 1998 0.10 0.00 0.00 0.00 0.00 0.90 0.00 0.00 0.00 0.10        36
***** 1998 1.00 0.10 0.00 1.40 0.60 0.00                            37
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***** 1999 0.90 0.10 1.20 0.10 0.00 0.40 0.00 0.00 0.00 0.00         2
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***** 1999 0.00 1.10 0.00 0.00 3.10 0.00 0.00 1.20 2.10 0.10         5
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         7
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        11
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
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***** 1999 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.30 0.00 0.00        28
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***** 1999 0.00 0.00 1.50 1.40 0.00 0.20 0.00 0.00 0.00 0.00        30
***** 1999 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.20 0.00        31
***** 1999 0.00 1.40 0.60 0.10 0.00 0.00 0.00 0.00 0.20 0.00        32
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***** 1999 0.00 0.00 0.20 0.10 0.00 0.00 0.80 0.00 0.00 0.00        35
***** 1999 0.00 0.50 0.10 0.00 0.00 0.40 0.00 0.50 0.30 0.60        36
***** 1999 0.10 0.50 0.20 0.60 0.00 0.00                            37
***** 2000 0.00 0.40 0.10 1.00 0.50 0.00 0.40 0.80 0.00 0.90         1
***** 2000 0.00 0.20 0.00 0.50 1.10 0.10 0.40 0.70 0.00 0.00         2
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***** 2000 0.20 0.00 0.00 0.40 1.40 0.00 0.20 0.10 0.40 0.90         4
***** 2000 0.30 0.30 0.10 0.50 0.00 0.00 0.00 0.00 0.00 0.00         5
***** 2000 0.10 0.00 0.20 0.50 0.00 0.00 0.00 0.00 0.00 0.00         6
***** 2000 0.40 0.00 0.00 0.00 0.10 0.00 0.60 1.40 1.40 1.00         7
***** 2000 0.10 1.30 1.30 0.00 0.30 0.00 0.00 0.70 0.10 0.00         8
***** 2000 0.70 0.50 0.00 0.00 0.00 0.00 0.00 0.00 1.50 0.00         9
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***** 2000 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2000 0.00 0.00 0.00 0.00 0.80 0.00 0.00 0.00 0.00 0.40        16
***** 2000 0.50 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00        17
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***** 2000 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 2000 0.00 0.00 0.00 0.00 0.30 0.00 0.00 0.00 0.00 0.60        29
***** 2000 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.80 0.00        30
***** 2000 0.00 0.50 0.00 0.00 0.00 0.00 0.00 0.10 0.10 0.00        31
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***** 2000 1.60 0.90 0.10 2.50 1.10 1.30 0.70 1.10 0.00 0.00        35
***** 2000 0.20 1.50 0.00 0.00 0.00 0.00 0.00 0.20 0.00 2.20        36
***** 2000 0.10 0.00 0.40 1.30 0.00 0.40                            37
***** 2001 0.10 0.90 0.30 0.40 1.30 0.40 0.00 0.00 0.10 0.00         1
***** 2001 0.00 3.30 0.00 1.10 1.40 0.40 0.10 0.00 1.30 0.80         2
***** 2001 1.30 1.20 0.10 0.70 0.20 3.70 0.60 0.00 0.00 0.00         3
***** 2001 0.30 0.00 0.70 0.00 2.80 0.70 0.10 0.00 0.00 0.00         4
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***** 2001 0.30 0.00 0.00 0.10 0.00 0.50 0.10 1.10 0.40 0.00         6
***** 2001 0.50 0.60 0.00 0.10 0.40 0.20 1.40 1.50 1.80 0.00         7
***** 2001 0.20 0.00 0.10 0.70 0.10 0.50 1.20 0.00 0.00 0.00         8
***** 2001 1.40 0.70 1.00 0.00 0.00 0.00 0.40 0.00 0.00 0.00         9
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
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***** 2001 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        13
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***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00        17
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.90        18
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00        19
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
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***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.30 0.70        23
***** 2001 0.50 0.00 1.30 0.10 0.00 0.00 0.00 0.00 0.00 0.00        24
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***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.30        26
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
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***** 2001 0.00 0.00 0.00 0.00 0.00 0.50 0.20 0.00 0.10 0.40        29
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***** 2001 0.00 0.00 0.00 0.90 0.00 0.00 1.40 0.70 0.40 0.00        31
***** 2001 0.00 0.10 0.00 0.10 0.00 0.60 0.00 0.00 0.00 0.00        32
***** 2001 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        33
***** 2001 0.00 0.00 0.30 0.10 0.30 0.10 0.00 0.10 0.00 0.00        34
***** 2001 0.00 0.00 0.00 0.40 0.50 0.10 0.00 0.00 0.00 0.10        35
***** 2001 0.70 0.00 0.00 0.10 0.40 0.00 0.00 2.00 0.60 0.70        36
***** 2001 0.40 0.00 0.10 0.20 0.70 0.00                            37
***** 2002 0.20 0.20 0.10 0.90 0.10 0.50 1.90 0.00 0.00 0.40         1
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.20 0.00 0.00 0.00         2
***** 2002 0.10 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.10 0.00         3
***** 2002 0.00 0.00 0.40 2.20 0.60 0.30 0.90 1.50 0.00 0.00         4
***** 2002 0.20 0.30 0.00 0.40 0.00 0.00 0.00 2.40 0.10 0.40         5
***** 2002 1.40 0.40 0.20 0.00 0.00 0.10 0.60 0.30 0.70 0.00         6
***** 2002 0.80 0.50 0.50 0.40 0.00 0.10 0.00 0.00 0.10 1.21         7
***** 2002 0.30 0.10 0.00 0.10 0.90 0.00 0.00 0.00 1.40 0.30         8
***** 2002 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         9
***** 2002 0.10 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00        10
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        11
***** 2002 0.00 0.00 0.00 0.50 0.30 0.10 1.10 0.10 0.00 0.00        12
***** 2002 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10        13
***** 2002 0.00 0.00 0.00 0.00 0.40 0.00 0.00 0.00 0.00 0.00        14
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        15
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        16
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        17
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        18
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        26
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        28
***** 2002 0.00 0.00 0.00 0.60 0.00 0.00 0.00 0.00 0.00 0.10        29
***** 2002 0.10 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00        30
***** 2002 0.00 0.00 0.00 0.00 1.50 0.10 0.00 0.80 0.30 0.00        31
***** 2002 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        32
***** 2002 0.00 0.00 0.10 0.00 0.00 0.00 0.10 0.10 0.00 0.50        33
***** 2002 1.30 0.00 0.40 0.00 0.00 0.00 0.00 1.60 0.00 1.40        34
***** 2002 0.00 0.00 0.00 0.00 0.80 0.80 0.00 0.00 0.00 0.00        35
```

```
***** 2002 0.00 0.00 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00         36
***** 2002 0.00 0.00 0.00 4.90 0.00 0.00                             37
***** 2003 0.30 0.10 2.70 0.00 1.70 0.50 0.60 0.00 0.00 0.00          1
***** 2003 0.70 0.40 2.40 1.00 0.50 1.60 2.30 0.60 4.40 0.60          2
***** 2003 0.50 0.60 0.40 2.00 2.80 0.10 3.70 0.10 0.00 0.20          3
***** 2003 0.10 0.20 0.00 0.00 0.00 0.00 0.40 0.00 0.00 1.50          4
***** 2003 0.30 0.90 0.00 0.00 0.60 0.00 0.10 0.00 0.00 0.00          5
***** 2003 0.00 0.10 0.10 0.00 0.00 0.10 0.00 0.20 0.00 0.00          6
***** 2003 0.00 0.00 2.10 0.00 0.10 0.90 0.10 0.10 0.00 0.00          7
***** 2003 1.20 0.00 0.00 1.90 0.00 0.70 1.80 0.10 0.10 0.00          8
***** 2003 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.50 0.00          9
***** 2003 0.90 0.40 0.00 0.00 0.00 1.80 0.00 0.00 0.10 0.00         10
***** 2003 0.00 0.30 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00         11
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         12
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         13
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.10 0.00 0.00         14
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         15
***** 2003 0.00 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00         16
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         17
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         18
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         19
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         20
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         21
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01         22
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         23
***** 2003 0.00 0.00 0.00 0.00 0.10 0.00 0.60 0.00 0.00 0.00         24
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         25
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         26
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         27
***** 2003 0.00 0.00 0.40 0.20 0.10 0.00 0.10 0.00 0.00 0.00         28
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         29
***** 2003 0.00 0.10 0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00         30
***** 2003 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         31
***** 2003 0.00 0.00 0.00 0.10 0.00 0.00 0.00 0.00 0.00 0.00         32
***** 2003 0.00 1.40 0.80 0.10 0.00 0.00 0.00 0.00 0.00 0.00         33
***** 2003 2.10 2.50 0.30 0.50 0.20 0.00 0.20 0.00 0.70 0.00         34
***** 2003 0.00 0.50 0.40 0.00 0.00 0.20 0.60 0.10 0.10 1.30         35
***** 2003 0.60 0.20 0.00 0.20 0.80 0.00 0.00 0.00 0.00 0.40         36
***** 2003 0.50 0.00 0.50 0.00 0.20 0.00                             37
***** 2004 0.90 1.50 2.50 0.10 0.00 0.00 0.00 1.10 1.00 0.00          1
***** 2004 0.00 0.60 1.30 0.50 0.10 3.20 2.00 0.00 0.00 0.00          2
***** 2004 0.10 0.00 0.50 2.70 0.30 0.30 0.00 0.00 0.20 0.00          3
***** 2004 0.00 3.30 0.80 0.00 0.00 0.90 0.00 0.00 0.90 2.30          4
***** 2004 0.60 0.90 0.20 0.30 0.00 1.90 1.70 0.00 0.40 0.30          5
***** 2004 0.20 0.40 0.00 0.00 0.60 0.00 0.00 0.20 0.00 1.10          6
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.40 0.10          7
***** 2004 0.00 0.20 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.00          8
***** 2004 0.00 0.00 0.10 0.10 0.10 0.00 0.00 0.10 0.00 0.00          9
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         10
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         11
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         12
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         13
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         14
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         15
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         16
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         17
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00         18
```

```
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        19
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        20
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        21
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        22
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        23
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        24
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        25
***** 2004 0.00 0.00 0.00 0.00 0.00 2.10 0.60 1.20 0.20 0.00        26
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00        27
***** 2004 0.00 0.00 0.00 0.30 0.00 0.00 0.00 0.00 0.10 0.00        28
***** 2004 0.10 0.00 0.10 0.30 0.00 0.00 0.00 0.00 0.00 0.00        29
***** 2004 0.60 0.00 0.20 0.00 0.00 0.00 0.00 0.00 0.00 0.00        30
***** 2004 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.20 0.50 0.00        31
***** 2004 0.50 0.00 0.00 0.00 0.40 0.20 1.20 0.10 0.10 0.30        32
***** 2004 0.00 0.00 0.00 0.40 0.00 1.30 2.40 0.00 2.40 3.00        33
***** 2004 0.00 0.00 0.00 0.20 0.00 0.00 0.00 0.00 0.40 0.00        34
***** 2004 0.90 0.10 0.00 0.00 0.10 0.10 0.00 0.10 0.90 0.20        35
***** 2004 0.40 0.00 0.00 0.00 1.00 0.00 0.00 0.00 0.00 0.60        36
***** 2004 0.50 0.00 0.10 0.00 0.20 0.00                            37
```

C.2 Input parameter files for validation of 2008-2009 season data

C.2.1 Cebada Jichana (CBJ)

Hydrology

```
CEBADA JICHANA HYDROLOGY Validation with base values
Entered 29 July 2009
TORALAPA PRECIP
 2008313       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

  0.5843     0.5     0.1     4.5      86   0.037   88.52    40.0  3554.0  -17.48
       2       2    15.0    40.0
    0.56    0.56
    0.18    0.18
    0.07    0.07
    0.50    0.50
     2.0     2.0
    20.0    20.0
    50.0    50.0
     6.1     6.1
    69.0    69.0
    17.4    17.7    18.4    19.4    20.1    18.9    18.8    19.1    19.2    20.4
    21.2    18.6
     5.3     5.1     4.2     2.2    -0.6    -2.7    -3.1    -1.7     0.6     3.3
     4.7     5.6
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     5.3     5.1     4.2     2.2    -0.6    -2.7    -3.1    -1.7     0.6     3.3
     4.7     5.6
    2008    2009       2
      79    1314    2074            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
```

```
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
```

Erosion

```
CEBADA JICHANA EROSION Validation with base values
Entered 29 July 2009

    2008    2009       2       3       1
    30.0
       5  0.0033
    0.15   0.002    0.15    2.15    0.24    2.15    0.24   0.002    0.31   0.002
       1     1.0    0.43
       1       3                   0.003     0.0    0.46
    54.0  0.0370
    0.46     0.3   0.037
       2
     001     314     355
      29      48      74     111
       3     0.5     0.8     1.0
    0.43    0.64    0.56
     1.0     1.0     0.5
   0.014   0.014   0.015
    0.43    0.64    0.43
     1.0     1.0     1.0
   0.014   0.014   0.015
    0.43    0.64    0.43
     1.0     1.0     0.5
   0.014   0.014   0.015
    0.18    0.13    0.56    0.43
     0.5     0.5     0.5     1.0
   0.015   0.023   0.023   0.014
    0.56    0.18    0.18    0.43
     1.0     1.0     1.0     1.0
   0.015   0.023   0.023   0.014
    0.56    0.18    0.18    0.43
     0.5     0.5     0.5     1.0
   0.015   0.023   0.023   0.014
       1     1.0
   0.033   0.033   0.040
   -0.40   -0.40    0.05
    10.0    10.0    0.13
   0.040   0.050   0.050   0.033
    0.05    0.05    0.05   -0.40
    0.13    0.13    0.13    10.0
```

Nutrient

```
CEBADA JICHANA NUTRIENT
Entered 29 July 2009

    2008    2009       1       2       1
     0.0     0.4
    0.13    0.13
```

```
   342.0   342.0


    9.45    9.45

    1313
       2       2    2074
      79       0  9000.0     1.5    60.0    8.03    1.67   -0.48
    1314      01       0      15
    1.57     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1314       1       0      15
     2.4     0.0     1.5     1.0     0.5     .48     .31    37.2       1
    1315      23    15.0     1.0     1.0
    2111       8    15.0
       0
```

C.2.2 Dami Rancho (DMR)

Hydrology

```
DAMI RANCHO HYDROLOGY Validation
Entered 25 AUGUST 2009

 2008288       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

  0.4142     0.5     0.1     4.5      86   0.022   69.23    40.0  3575.0  -17.48
       2       2    15.0    40.0
    0.53    0.53
    0.18    0.18
    0.07    0.07
    0.50    0.50
     2.1     2.1
    21.0    21.0
    57.0    57.0
     5.3     5.3
    69.0    69.0
    17.4    17.7    18.4    19.4    20.1    18.9    18.8    19.1    19.2    20.4
    21.2    18.6
     5.3     5.1     4.2     2.2    -0.6    -2.7    -3.1    -1.7     0.6     3.3
     4.7     5.6
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     5.3     5.1     4.2     2.2    -0.6    -2.7    -3.1    -1.7     0.6     3.3
     4.7     5.6
    2008    2009       2
      79    1289    2074            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
```

```
       0       0       0       0
      -1       0       0       0
```

Erosion

```
DAMI RANCHO EROSION Validation with base values
Entered 29 July 2009

    2008    2009       2       3       1
    30.0
       5  0.0029
    0.15   0.002    0.15    1.74    0.26    1.74    0.26   0.002    0.33   0.002
       1     1.0    0.44
       1       3                   0.003     0.0    0.58
    45.0   0.022
    0.58     0.3   0.022
       2
     001     289     346
      20      43      74      91
       3     0.5     0.8     1.0
    0.43    0.64    0.56
     0.5     0.5     0.6
   0.014   0.014   0.015
    0.43    0.64    0.43
     0.5     0.5     1.0
   0.014   0.014   0.015
    0.43    0.64    0.43
     0.5     0.5     0.6
   0.014   0.014   0.015
    0.18    0.13    0.56    0.43
     0.6     0.6     0.6     0.5
   0.015   0.023   0.023   0.014
    0.56    0.18    0.18    0.43
     1.0     1.0     1.0     0.5
   0.015   0.023   0.023   0.014
    0.56    0.18    0.18    0.43
     0.6     0.6     0.6     0.5
   0.015   0.023   0.023   0.014
       1     1.0
   0.033   0.033   0.040
   -0.40   -0.40    0.05
    10.0    10.0    0.13
   0.040   0.050   0.050   0.033
    0.05    0.05    0.05   -0.40
    0.13    0.13    0.13    10.0
```

Nutrients

```
DAMI RANCHO SENSITIVITY NUTRIENT BASE
Entered 25 AUGUST 2009

    2008    2009       1       2       1
     0.0     0.4
    0.13    0.13

   361.0   361.0


    11.6    11.6

    1288
       1       2    2074
```

```
      79       0  9000.0     1.3    60.0    9.23    1.67   -0.48
    1289      01       0      15
    6.27     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1290      23    15.0     1.0     1.0
    2091       8    15.0
       0
```

C.2.3 Totora Kocha (TTK)

Hydrology

```
TOTORA KOCHA HYDROLOGY Validation with base values
Entered 29 July 2009
SANKAYANI CLIMATE DATA
 2008309       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

  0.2532     0.5     0.1     4.5      86   0.013  114.93    40.0  3784.0  -17.45
       2       2    15.0    40.0
    0.55    0.55
    0.29    0.29
    0.15    0.15
    0.50    0.50
     2.0     2.0
    20.0    20.0
    61.0    61.0
     5.2     5.2
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1310    2074            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

```
TOTORA KOCHA EROSION Validation with base values
Entered 29 July 2009

    2008    2009       2       3       1
    30.0
```

```
       5  0.0052
    0.16   0.002    0.16    1.35    0.31    1.35    0.31   0.002    0.34   0.002
       1     1.0    0.44
       1       3                   0.005     0.0    0.74
    77.0  0.0130
    0.74     0.3   0.013
       2
     001     310     355     365
      29      74     111
       3     0.5     0.9     1.0
    0.43    0.64    0.56    0.18
     1.0     1.0     0.6     0.6
   0.014   0.014   0.015   0.015
    0.43    0.64    0.43    0.56
     1.0     1.0     1.0     1.0
   0.014   0.014   0.015   0.015
    0.43    0.64    0.43    0.56
     1.0     1.0     0.6     0.6
   0.014   0.014   0.015   0.015
    0.13    0.56    0.43
     0.6     0.6     1.0
   0.023   0.023   0.014
    0.18    0.18    0.43
     1.0     1.0     1.0
   0.023   0.023   0.014
    0.18    0.18    0.43
     0.6     0.6     1.0
   0.023   0.023   0.014
       1     1.0
   0.033   0.033   0.040   0.040
   -0.40   -0.40    0.05    0.05
    10.0    10.0    0.05    0.05
   0.050   0.050   0.033
    0.05    0.05   -0.40
    0.05    0.05    10.0
```

Nutrients

```
TOTORA KOCHA NUTRIENT
Entered 29 July 2009

    2008    2009       1       2       1
     0.0     0.4
    0.22    0.22

   582.0   582.0


   13.73   13.73

    1309
       1       2    2074
      79       0  9000.0     1.6    60.0    10.9    1.67   -0.48
    1310       1       0      15
     3.9     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1311      23    15.0     1.0     1.0
    2111       8    15.0
       0
```

C.2.4 Sankayani Alto- Puruma (SAR)

Hydrology

```
SANKAYANI ALTO PURUMA HYDROLOGY Validation with base values
Entered 29 July 2009
SANKAYANI ALTO CLIMATE DATA
 2008274       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

  0.2244     0.5     0.1     4.5      86   0.048   58.33    40.0  4036.0  -17.45
       2       2    15.0    40.0
    0.68    0.68
    0.26    0.26
    0.12    0.12
    0.50    0.50
     2.5     2.5
    15.0    15.0
    61.0    61.0
     5.5     5.5
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1275    2074            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

```
SANKAYANI ALTO PURUMA EROSION Validation with base values
Entered 29 July 2009

    2008    2009       2       3       1
    30.0
       5  0.0030
    0.17   0.002    0.17    1.51    0.31    1.51    0.31   0.002    0.36   0.002
       1     1.0    0.41
       1       3                   0.003     0.0    0.66
    42.0  0.0476
    0.66     0.3   0.048
```

```
       2
     001     275
      15      29      40      74     120
       3     0.5     0.9     1.0
    0.43    0.64
     1.0     1.0
   0.032   0.032
    0.43    0.64
     1.0     1.0
   0.032   0.032
    0.43    0.64
     1.0     1.0
   0.032   0.032
    0.56    0.18    0.13    0.56    0.43
     0.5     0.5     0.5     0.5     1.0
   0.032   0.032   0.032   0.032   0.032
    0.43    0.43    0.43    0.43    0.43
     1.0     1.0     1.0     1.0     1.0
   0.032   0.032   0.032   0.032   0.032
    0.43    0.43    0.43    0.43    0.43
     0.5     0.5     0.5     0.5     1.0
   0.032   0.032   0.032   0.032   0.032
       1     1.0
   0.060   0.060
   -0.40   -0.40
    10.0    10.0
   0.060   0.060   0.060   0.060   0.060
    0.05    0.05    0.05    0.05   -0.40
    0.10    0.10    0.10    0.10    10.0
```

Nutrients

```
SANKAYANI ALTO-PURMA INJECTED MINERAL FERT
Entered 29 July 2009

    2008    2009       1       2       1
  2290.0     0.4
    0.28    0.28

   537.0   537.0


    9.45    9.45

    1274
       2       2    2074
      79       0  9000.0    1.54    60.0    6.95    1.67   -0.48
    1275       1       0      15
     7.3     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1275       0       2
            19.0    50.0    15.0
    1276      23    15.0     1.0     1.0
    2120       8    15.0
       0
```

C.2.5 Sankayani Alto- Papa (SAP)

Hydrology

```
SANKAYANI ALTO PAPA HYDROLOGY Validation with base values
Entered 29 July 2009
High zone climate data
 2008274       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

   0.146     0.5     0.1     4.5      86   0.032   46.01    40.0  4026.0  -17.45
       2       2    15.0    40.0
    0.63    0.63
    0.26    0.26
    0.12    0.12
    0.50    0.50
     2.7     2.7
    15.0    15.0
    58.0    58.0
     5.1     5.1
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1275    2074            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

```
SANKAYANI ALTO PAPA EROSION Validation with base values
Entered 29 July 2009

    2008    2009       2       3       1
    30.0
       5  0.0021
    0.17   0.002    0.17    1.40    0.29    1.40    0.29   0.002    0.34   0.002
       1     1.0    0.41
       1       3                   0.002     0.0    0.71
    31.0  0.0323
    0.71     0.3   0.032
       2
```

```
     001     275
      15      29      40      74     120
       3     0.5     0.9     1.0
    0.43    0.64
     1.0     1.0
   0.018   0.018
    0.43    0.64
     1.0     1.0
   0.018   0.018
    0.43    0.64
     1.0     1.0
   0.018   0.018
    0.56    0.18    0.13    0.56    0.43
     0.5     0.5     0.5     0.5     1.0
   0.018   0.018   0.018   0.018   0.018
    0.43    0.43    0.43    0.43    0.43
     1.0     1.0     1.0     1.0     1.0
   0.018   0.018   0.018   0.018   0.018
    0.43    0.43    0.43    0.43    0.43
     0.5     0.5     0.5     0.5     1.0
   0.018   0.018   0.018   0.018   0.018
       1     1.0
   0.050   0.050
   -0.40   -0.40
    10.0    10.0
   0.050   0.050   0.050   0.050   0.050
    0.05    0.05    0.05    0.05   -0.40
    0.10    0.10    0.10    0.10    10.0
```

Nutrients

```
SANKAYANI ALTP PAPA- INJECTED MINERAL FERT
Entered 30 July 2009

    2008    2009       1       2       1
   973.0     0.4
    0.31    0.31

   675.0   675.0


   19.08   19.08

    1274
       2       2    2074
      79       0  9000.0    1.32    60.0    7.85    1.67   -0.48
    1275       1       0      15
     8.4     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1275       0       2
            19.0    50.0    15.0
    1276      23    15.0     1.0     1.0
    2120       8    15.0
       0
```

C.2.6 Villa Flores, experimental plot 2 (VF2)

Hydrology

```
VILLA FLORES PAPA 2 HYDROLOGY Validation with base values
Entered 29 July 2009
Sankayani Precip and Villa Flores precip after 1/16/2009
 2008318       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

   0.001     0.5     0.1     4.5      90  0.0002    3.34    40.0  3971.0  -17.43
       2       2    15.0    40.0
    0.63    0.63
    0.24    0.24
    0.10    0.10
    0.50    0.50
     2.3     2.3
    15.0    15.0
    52.0    52.0
     5.4     5.4
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1319    2088            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

```
VILLA FLORES POTATO EROSION Validation with base values
Entered 29 July 2009
OVERLAND-CHANNEL
    2008    2009       2       3       1
    30.0
       5  0.0001
    0.13   0.002    0.13    1.33    0.25    1.33    0.25   0.002    0.30   0.002
       1     1.0    0.46
       1       3                   .0001     0.0    0.75
     2.0  0.0002
    0.75   0.012   .0002
```

```
       2
     001     319
     008      40      60      88     120
       3     0.4     0.8     1.0
    0.43    0.64
     0.9     0.9
   0.014   0.014
    0.43    0.64
     0.9     0.9
   0.014   0.014
    0.43    0.64
     0.9     0.9
   0.014   0.014
    0.56    0.18    0.13    0.56    0.43
     0.5     0.5     0.5     0.5     0.9
   0.014   0.014   0.014   0.014   0.014
    0.43    0.43    0.43    0.43    0.43
     1.0     1.0     1.0     1.0     0.9
   0.014   0.014   0.014   0.014   0.014
    0.43    0.43    0.43    0.43    0.43
     0.5     0.5     0.5     0.5     0.9
   0.014   0.014   0.014   0.014   0.014
       1     1.0
   0.033   0.033
   -0.40   -0.40
    10.0    10.0
   0.033   0.033   0.033   0.033   0.033
    0.05    0.05    0.05    0.05   -0.40
    0.11    0.11    0.11    0.11    10.0
```

Nutrients

```
VILLA FLORES 2 NUTRIENT
Entered 30 July 2009

    2008    2009       1       2       1
     0.0     0.4
    0.25    0.25

   545.0   545.0


   34.06   34.06

    1318
       1       2    2088
      79       0  9000.0    1.60    60.0    6.65    1.67   -0.48
    1319       1       0      15
    5.78     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1320      23    15.0     1.0     1.0
    2120       8    15.0
       0
```

C.2.7 Villa Flores, experimental plot 4 (VF4)

Hydrology

```
VILLA FLORES PAPA 4 HYDROLOGY Validation with base values
Entered 29 July 2009
Sankayani Precip and Villa Flores precip after 1/16/2009
 2008318       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

   0.001     0.5     0.1     4.5      90  0.0002    3.34    40.0  3971.0  -17.43
       2       2    15.0    40.0
    0.61    0.61
    0.24    0.24
    0.10    0.10
    0.50    0.50
     2.2     2.2
    15.0    15.0
    52.0    52.0
     5.6     5.6
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1319    2088            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

(same erosion input paramerter file as VF2)

Nutrients

```
VILLA FLORES 4 NUTRIENT
Entered 30 July 2009

    2008    2009       1       2       1
     0.0     0.4
    0.23    0.23
```

```
   534.0   534.0


   15.87   15.87

    1318
       1       2    2088
      79       0  9000.0    1.60    60.0    6.65    1.67   -0.48
    1319       1       0      15
    5.78     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1320      23    15.0     1.0     1.0
    2120       8    15.0
       0
```

C.2.8 Villa Flores, experimental plot 8 (VF8)

Hydrology

```
VILLA FLORES PAPA 8 HYDROLOGY Validation with base values
Entered 29 July 2009
Sankayani Precip and Villa Flores precip after 1/16/2009
 2008318       0       1       1       0       0       1       0       1       0
     958     961     957     950     955     965     966     975     976

   0.001     0.5     0.1     4.5      90  0.0002    3.34    40.0  3971.0  -17.43
       2       2    15.0    40.0
    0.60    0.60
    0.24    0.24
    0.10    0.10
    0.50    0.50
     2.0     2.0
    15.0    15.0
    52.0    52.0
     5.3     5.3
    69.0    69.0
    12.3    12.5    12.6    12.7    13.5    13.7    13.4    14.4    13.8    13.4
    14.7    12.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    18.3    19.3    19.8    21.0    20.6    18.9    20.0    21.4    23.4    24.2
    23.1    20.7
   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8   172.8
   172.8   172.8
     4.1     4.6     4.0     2.8     2.7     2.2     1.4     2.2     2.2     3.6
     4.4     4.3
    2008    2009       2
      79    1319    2088            30.0    0.60       0
       0
       0
      79      10
    0.00    0.00
    0.36    0.35
    0.43    0.70
    0.50    1.35
    0.57    2.00
    0.64    3.00
    0.71    3.50
    0.79    3.90
    0.86    3.90
    1.00    2.35
       0       0       0       0
      -1       0       0       0
```

Erosion

(same erosion input paramerter file as VF2)

Nutrients

```
VILLA FLORES 8 NUTRIENT
Entered 30 July 2009

    2008    2009       1       2       1
     0.0     0.4
    0.22    0.22

   521.0   521.0


   10.52   10.52

    1318
       1       2    2088
      79       0  9000.0    1.62    60.0    6.65    1.67   -0.48
    1319       1       0      15
    5.78     0.0     2.7     2.1     0.5    1.98    1.52    44.7       1
    1320      23    15.0     1.0     1.0
    2120       8    15.0
       0
```

Appendix D. Results from phosphorus comparisons

D.1 Soil phosphate concentrations

The soil phosphate (mg kg^{-1}) by soil level is plotted with the observed soil phosphate concentrations at potato flowering and potato harvest to graphically compare the data. Continuous lines represent the simulated concentration for the corresponding soil horizon (depths shown are increment depths, not cumulative depths). Points represent measured data from the 0-15 cm and 15-30 cm potato hill depths.

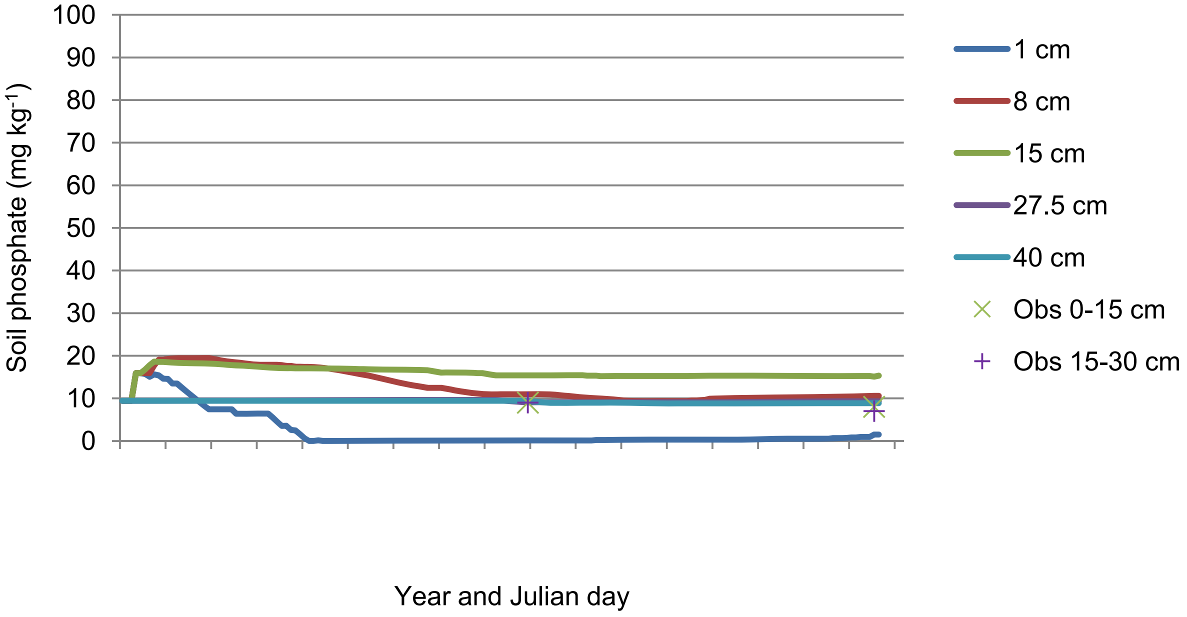

Figure D.1 Site CBJ simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed Olsen-P concentration at potato flowering and harvest.

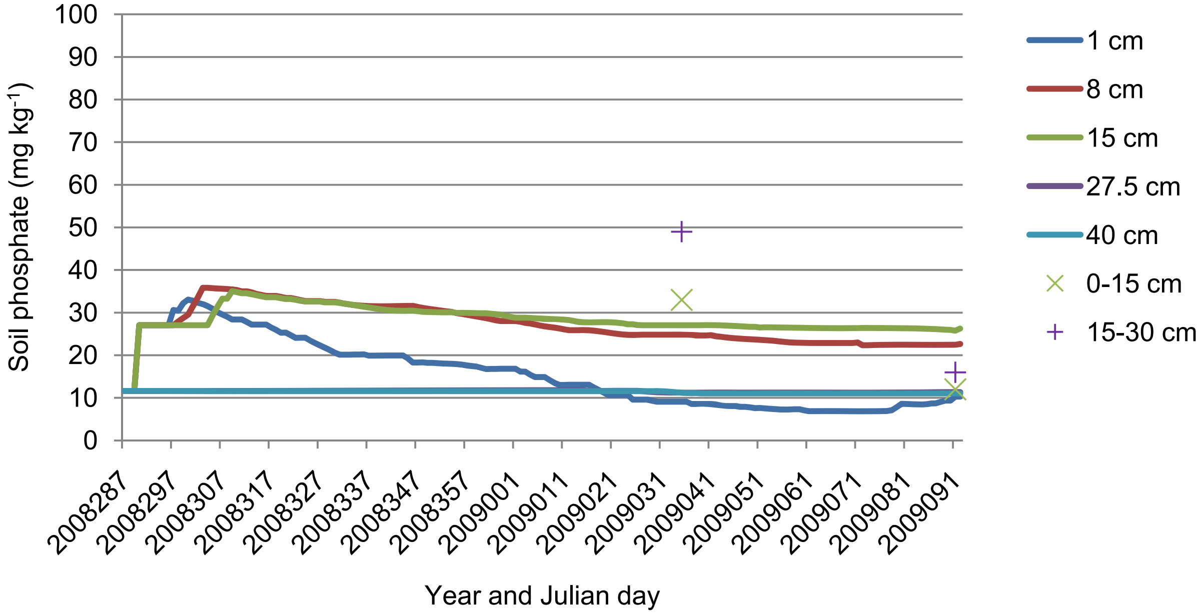

Figure D.2 Site DMR simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed Olsen-P concentration at potato flowering and harvest.

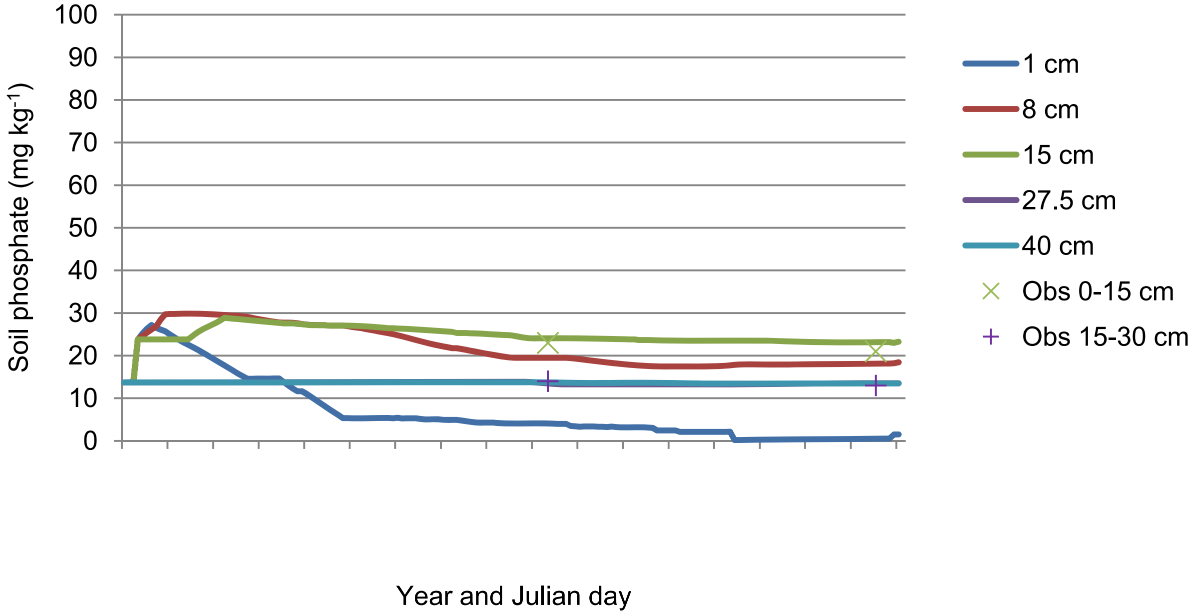

Figure D.3 Site TTK simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed Olsen-P concentration at potato flowering and harvest.

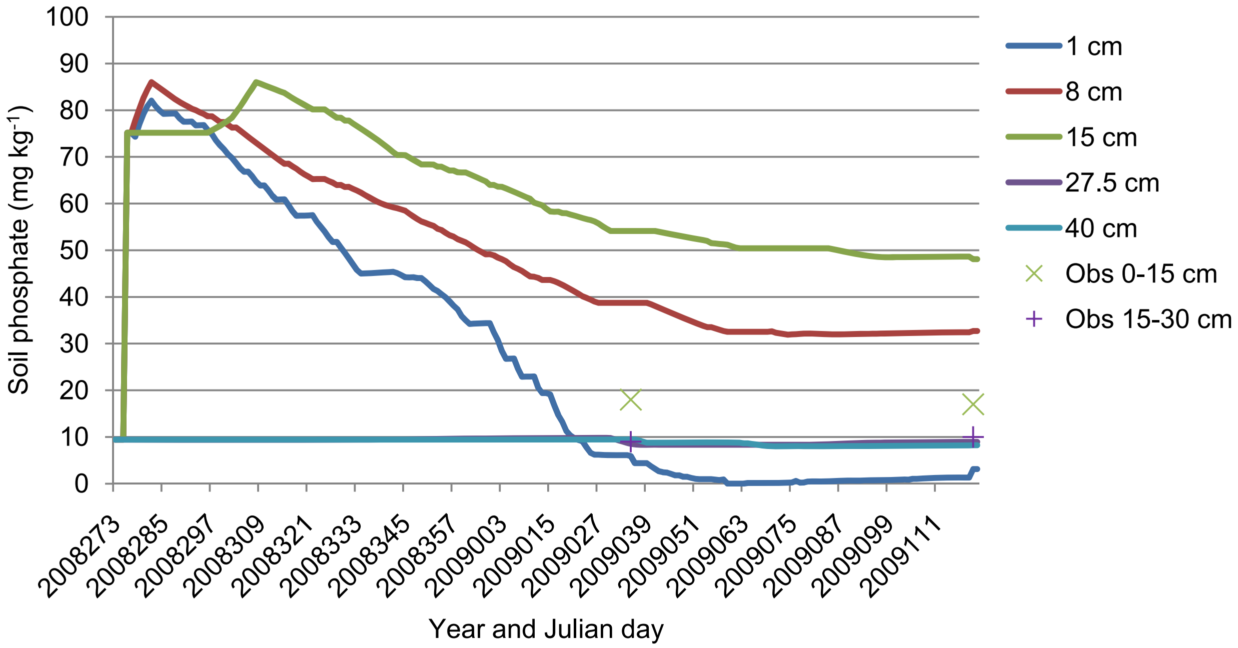

Figure D.4 Site SAR simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed Olsen-P concentration at potato flowering and harvest.

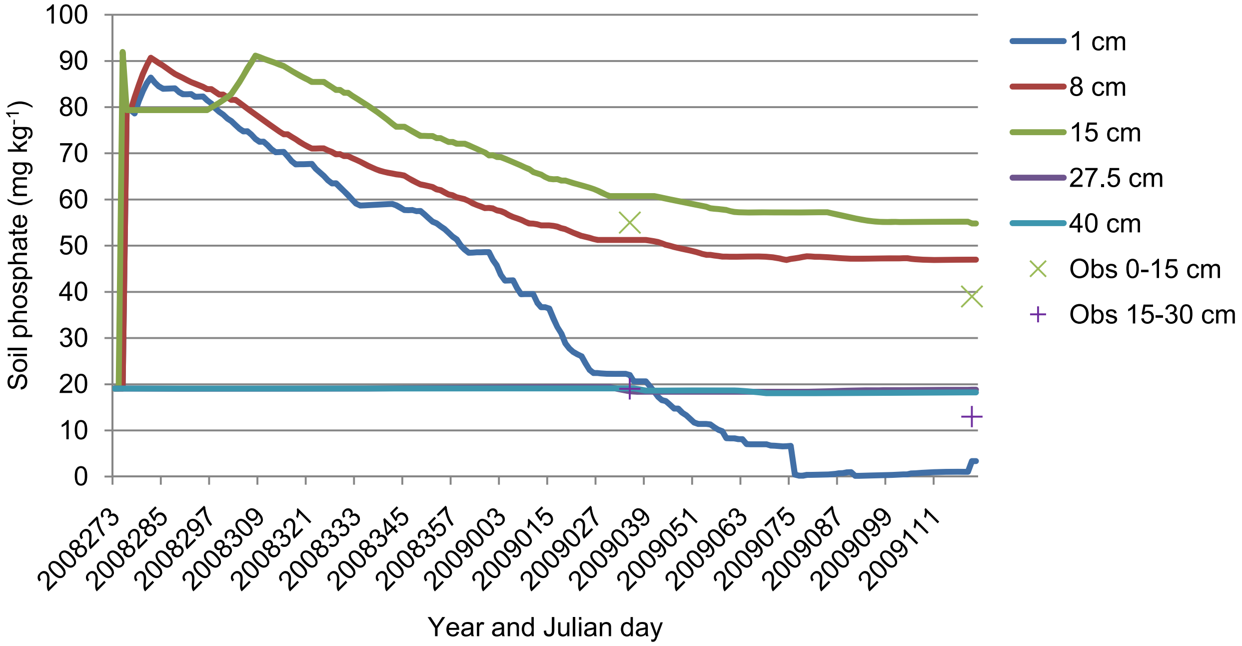

Figure D.5 Site SAP simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed Olsen-P concentration at potato flowering and harvest.

Figure D.6 Site VF2 simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed phosphate concentration prior to potato flowering, at potato flowering, and harvest.

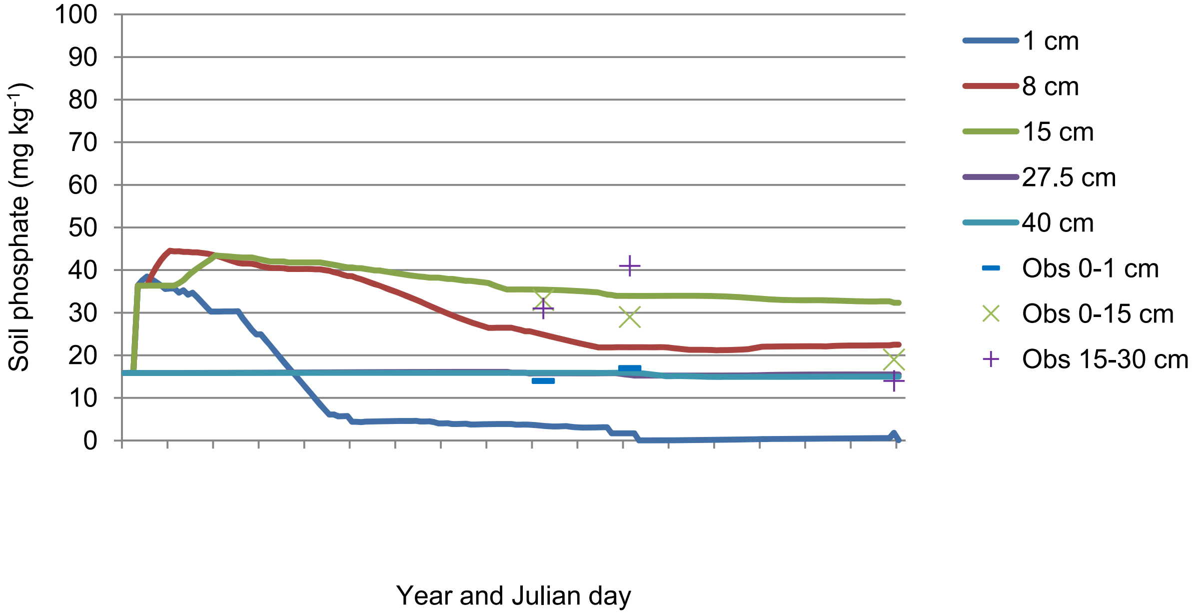

Figure D.7 Site VF4 simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed phosphate concentration prior to potato flowering, at potato flowering, and harvest.

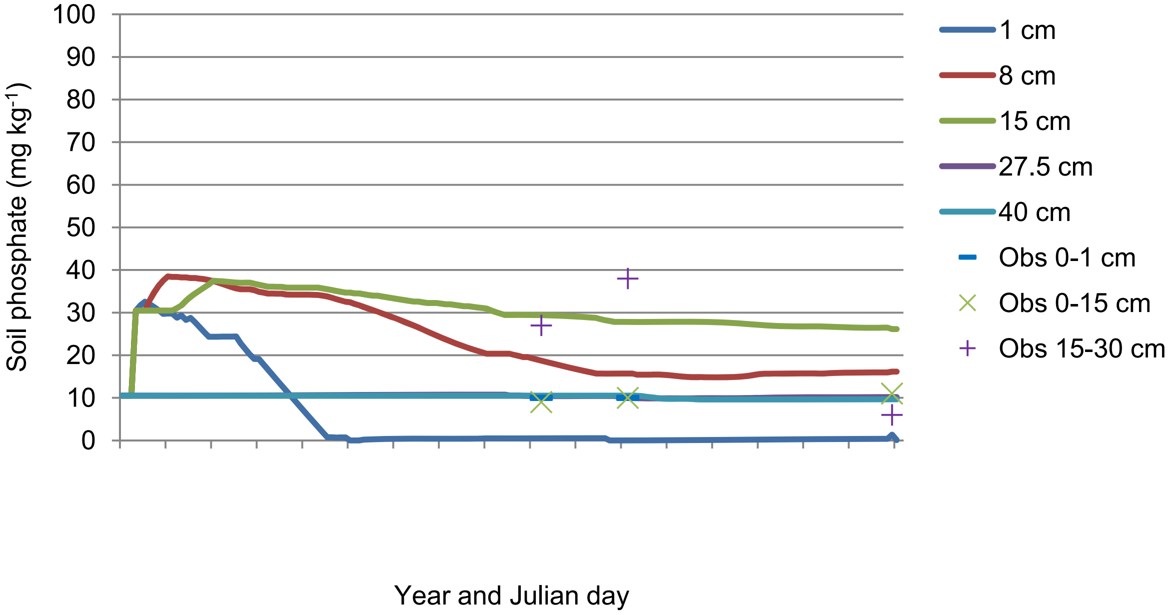

Figure D.8 Site VF8 simulated daily soil phosphate concentration (mg kg^{-1}) from planting to harvest by incremental soil depth with point observed phosphate concentration prior to potato flowering, at potato flowering, and harvest.

D.2 Crop P uptake

The results from the comparisons between observed and simulated crop P uptake and P in yield are included from the data collected over the 2008-2009 growing season.

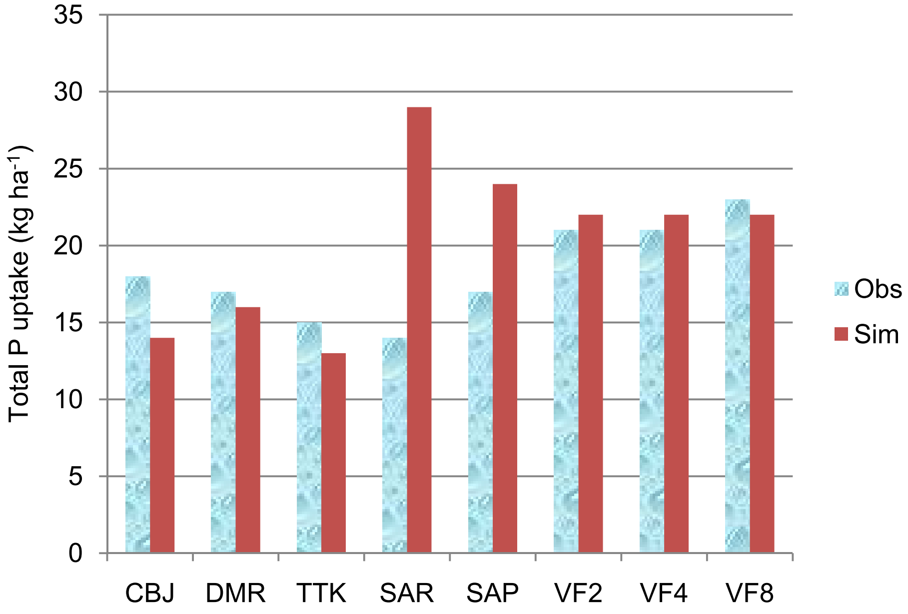

Figure D.9 Observed and simulated seasonal crop P uptake (dry basis) for all sites.

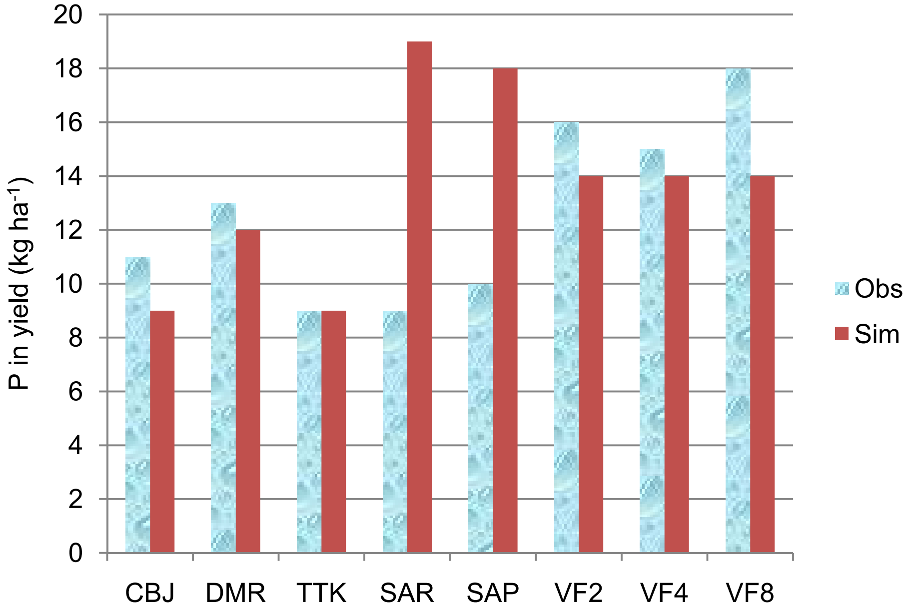

Figure D.10 Observed and simulated P in yield (dry basis) for all sites.

Table D.1 Observed and simulated crop P uptake and P in yield and corresponding root mean square error and standard deviation ratio.

Site	Total P uptake (kg ha^{-1})		P in yield (kg ha^{-1})	
	Obs	Sim	Obs	Sim
CBJ	18	14	11	9
DMR	17	16	13	12
TTK	15	13	9	9
SAR	14	29	9	19
SAP	17	24	10	18
VF2	21	22	16	14
VF4	21	22	15	14
VF8	23	22	18	14
RSR		5		4
PBIAS		-11%		-12%

Appendix E. Villa Flores mineralization printed output error

The N and P mineralization output printed in the GLEAMS standard nutrient output for the Villa Flores site was extremely large on a monthly basis which led to reported annual mineralization amounts to be unrealistically high. This high reported value appeared to reflect an error in how the model output was printing the monthly mineralization amount. The high printed mineralization amount did not appear to be the mineralization value used in the annual nutrient balance because it did not cause crop N uptake or N losses in runoff, leaching, volatilization, and denitrification to be unrealistically high. Although the mineralization amount appears to be in error only in the printed GLEAMS standard nutrient output and not the actual value used in the model processes, it is an example of how printed output of interest should be verified for general expected trends and reasonable values prior to model output analysis. An example of a portion the GLEAMS standard nutrient output for Villa Flores site, experimental plot 2 (VF2) is shown below in tables E.1- E.5

E.1 Monthly nutrient output for VF2

The VF2 plot was fertilized with 156 kg N ha^{-1} from a manure (chicken litter) application of 5.8 t ha^{-1}. The chicken litter had 2.7% total N content and 2.1% organic N content, the same chicken litter nutrient contents used for all sites (table E.1). The unrealistically high mineralization output occurred for all months over the 2008-2009 simulation period, though only the outputs for November, January, and March are shown in tables E.2-E.4.

Table E.1 Plot VF2 November output showing planting and fertilization inputs.

```
                         UPDATEABLE PLANT NUTRIENT INPUTS
                         --------------------------------

 POT. YIELD    9000. KG/HA;  DRY MATTER:YIELD   1.60
 COEFFICIENTS OF N-CONTENT: C1    1.67000  C2   -0.48000
 DATE OF HARVEST  2009088
 CROP


                                  ORGANIC FERTILIZATION
    DATE     RATE  TOTAL-N  ORGN.-N     NO3      NH4   TOTAL-P  ORGN.-P   SOL.-P
O.M.   METH. MAN.  WASTE DEPTH
          T/HA     %        %         %        %       %        %        %        %
APPL. TYPE  TYPE   CM
 2008319    5.78     2.70     2.10     0.10     0.50     1.98     1.52     0.46
44.70     0    15     1   0.00


TILLAGE OPERATIONS THAT INCORPORATE RESIDUE

     DATE   TYPE   DEPTH(CM)    INC. EFF.    MIX. EFF.

 2008320    23      15.0         1.00         1.00
 2009120     8      15.0         0.15         0.05

                              TILLAGE PERFORMED ON 2008320
          RESIDUE   YIELD   NITROGEN  PHOSPHORUS  DEPTH TILL.  MIX. EFF.
           (KG/HA)  (KG/HA)   (KG/HA)    (KG/HA)      (CM)
             0.00      0.00      0.00      0.00     15.00        1.00
```

Table E.2 Plot VF2 November 2009 monthly nutrient losses and transformations.

```
MONTHLY NUTRIENT LOSSES AND TRANSFORMATIONS
                   NITROGEN      PHOSPHORUS
                   --------      ----------
                    (KG/HA)        (KG/HA)
RUNOFF                 0.00            0.00
SEDIMENT               0.00            0.00
UPTAKE                 8.58            1.29
MINERALIZATION       141.87           99.16
LEACHED, TOTAL         0.00            0.00
  NITRATE              0.00        -------
  AMMONIA              0.00        -------
RAINFALL               0.08        -------
IRRIGATION             0.00            0.00
DENITRIFICATION        0.01        -------
AMMONIA VOLATIZED      4.56        -------
NITRATE FIXED          0.00        -------
```

Table E.3 Plot VF2 January 2009 monthly nutrient losses and transformations.

```
       MONTHLY NUTRIENT LOSSES AND TRANSFORMATIONS
                   NITROGEN      PHOSPHORUS
                   --------      ----------
                    (KG/HA)        (KG/HA)
RUNOFF                 0.01            0.02
SEDIMENT               4.40            1.49
UPTAKE                29.75            8.13
MINERALIZATION       236.37          170.03
LEACHED, TOTAL        15.38            0.19
  NITRATE             15.38        -------
  AMMONIA              0.00        -------
RAINFALL               0.60        -------
IRRIGATION             0.00            0.00
DENITRIFICATION        0.65        -------
AMMONIA VOLATIZED      0.00        -------
NITRATE FIXED          0.00        -------
```

Table E.4 Plot VF2 March 2009 monthly nutrient losses and transformations.

```
       MONTHLY NUTRIENT LOSSES AND TRANSFORMATIONS
                   NITROGEN      PHOSPHORUS
                   --------      ----------
                    (KG/HA)        (KG/HA)
RUNOFF                 0.00            0.00
SEDIMENT               0.25            0.08
UPTAKE                 0.83            2.90
MINERALIZATION       233.64          168.29
LEACHED, TOTAL         0.00            0.00
  NITRATE              0.00        -------
  AMMONIA              0.00        -------
RAINFALL               0.24        -------
IRRIGATION             0.00            0.00
DENITRIFICATION        0.02        -------
AMMONIA VOLATIZED      0.00        -------
NITRATE FIXED          0.00        -------
```

E.2 Annual nutrient balance output for VF2

The high printed mineralization does not appear to affect the annual nutrient balance, shown for 2009 in table E.5. In spite of large reported mineralization amounts in the monthly output, there is no accumulation of soil NO_3^- or soil NH_4^+; nor unreasonable runoff, leached, or N uptake reported.

Table E.5 Plot VF2 annual nitrogen balance for 2009.

```
                     ANNUAL NUTRIENT BALANCES

                               NITROGEN
                   BEGIN          END        NET CHANGE
                ----------    ----------   -----------
                  (KG/HA)       (KG/HA)      (KG/HA)
SOIL
  NO3                 39.69          5.91       -33.78
  NH4                  0.00          0.00        +0.00
  POT MIN N          1097.96       1100.29        +2.32
  STABLE SOIL N      8666.90       8663.27        -3.63
  CROP ORG N           30.33         41.39       +11.06
  A.W. ORG N           83.08         71.42       -11.67
SURFACE
  RESIDUE N            0.00          7.06        +7.06
  SOL NH               0.00          0.00        +0.00
  SOL NO3              0.00          0.00        +0.00
  A.W. ORG N           0.00          0.00        +0.00
  A.W. NH4             0.00          0.00        +0.00
PLANT N               32.68          0.00       -32.68
                 --------------------------------------
RUNOFF N         -      0.02
SED N            -      4.78
NO3 LEACHED      -     15.38
NH4 LEACHED      -      0.00
VOLATIZED NH     -      0.00
DNI N            -      0.70
YEILD N          -     41.56
BALE N           -      0.00
BURN N           -      0.00
FIXN N           +      0.00
RAINFALL N       +      1.19
IRRIGATION N     +      0.00
FERT NO3         +      0.00
FERT NH          +      0.00
A.W. ORG N       +      0.00
A.W. NO3         +      0.00
A.W. NH          +      0.00
SUM BEG POOLS    +   9950.65
SUM END POOLS    -   9889.34
                 ----------
NITROGEN BALANCE        +0.07
```

Appendix F. Simulated soil nitrogen pools over 2008-2009 validation period

F.1 Cebada Jichana

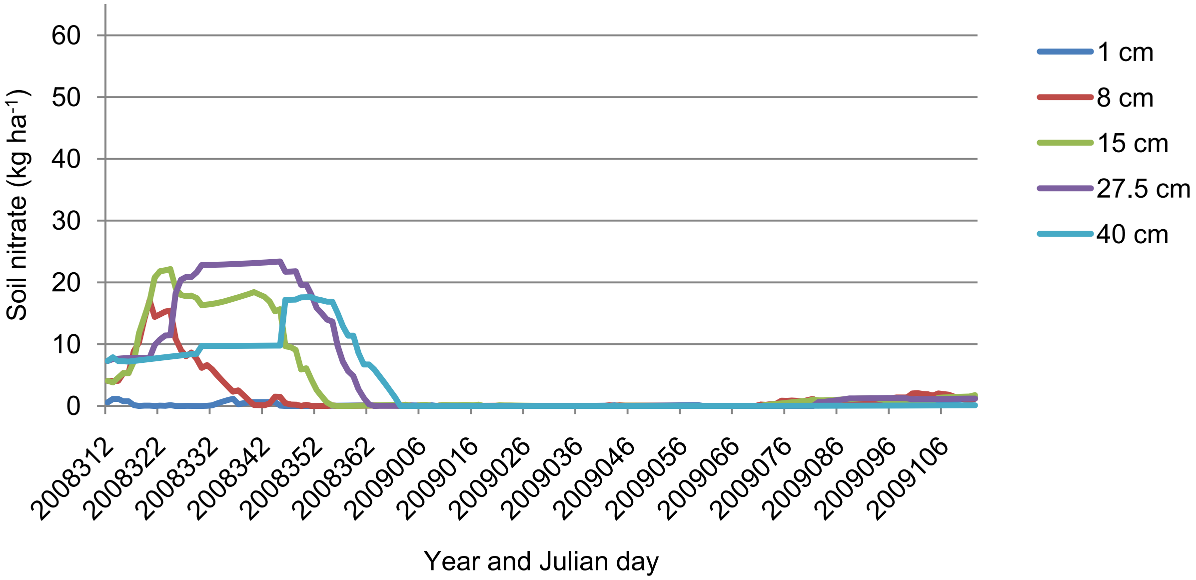

Figure F.1 Simulated soil nitrate over the 2008-2009 season by soil layer for site CBJ.

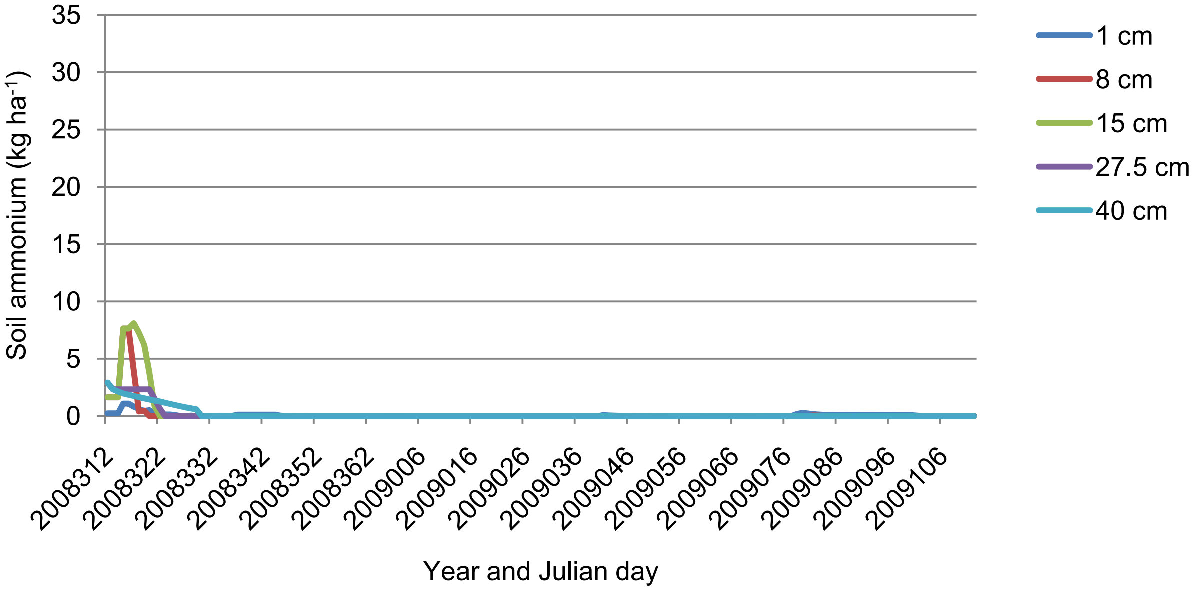

Figure F.2 Simulated soil ammonium over the 2008-2009 season by soil layer for site CBJ.

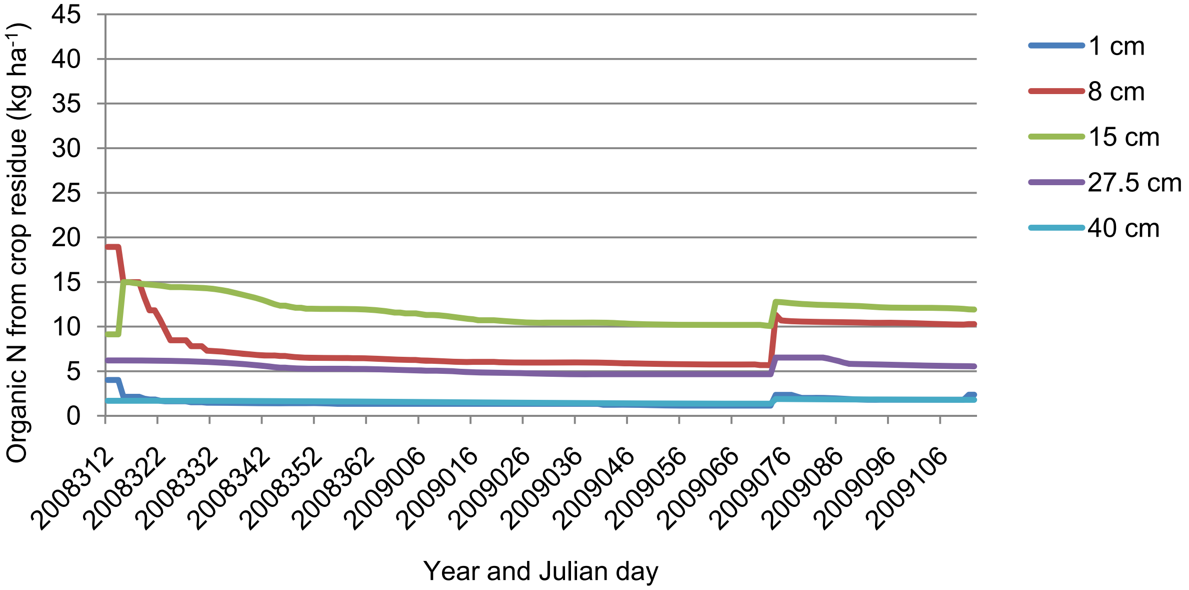

Figure F.3 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for site CBJ.

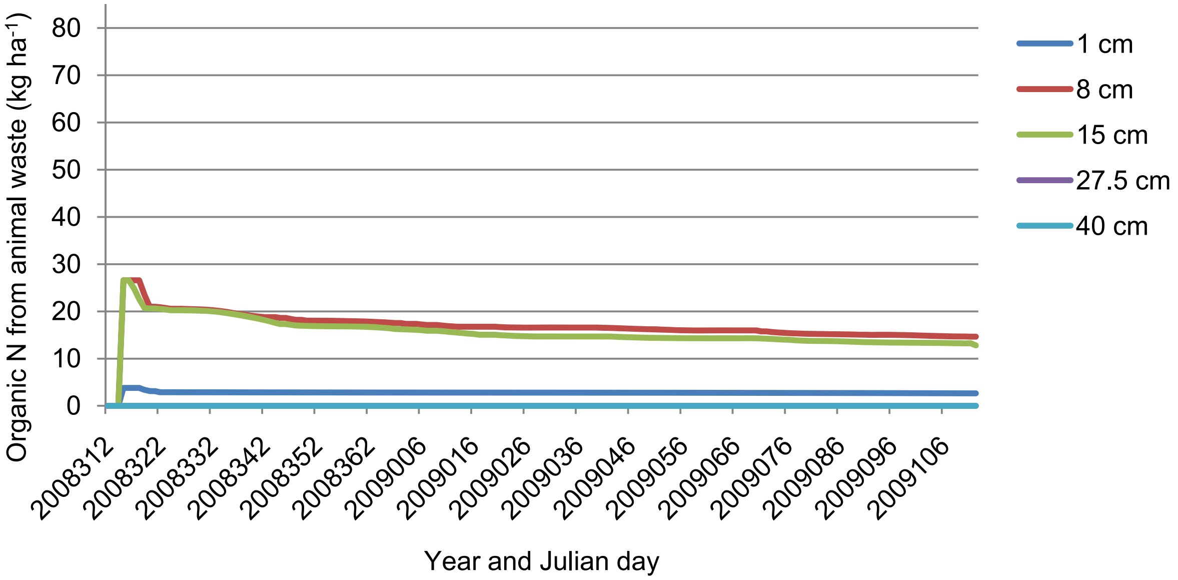

Figure F.4 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for site CBJ.

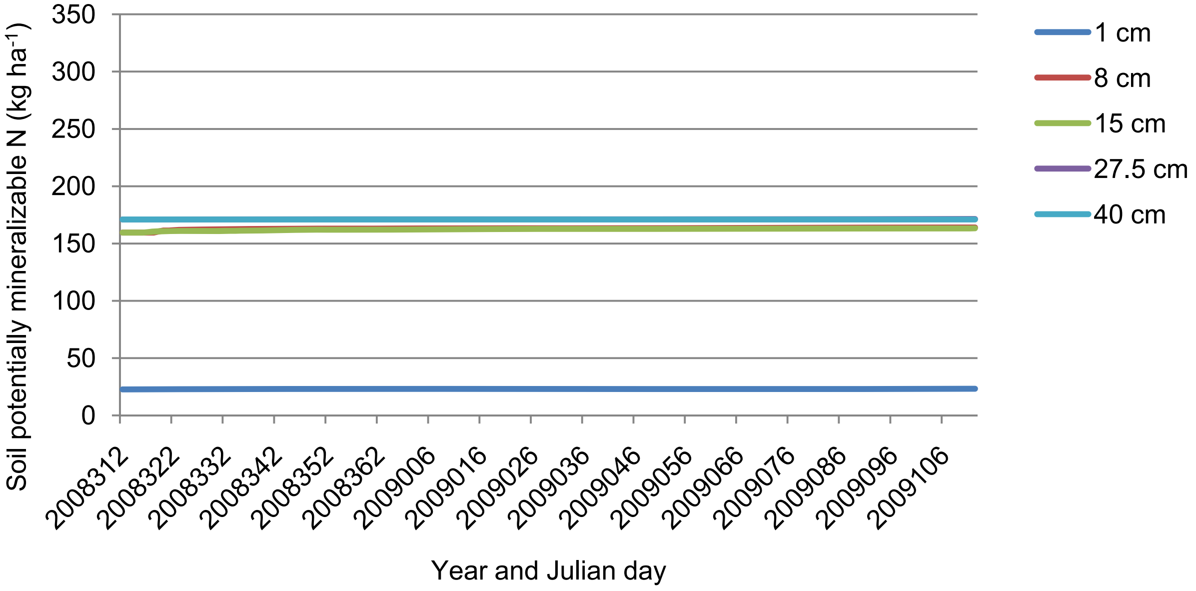

Figure F.5 Simulated soil potentially mineralizable nitrogen over the 2008-2009 season by soil layer for site CBJ.

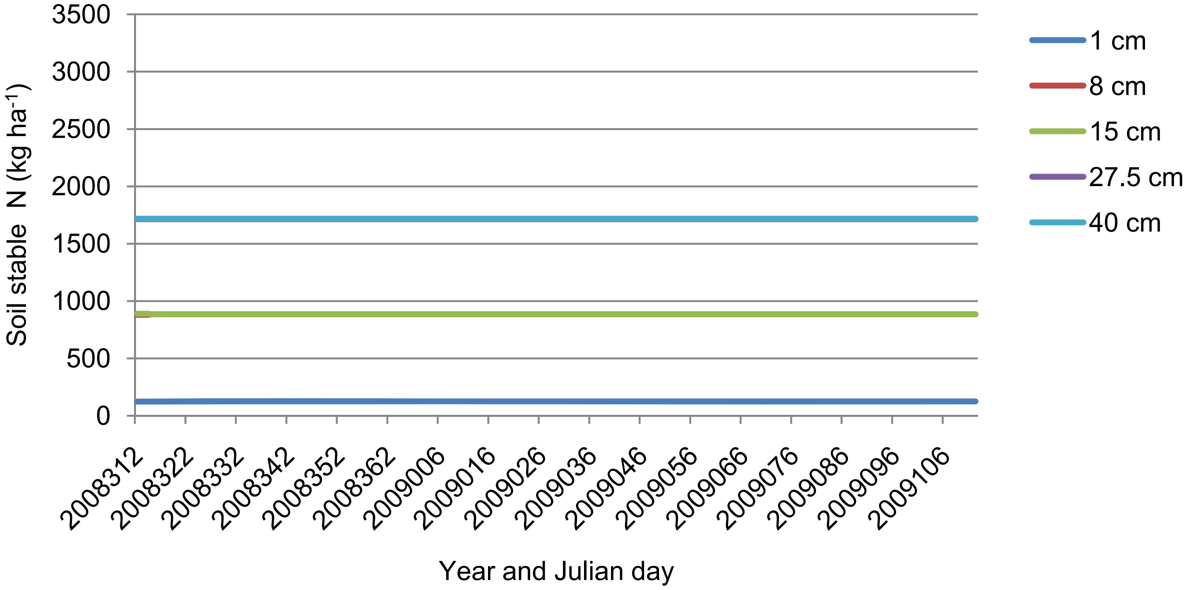

Figure F.6 Simulated soil stable N over the 2008-2009 season by soil layer for site CBJ.

F.2 Dami Rancho

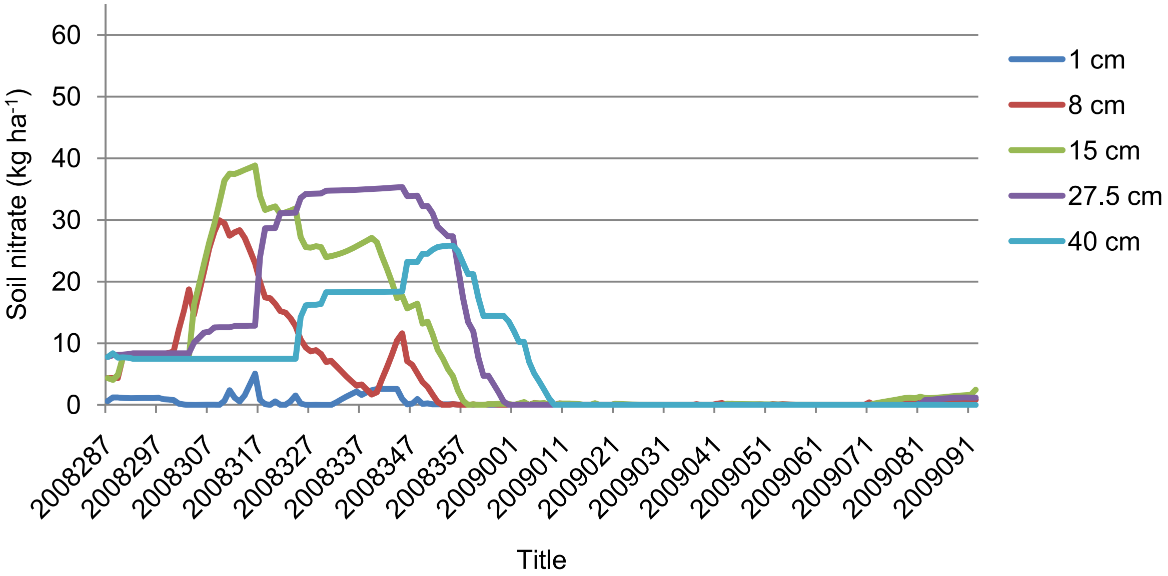

Figure F.7 Simulated soil stable N over the 2008-2009 season by soil layer for site DMR.

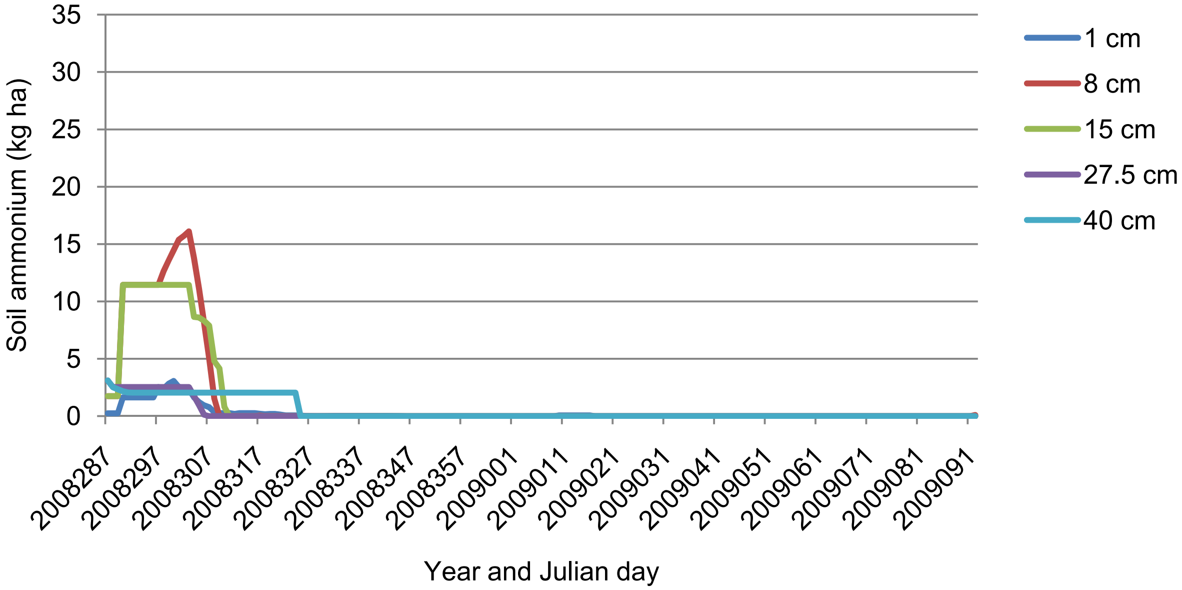

Figure F.8 Simulated soil ammonium over the 2008-2009 season by soil layer for site DMR.

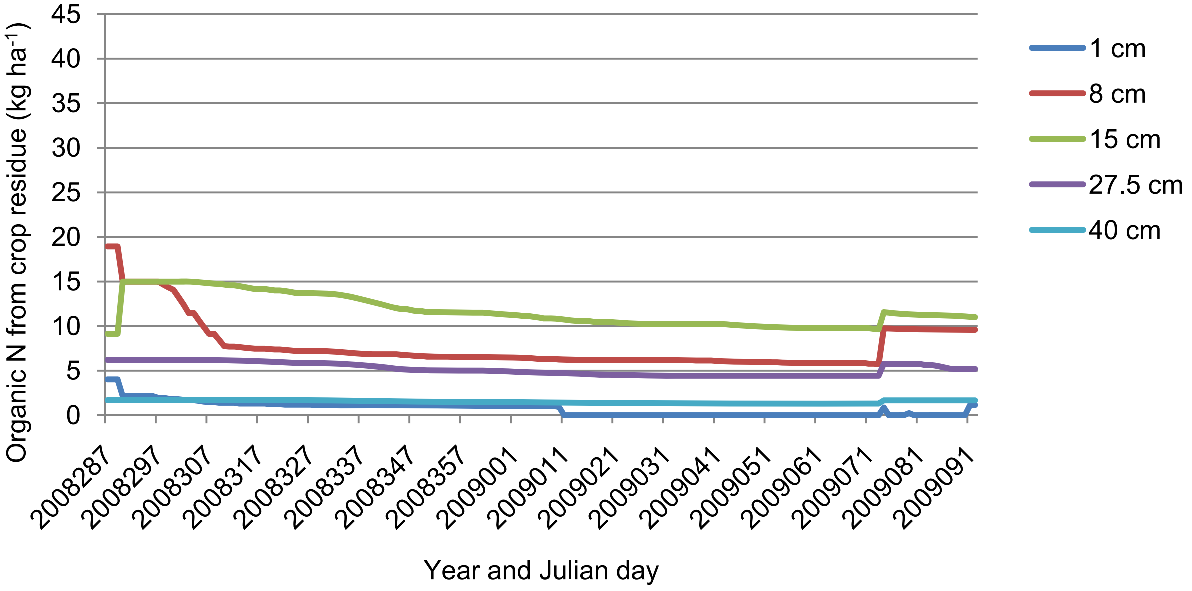

Figure F.9 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for site DMR.

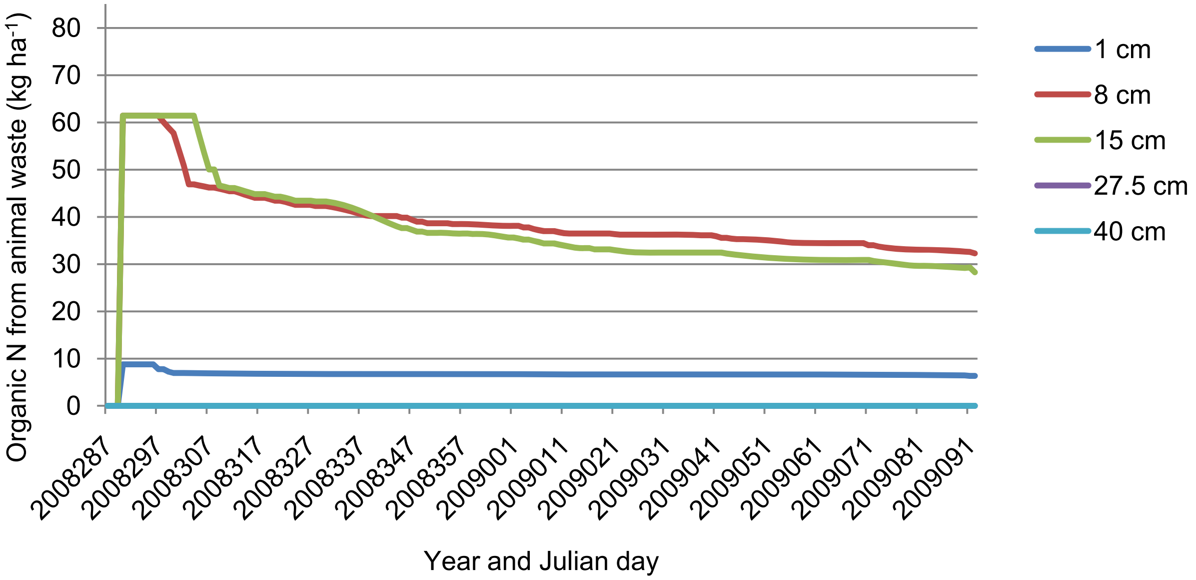

Figure F.10 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for site DMR.

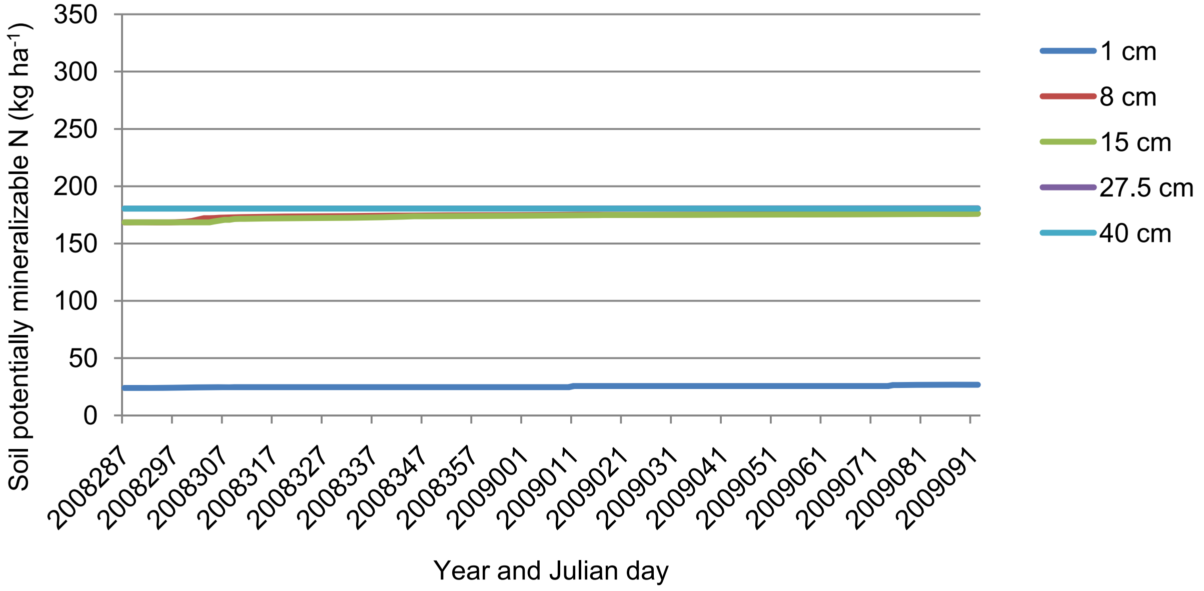

Figure F.11 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for site DMR.

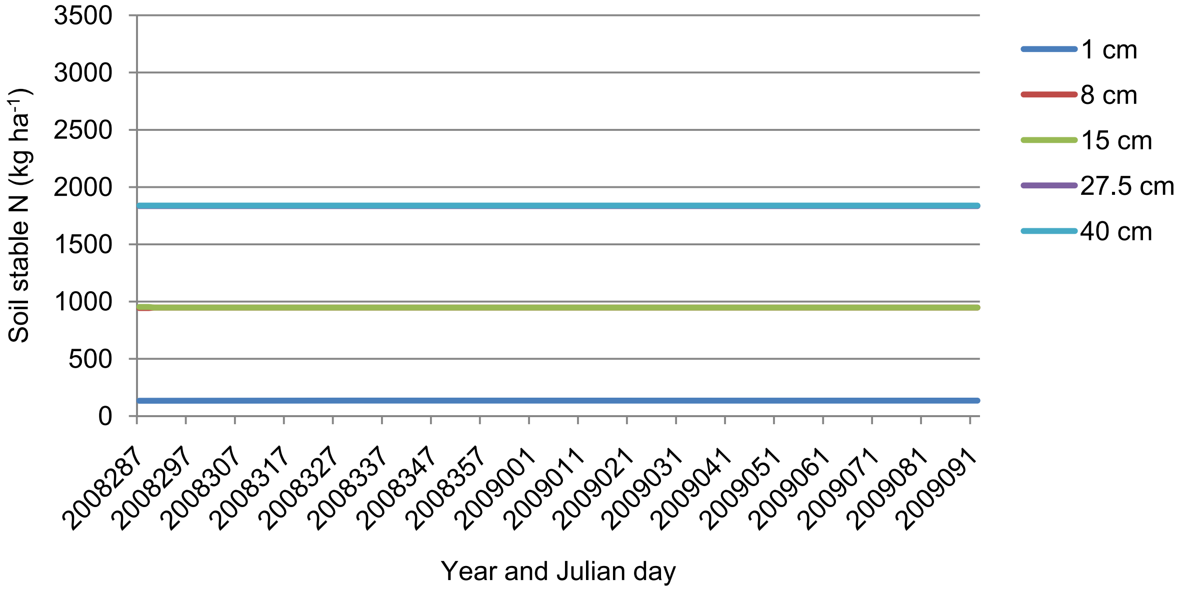

Figure F.12 Simulated soil stable N over the 2008-2009 season by soil layer for site DMR.

F.3 Sankayani Alto- Puruma

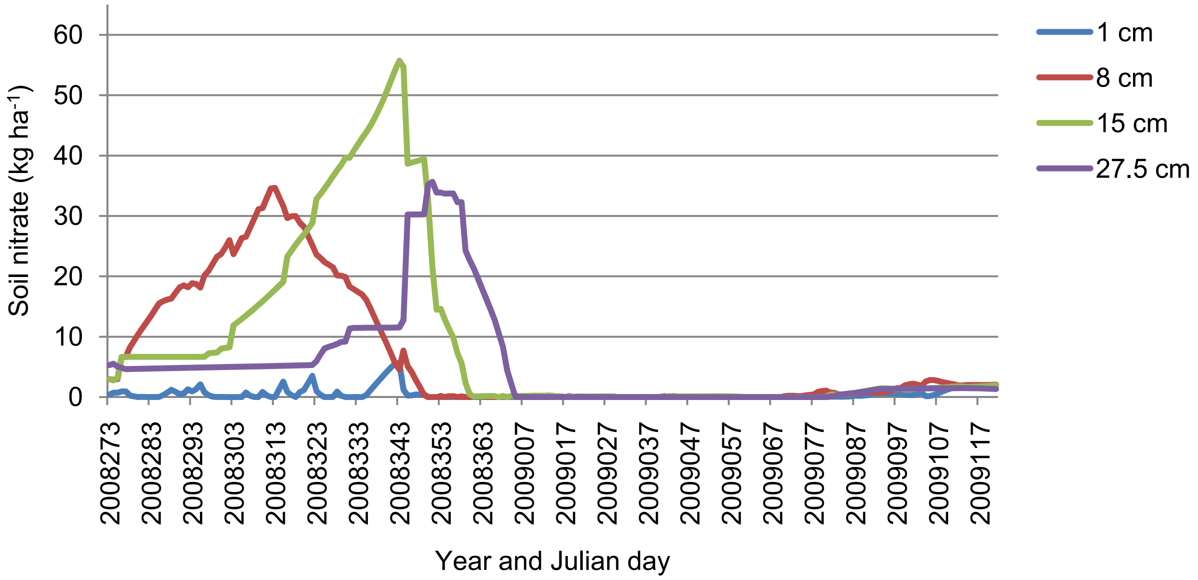

Figure F.13 Simulated soil nitrate over the 2008-2009 season by soil layer for site SAR.

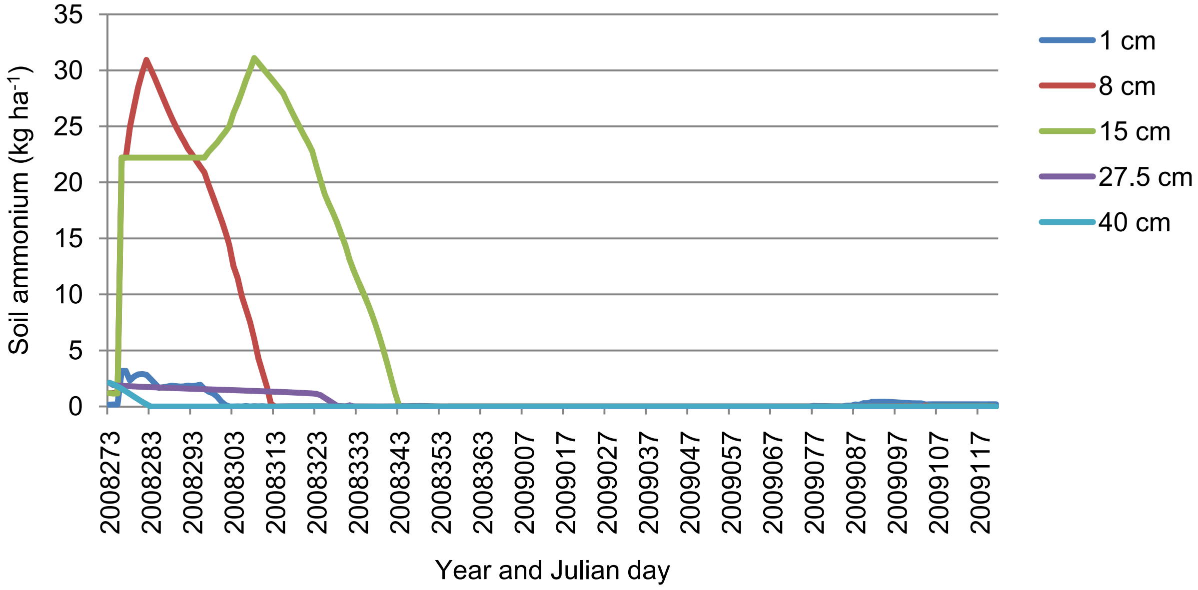

Figure F.14 Simulated soil ammonium over the 2008-2009 season by soil layer for site SAR.

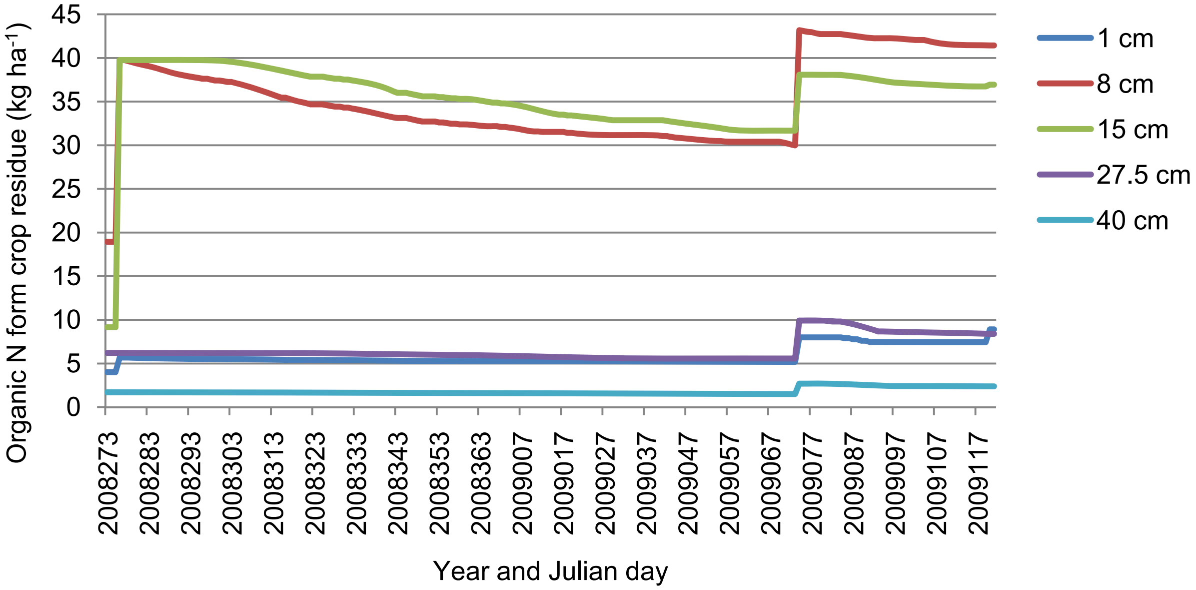

Figure F.15 Simulated soil organic N from crop waste over the 2008-2009 season by soil layer for site SAR.

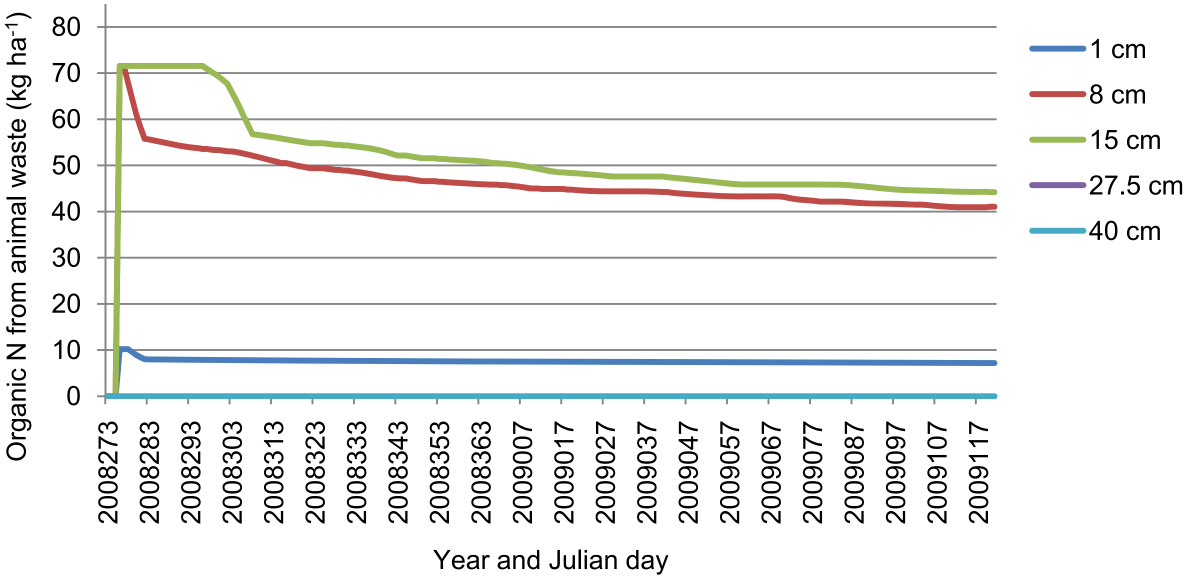

Figure F.16 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for site SAR.

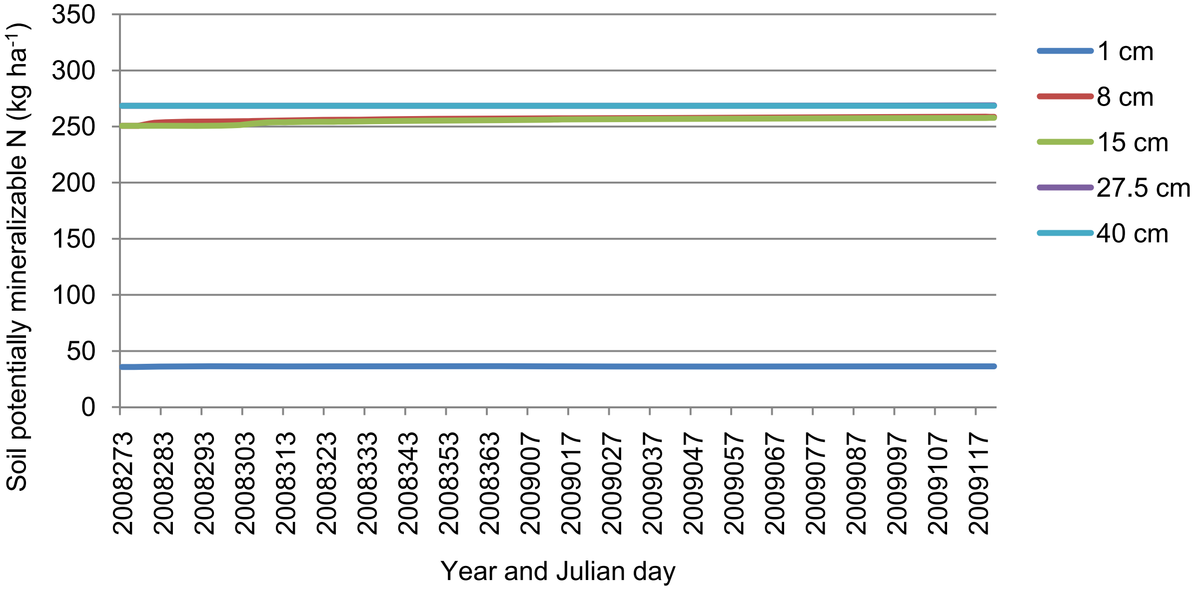

Figure F.17 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for site SAR.

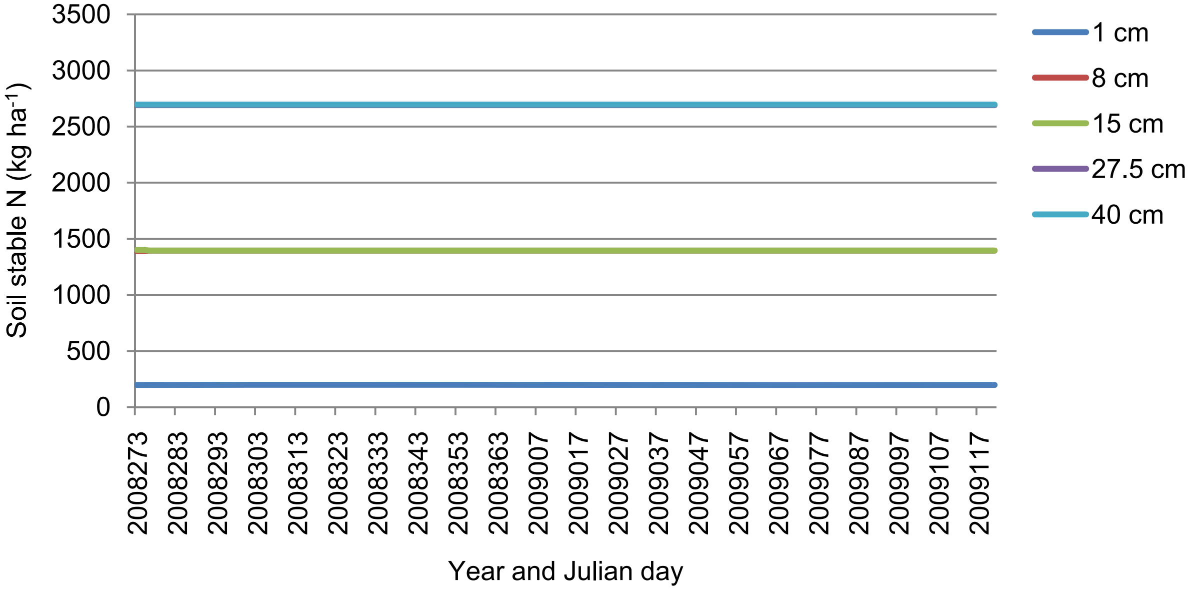

Figure F.18 Simulated soil stable N over the 2008-2009 season by soil layer for site SAR.

F.4 Sankayani Alto- Papa

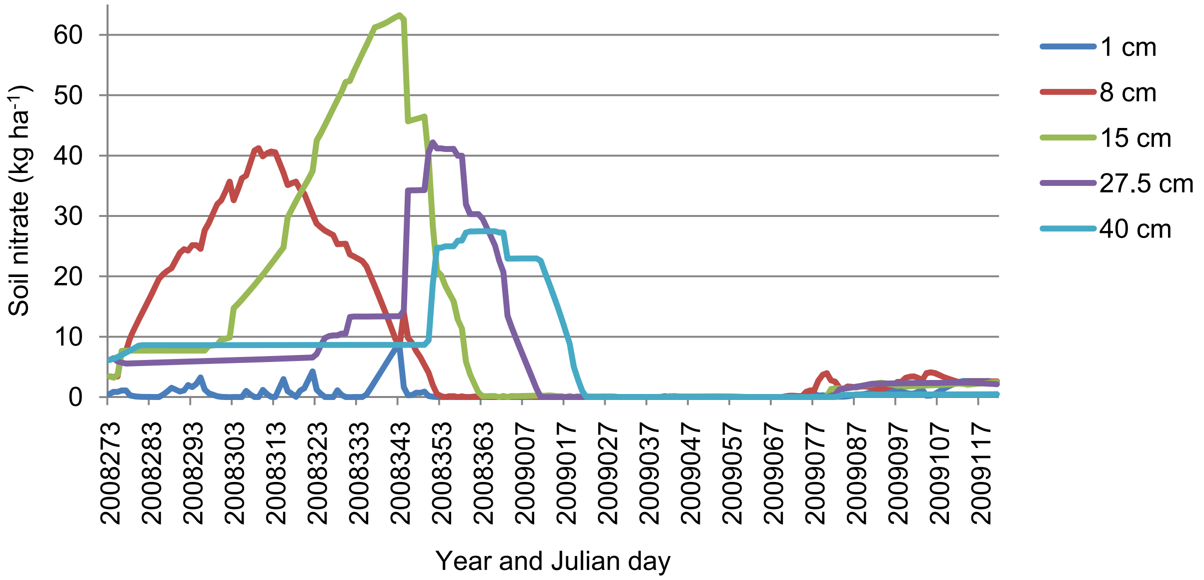

Figure F.19 Simulated soil nitrate over the 2008-2009 season by soil layer for site SAP.

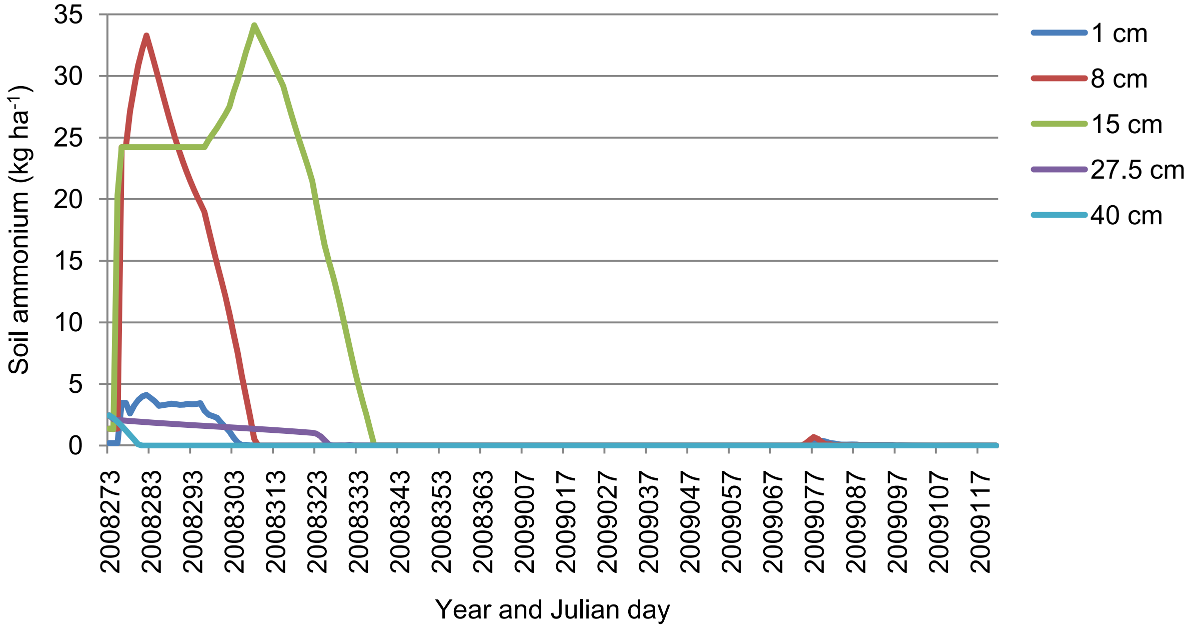

Figure F.20 Simulated soil ammonium over the 2008-2009 season by soil layer for site SAP.

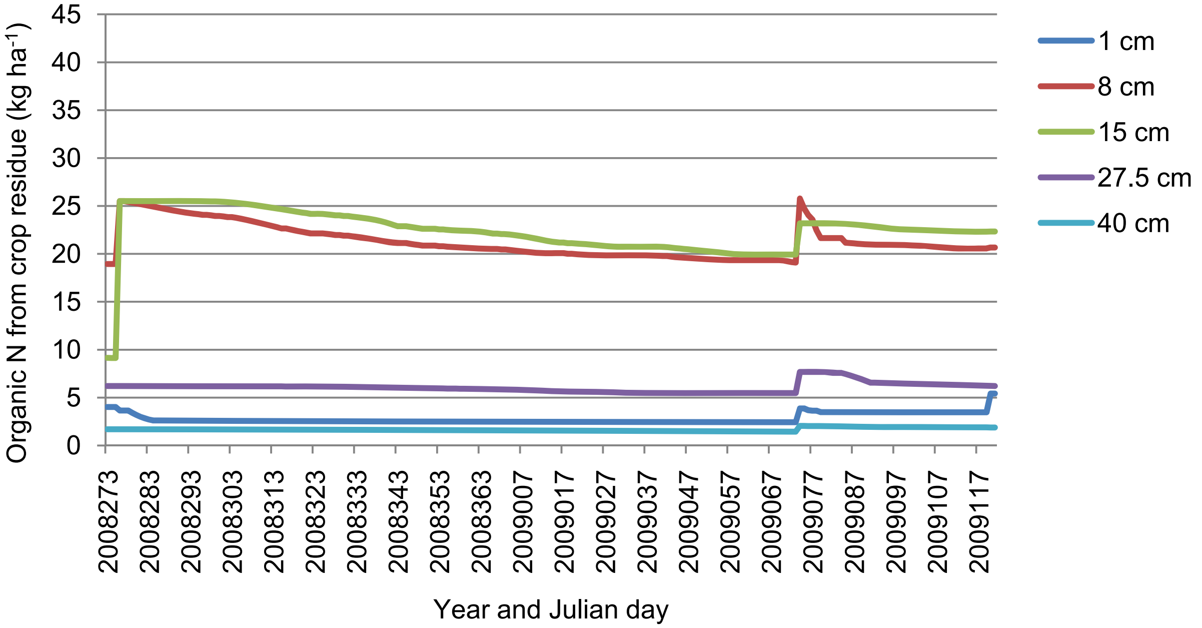

Figure F.21 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for site SAP.

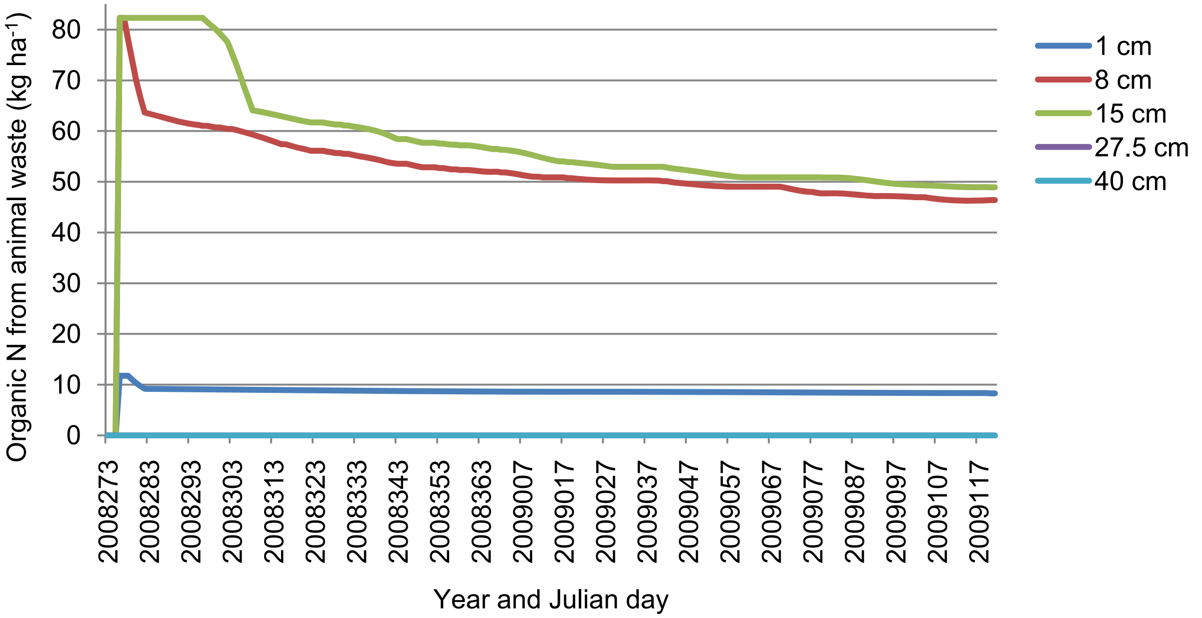

Figure F.22 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for site SAP.

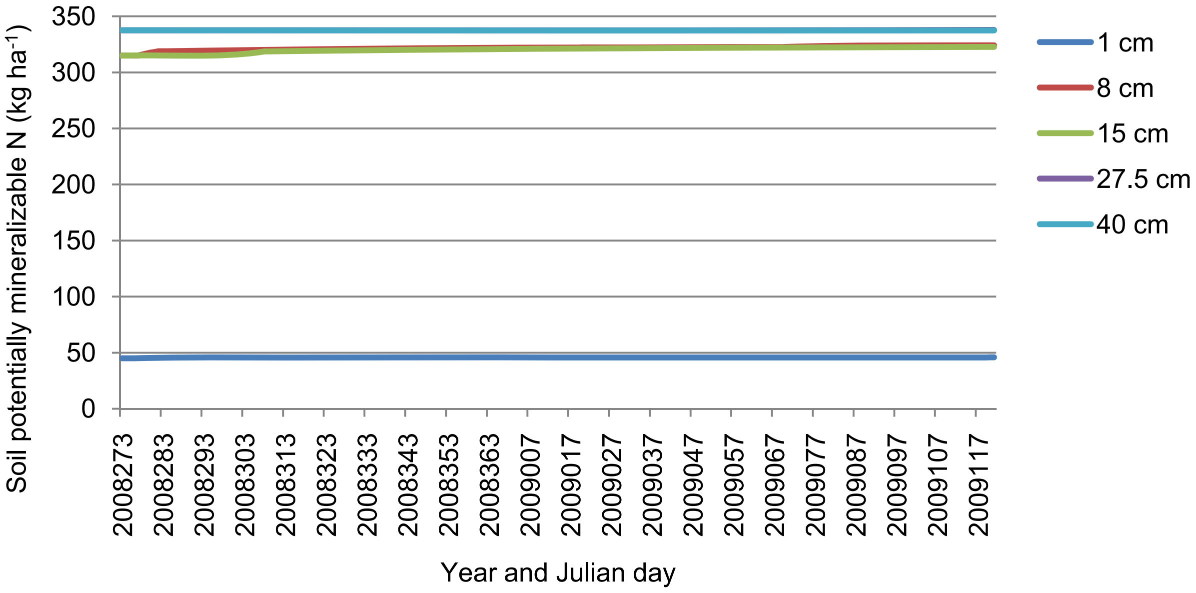

Figure F.23 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for site SAP.

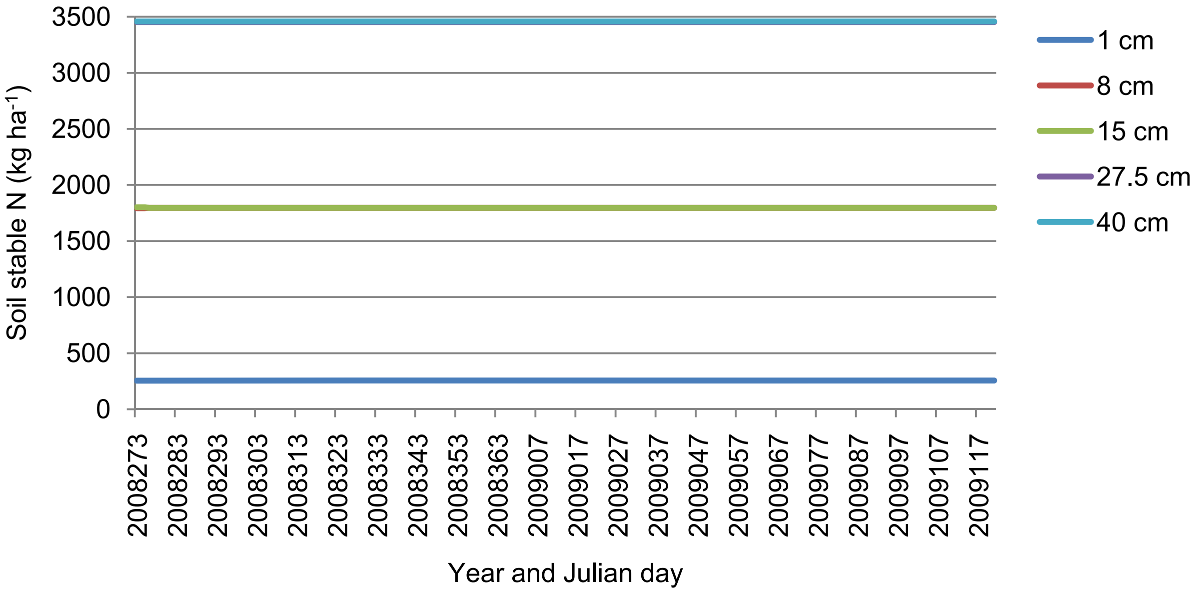

Figure F.24 Simulated soil stable N over the 2008-2009 season by soil layer for site SAP.

F.5 Villa Flores, experimental plot 2

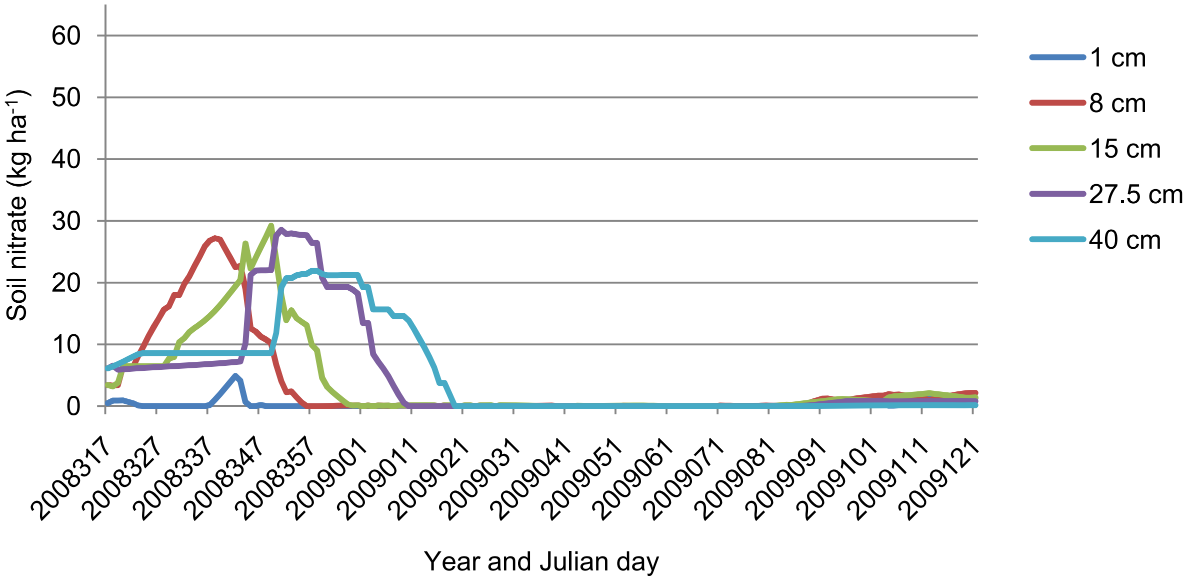

Figure F.25 Simulated soil nitrate over the 2008-2009 season by soil layer for VF2.

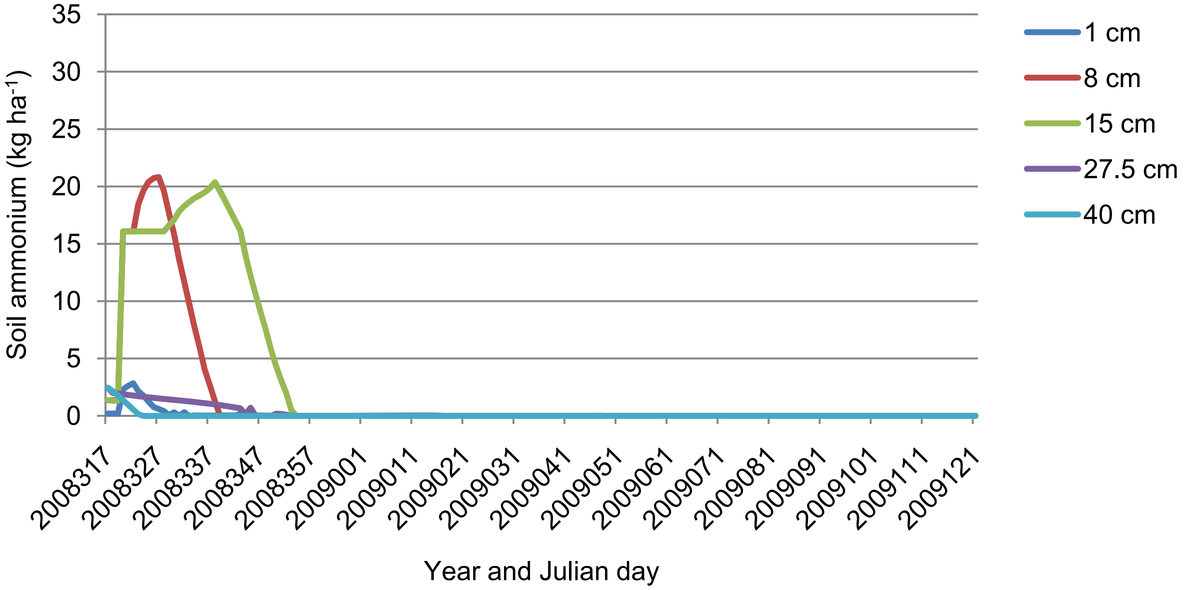

Figure F.26 Simulated soil ammonium over the 2008-2009 season by soil layer for VF2.

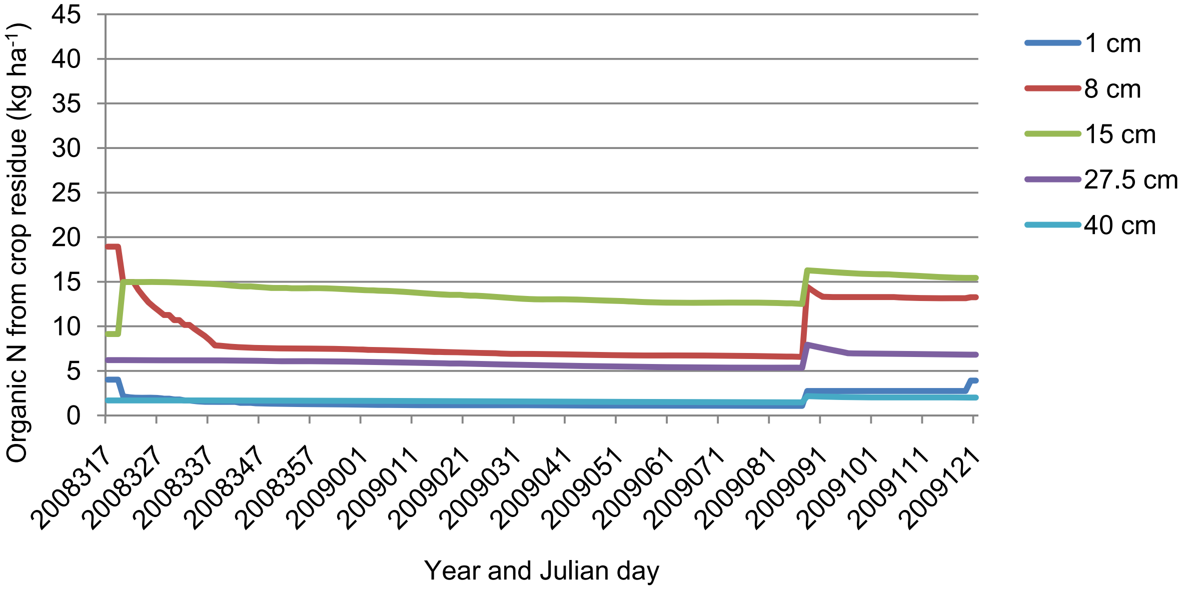

Figure F.27 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for VF2.

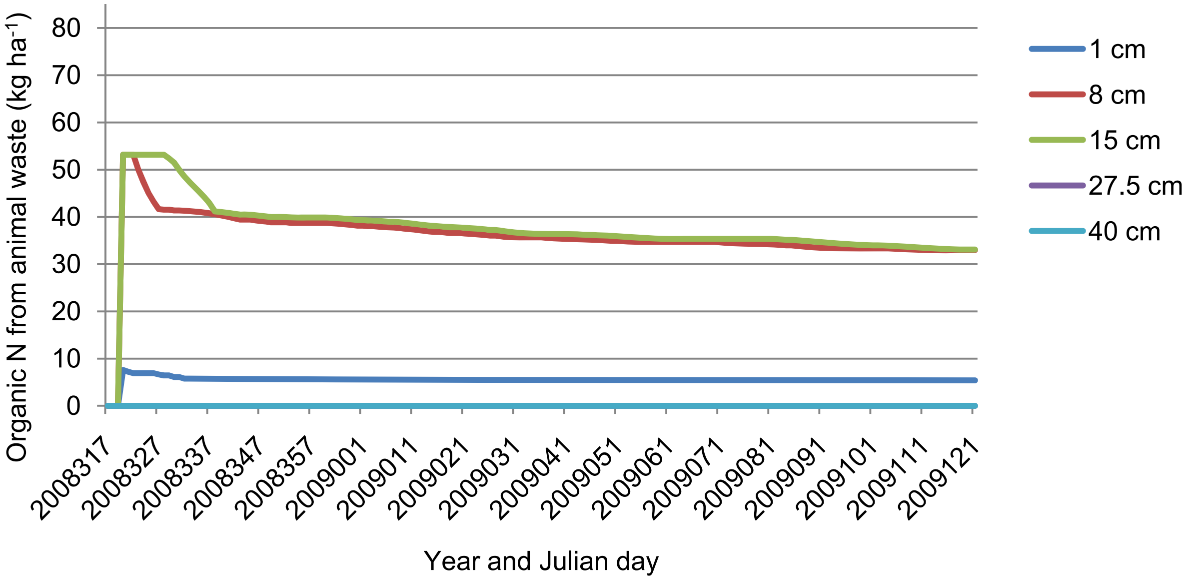

Figure F.28 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for VF2.

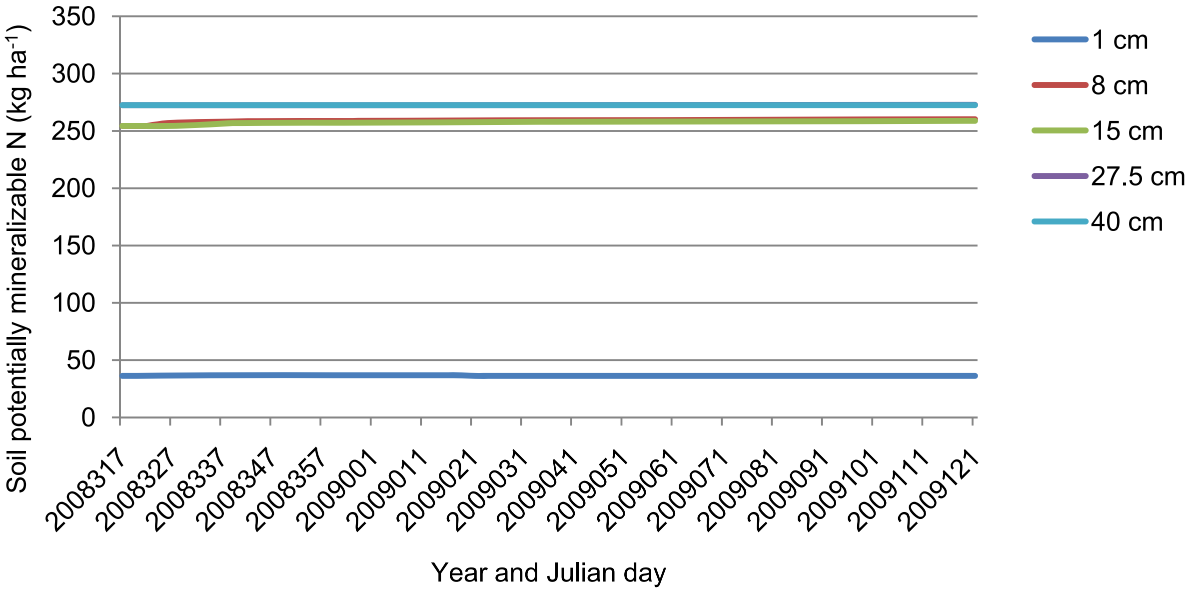

Figure F.29 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for VF2.

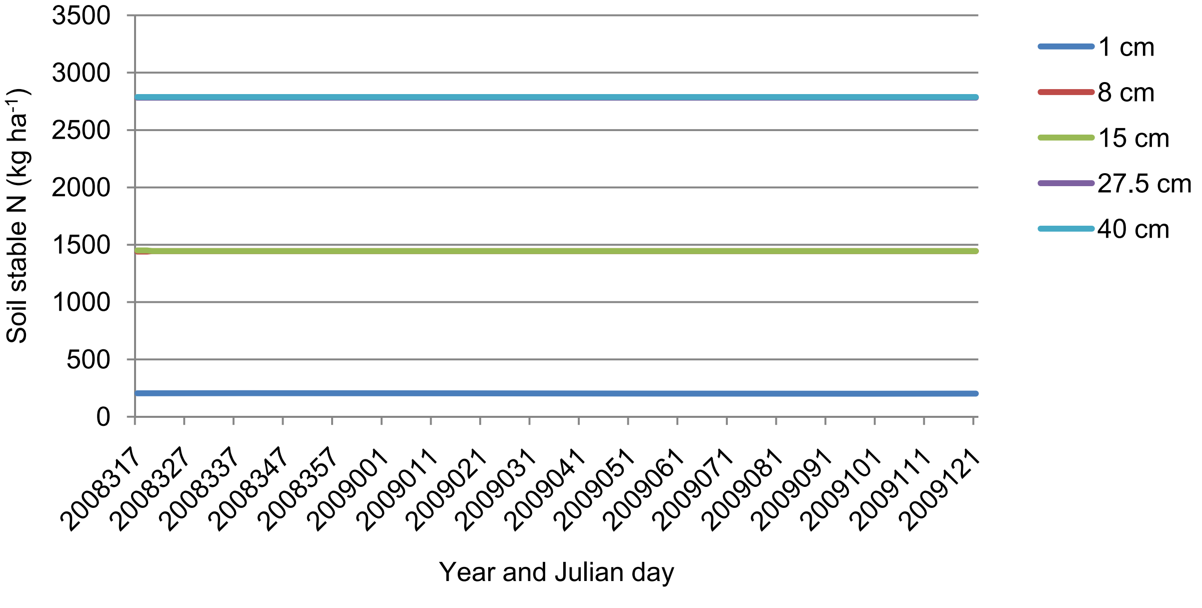

Figure F.30 Simulated soil stable N over the 2008-2009 season by soil layer for VF2.

F.6 Villa Flores, experimental plot 4

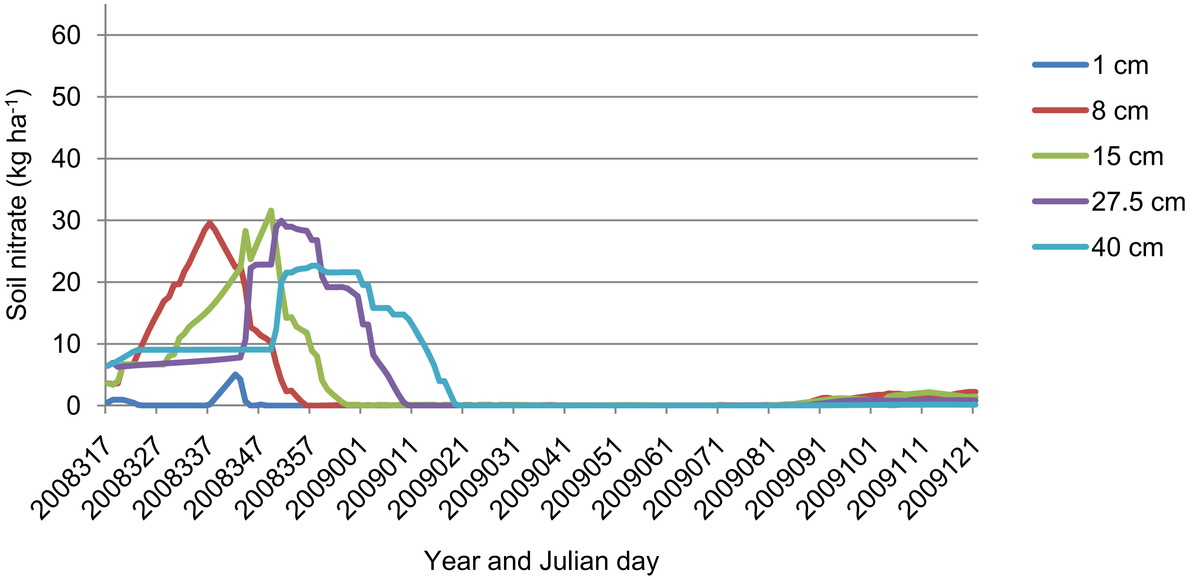

Figure F.31 Simulated soil nitrate over the 2008-2009 season by soil layer for VF4.

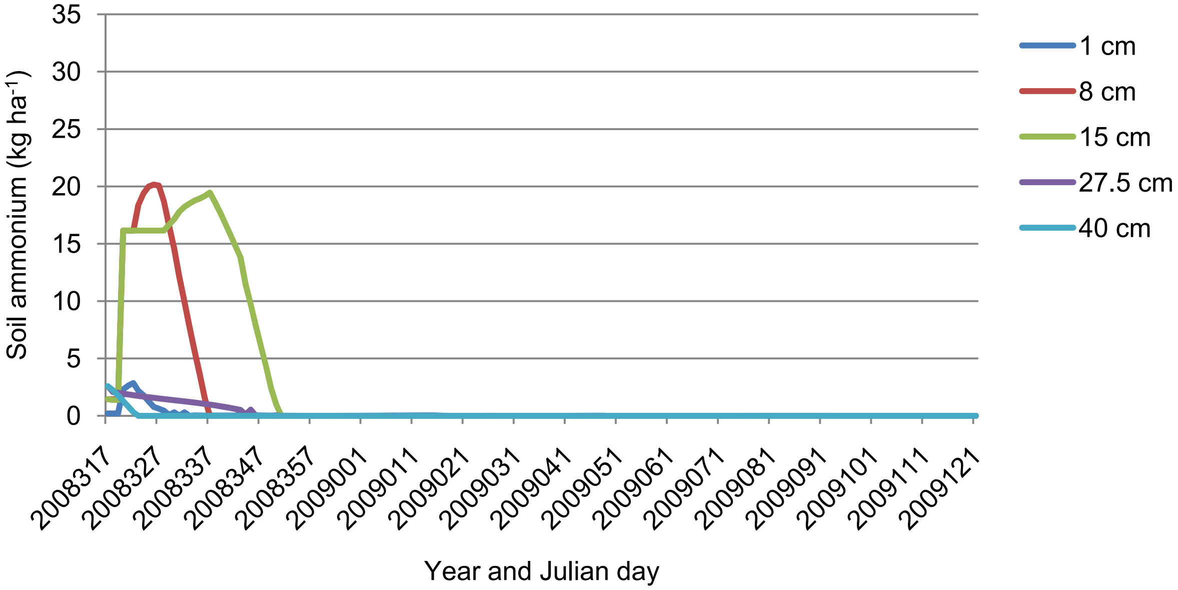

Figure F.32 Simulated soil ammonium over the 2008-2009 season by soil layer for VF4.

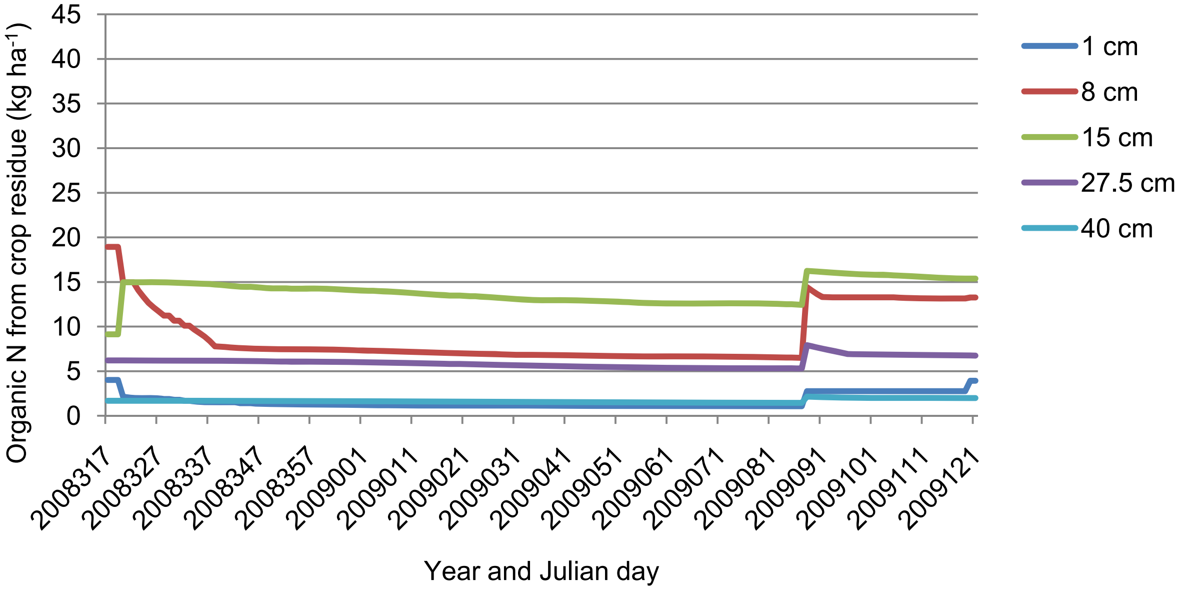

Figure F.33 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for VF4.

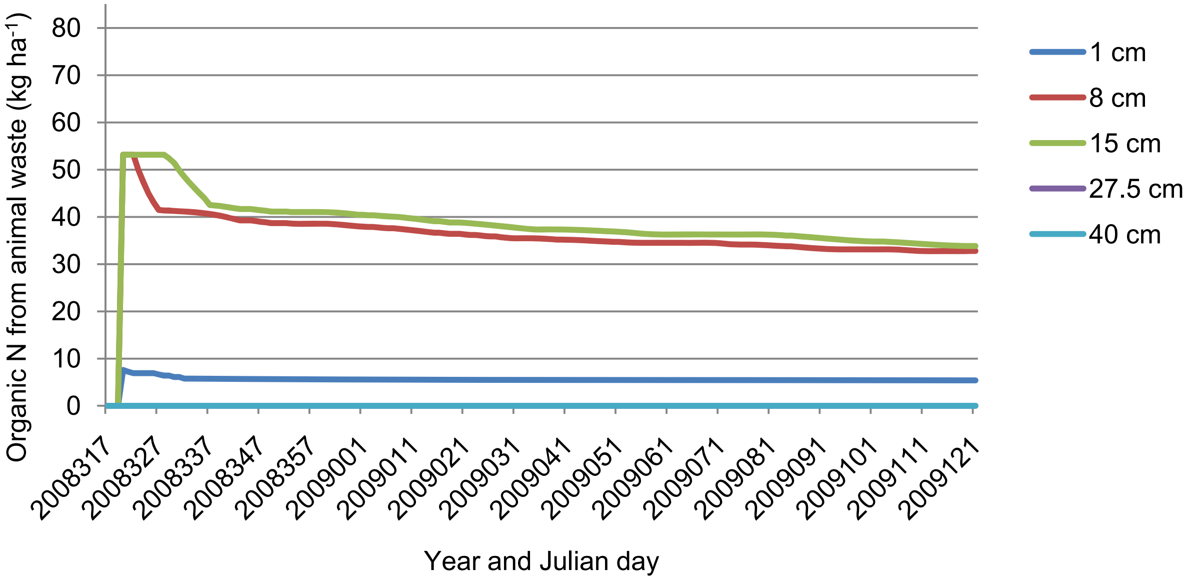

Figure F.34 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for VF4.

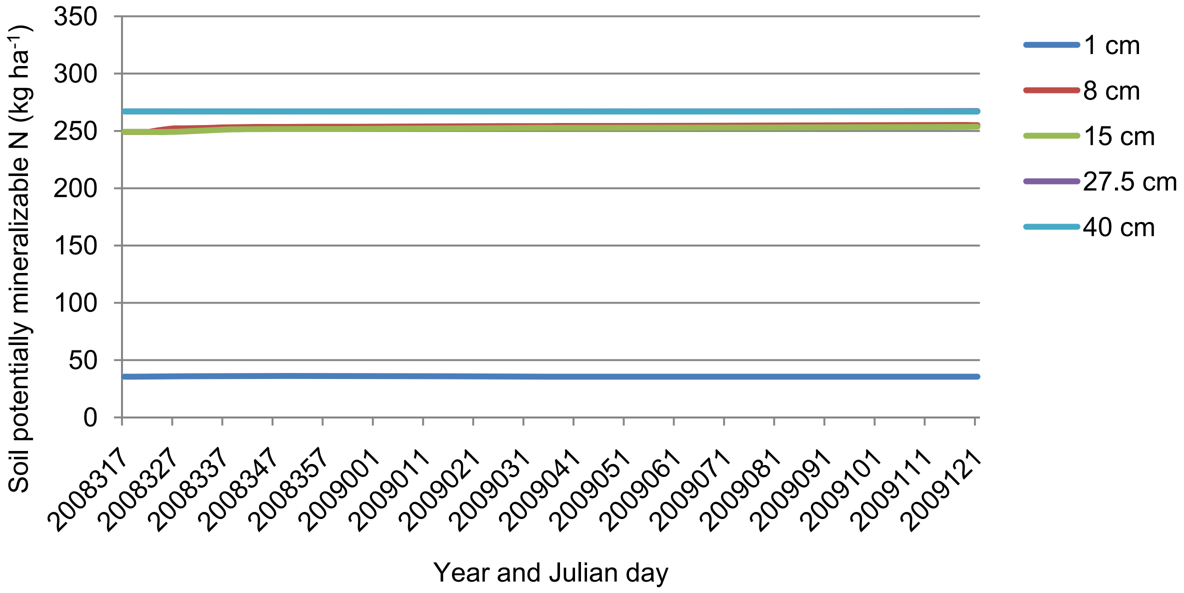

Figure F.35 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for VF4.

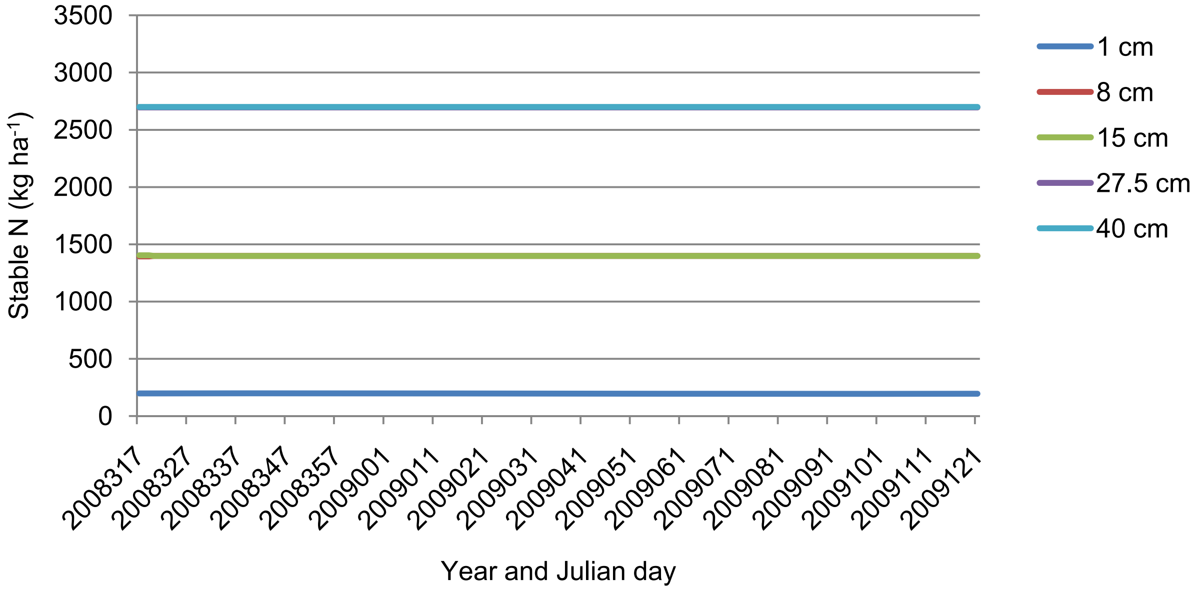

Figure F.36 Simulated soil stable N over the 2008-2009 season by soil layer for VF4.

F.7 Villa Flores experimental plot 8

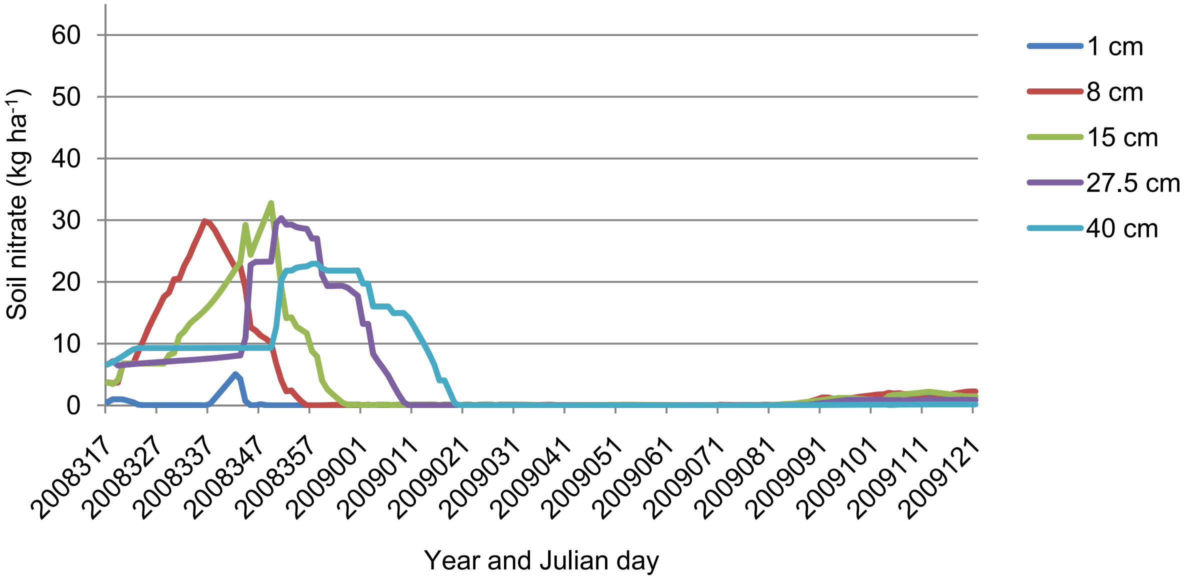

Figure F.37 Simulated soil nitrate over the 2008-2009 season by soil layer for VF8.

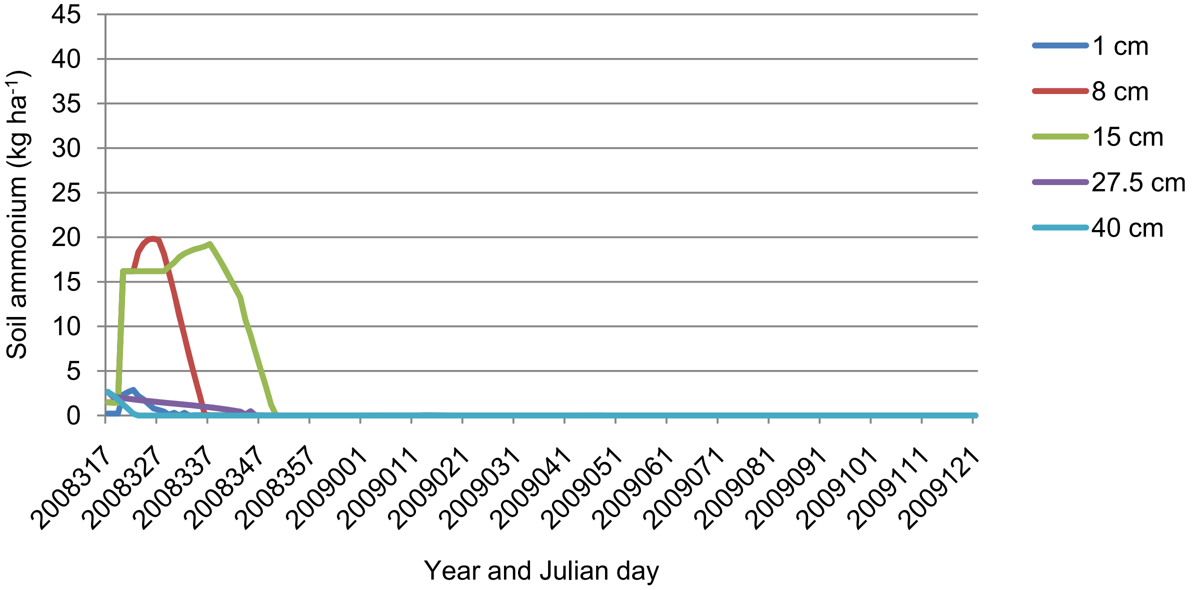

Figure F.38 Simulated soil ammonium over the 2008-2009 season by soil layer for VF8.

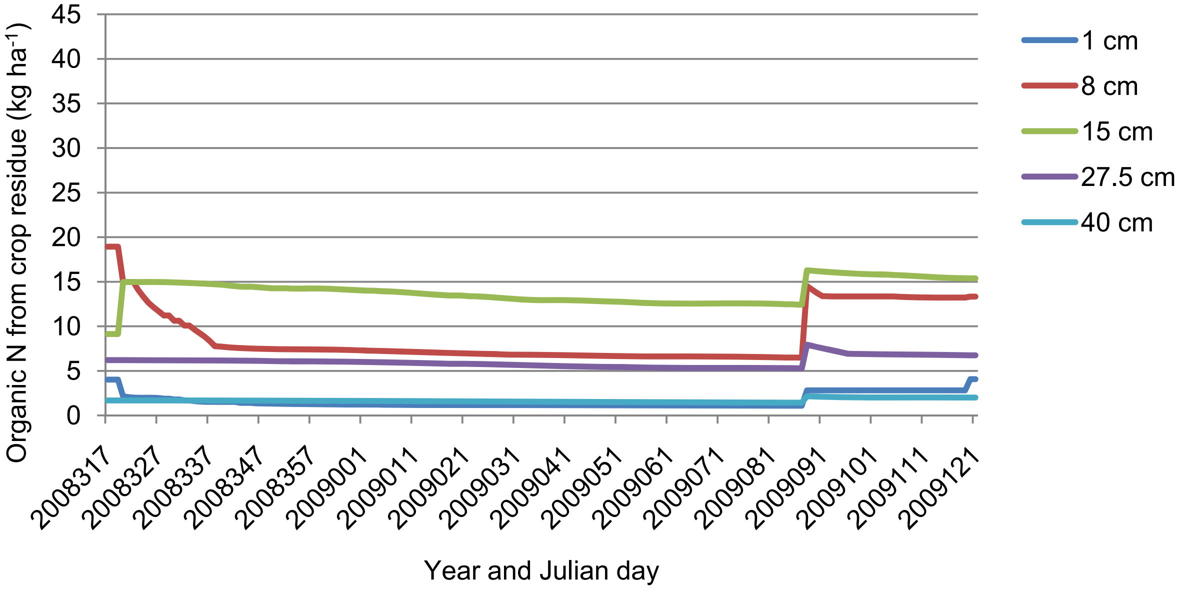

Figure F.39 Simulated soil organic N from crop residue over the 2008-2009 season by soil layer for VF8.

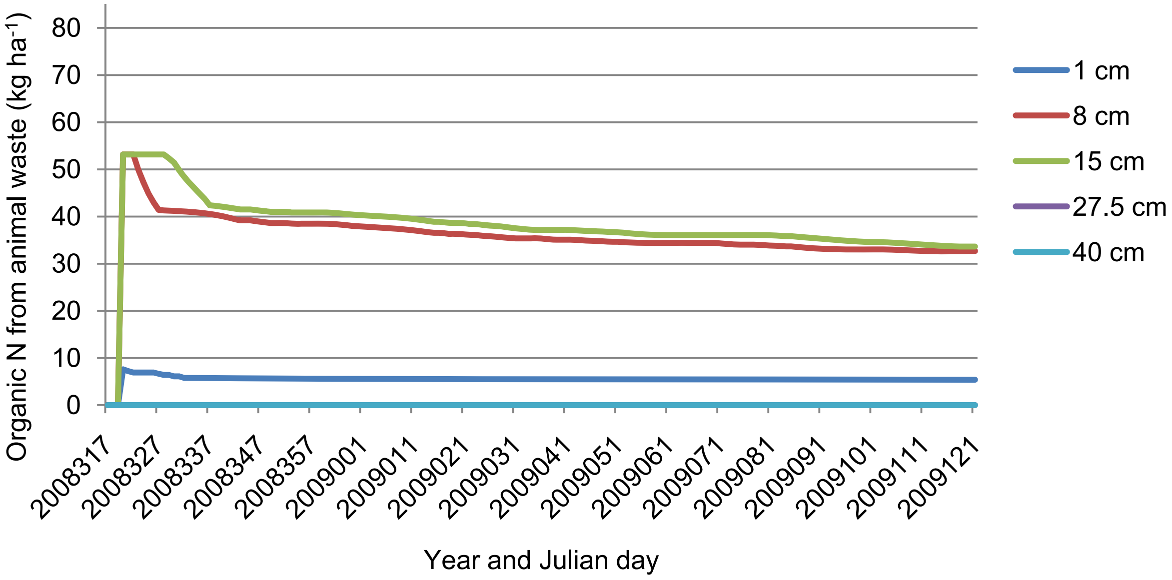

Figure F.40 Simulated soil organic N from animal waste over the 2008-2009 season by soil layer for VF8.

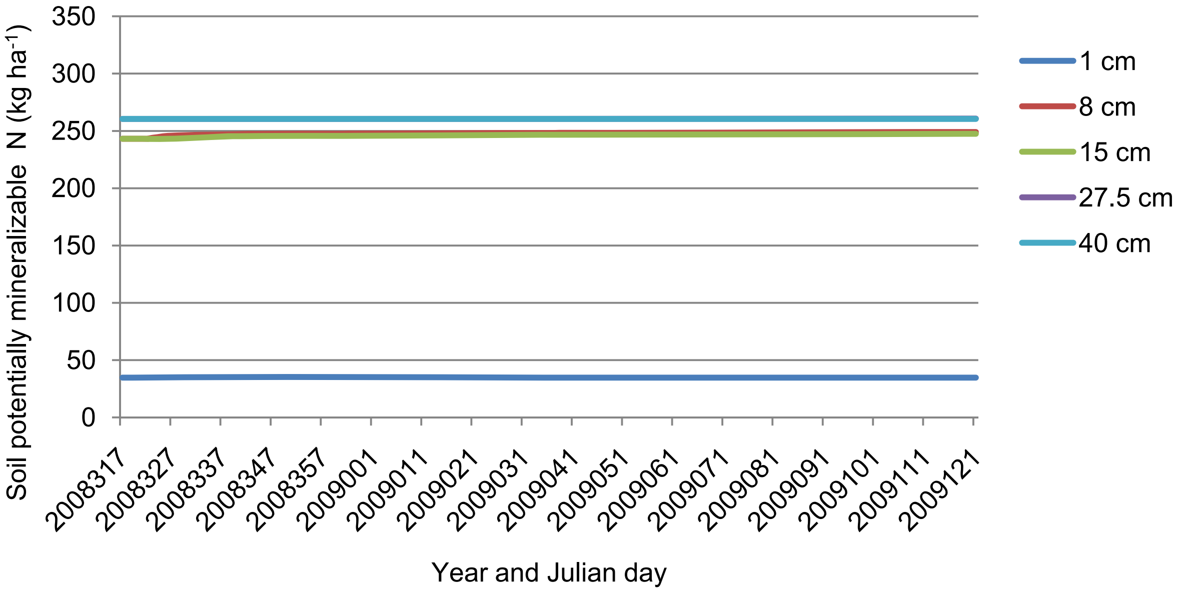

Figure F.41 Simulated soil potentially mineralizable N over the 2008-2009 season by soil layer for VF8.

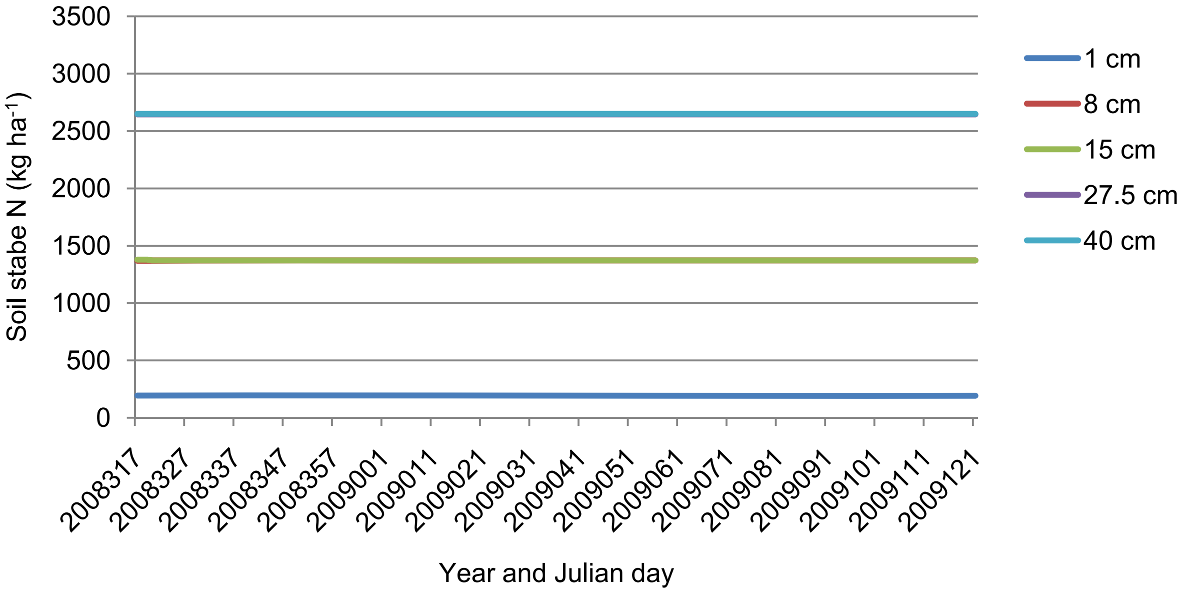

Figure F.42 Simulated soil stable N over the 2008-2009 season by soil layer for VF8.