# MODELING FATE AND TRANSPORT OF NITROGEN AND PHOSPHORUS IN CROP FIELDS UNDER TROPICAL CONDITIONS

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# MODELING FATE AND TRANSPORT OF NITROGEN AND PHOSPHORUS IN CROP FIELDS UNDER TROPICAL CONDITIONS

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## ABSTRACT

Modeling is a very important tool for developing nonpoint source (NPS) pollution control plans. Current NPS models were developed for temperate conditions and, thus, do not appropriately represent tropical conditions. The objective of this research was to develop or adapt a nonpoint source pollution model to simulate transformations and losses of nitrogen (N) and phosphorus (P) in leachate and runoff from crop fields under humid tropical conditions.

An extensive literature synthesis identified appropriate relationships for representing hydrologic and NPS processes in the tropics, as well as soil and climate conditions that differ from temperate conditions and impact NPS pollution. The GLEAMS model was selected for adaptation. Changes to the model included calculation of potential evapotranspiration (ET); changes in initial and default values of N and P pools, C:N ratio of soil organic matter, and soil P sorption; changes in simulation of transformations between N and P pools, along with the effect of temperature; and inclusion of a nitrate retardation factor (Ncrit) and pH in the calculation of N transformation and movement.

The adapted model, called TROPGLEAMS, was evaluated through model verification, application, and sensitivity analysis. Model verification comprised a mass balance of nutrients and analysis of the variation of variable values in time. Model validation included application of the GLEAMS and TROPGLEAMS to three sites in Brazil: a set of lysimeters planted with sugarcane in Piracicaba, SP; a set of plots planted with sugarcane in Piracicaba; and a set of plots planted in a wheat-soybean rotation in Lages, SC. Model sensitivity to temperature, Ncrit and pH were evaluated in the sensitivity analysis.

Model evaluation indicated that TROPGLEAMS is more accurate than GLEAMS in simulating fate and transport of nutrients under tropical conditions. Prediction of actual ET, effect of tillage on losses of N and P in runoff, and N and P kinetics was improved with TROPGLEAMS compared to GLEAMS. However, based on data from the Lages study, TROPGLEAMS did not simulate losses of nutrients in runoff well. Improvements in the model, especially related to losses in runoff, and application of TROPGLEAMS to different areas of the humid tropics are recommended.

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# DEDICATION

I dedicate this dissertation to Carla, my wife, who sacrificed her professional life to follow me in this challenging endeavor and whose support, love, and patience during all time helped me to accomplish this study.

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# CHAPTER I
# INTRODUCTION

Nonpoint source (NPS) water pollution, defined as the diffuse pollution which cannot be readily attributed to a point source, originates from a broad range of human activities. Runoff and snowmelt pick up and transport natural and human-made pollutants while moving over and through the soil, depositing them into lakes, rivers, wetlands, coastal waters, and ground water. Agricultural activities can be significant sources of NPS pollution and the release of sediments, pesticides, nutrients, and microorganisms can contribute to water quality deterioration (Ongley, 1996; EPA, 2003).

Nonpoint source pollution is a major environmental problem in developed countries, including in the USA (EPA, 2000) and countries in Europe (Shoumans et al., 2002; Paz and Ramos, 2004) and Asia (Zhang et al., 2003). Nonpoint source pollution has become a problem of even greater concern in tropical developing countries as areas used for subsistence or low intensity agriculture have transitioned to high technology agriculture with increased use of fertilizers and pesticides. Environmental problems caused by NPS pollution from agricultural fields have been reported in many tropical regions, including Nigeria (Ezeonu et al., 1994), Chile (Donoso et al., 1999), Brazil (Caiado, 1994), Hawaii (Yim and Dugan, 1995), Sierra Leone (Bashiro et al., 1997), India (Datta et al., 1997), Thailand (Tonmanee and Kanchanakool, 1999), Colombia (Ruppenthal et al., 1997), Venezuela (Hurtado and Mijares, 1978), and several Caribbean countries (Wright, 2000; Rawlins et al., 1998). The African great lakes have also experienced degradation from NPS pollution (Crul, 1998). High rates of deforestation around the lakes have increased soil erosion, causing large amounts of sediments and nutrients to be washed into the lakes. While Lakes Tanganyika and Malawi remain relatively unspoiled, increased nutrient loading into Lake Victoria, primarily from manure, has led to its eutrophication, resulting in higher algal biomass productivity, with frequent occurrence of algal blooms and prolonged deoxygenation of the hypolimnion (Crul, 1998).

According to the classification of Koeppen (SD/FAO, 1999), the humid tropics have a climate characterized by an average temperature of 18°C or higher in all months and precipitation greater than the potential evaporation and transpiration. The tropics comprise about 36% of the earth surface, mainly located between the tropics of Cancer and Capricorn, encompassing most of Central America, north and central South America, central Africa, southern Asia and northern Oceania (Figure 1.1).

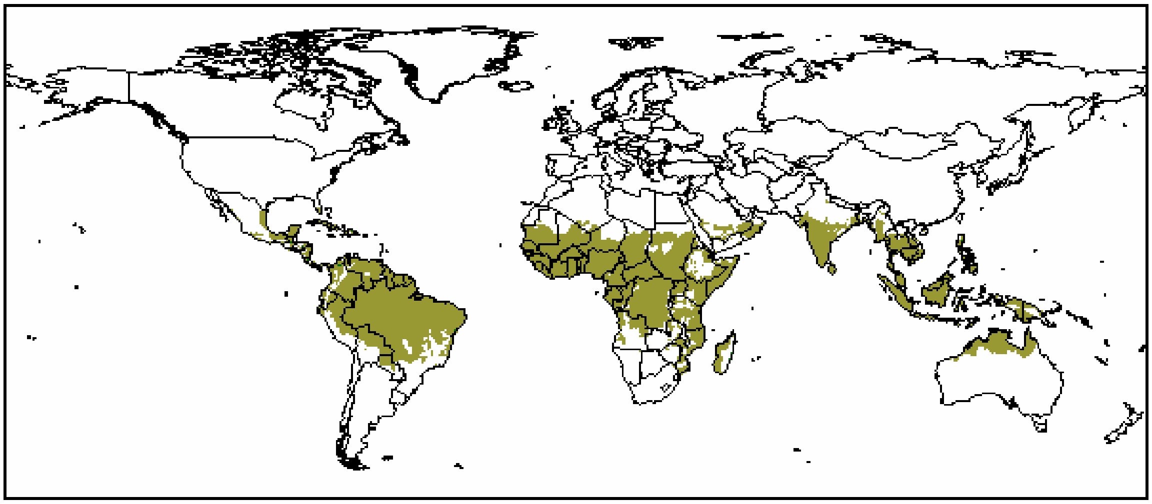

**Figure 1.1.** The humid tropics (SD/FAO, 1999).

Tropical areas differ from temperate areas in a number of aspects including higher air and soil temperatures, greater photoperiod uniformity throughout the year, higher rainfall intensity, different cropping systems, soil mineralogy dominated by kaolinite and iron and aluminum oxides and hydroxides, and different composition of soil microbiota. These differences must be considered when practices developed in temperate areas to control NPS pollution are applied in the tropics. In all climates, the control of NPS pollution is site specific and practices that are effective in one area may or may not perform well in others.

The effectiveness of NPS pollution control measures can be evaluated through monitoring and modeling approaches. With monitoring, practices are applied to an area and the impact is evaluated through real-time sensors or through sample collection and analysis. Drawbacks to monitoring are the cost of implementation and the complicating factors inherent in measuring NPS pollution, such as time scale, frequency, and geographic position of monitoring sites. The modeling approach provides a number of advantages over monitoring. NPS models simulate the application of pollution control practices to a specific field, crop system, climate, and time scale, enabling a time- and cost-efficient preview of their effectiveness. This makes it possible to rank alternatives and choose the most appropriate system of practices for a particular situation. Furthermore, because NPS models simulate pollutant fate and transport at both field and watershed scale, they may be used to identify critical areas of nutrient losses that should be prioritized for receiving pollution control.

NPS models such as GLEAMS, AGNPS, SHE, SWAT, and ANSWERS, which were developed to predict sediment and nutrient losses from upland areas, are commonly used for environmental evaluation and management in developed countries. Although widely used in temperate zones, the use of NPS models in the tropics has been limited and usually involves the application of models developed for temperate conditions with only minor--if any--adaptations to the tropics (e.g. Barra et al., 1995; Singh and Sondhi, 2001; Giuliano et al., 1995; and Rahman and Salbe, 1995). In actuality, as demonstrated in this study, NPS models developed for temperate conditions need careful adaptation to account for the environmental differences between the two climates before their application to tropical areas.

Components included in NPS models differ depending on the objectives of the model. Models that simulate loads of agrochemicals to water bodies have hydrology, erosion, nutrient, and pesticide processes as main components, integrated by the user interface and the input and output systems. The individual processes of importance in NPS modeling have, in many cases, been studied in the tropics, but have been carried out by groups in different centers and countries, usually working without collaboration or integration. Furthermore, many of these studies have been published as theses or dissertations, or are reported in proceedings of national meetings or journals of restricted circulation, making access difficult. In addition to the need for a comprehensive compilation and synthesis of the dispersed body of work, there is also the need to integrate the various component processes into a NPS model code that can more accurately represent tropical conditions.

# OBJECTIVES

The overall goal of this research was to adapt an existing NPS pollution model to simulate transformations and losses of nitrogen and phosphorus in leachate and runoff from crop fields under humid tropical conditions. The specific objectives of this research were to:

1. Identify equations and models that are appropriate for simulating the fate and transport of nitrogen and phosphorus in crop fields under tropical conditions.
2. Develop and evaluate a simulation model that provides improved prediction of the fate and transport of nitrogen and phosphorus in agricultural fields in the tropics in comparison with existing NPS models. Key tasks in accomplishing this objective include the following:
   a) Review existing NPS models and identify one with characteristics that make it suitable to be adapted to humid tropical conditions.
   b) Modify the code of the selected NPS model including equations and models identified as more representative for the conditions of the humid tropics.
   c) Evaluate the model through appropriate verification, validation with field data from tropical studies, and sensitivity analysis.
   d) Evaluate the improvement in prediction by comparison of the original (temperate) and modified (tropical) models.

# CHAPTER II
# LITERATURE REVIEW

This chapter is a review of studies on modeling hydrology, erosion, soil temperature, and transformation and losses of nutrients under tropical conditions. It describes specifics of the tropics that affect NPS modeling, identifies equations and models that can be used to create an NPS model appropriate for tropical agricultural fields, describes the parameters and input variables to be used in models and equations, and identifies sources where the parameter values can be found.

## 2.1. HYDROLOGY

Hydrological components of NPS pollution models have been extensively studied in the tropics. Studies on rainfall interception, infiltration, evapotranspiration, and runoff are used to determine hydrological parameters and to check the methodologies for determining these parameters in a given area.

### 2.1.1. RAINFALL INTERCEPTION

Gash (1979) developed a model to estimate rainfall interception by forests, which was revised in 1995 by Gash et al. (1995) to incorporate expressions for evaporation per unit area of canopy instead of per unit ground area, enabling application of the model to sparse canopies. The revised model was tested in tropical conditions by Dykes (1997), who studied rainfall interception in a tropical rainforest in Brunei. The author obtained parameters for the revised model from one of two sets of studied storms. The model's prediction of total interception loss from both sets of storms was in very good agreement with that derived from throughfall measurements.

In Puerto Rico, both the Rutter (Rutter et al., 1971) and Gash (1979) models were applied to data of throughfall and above-canopy climatic data in a tropical forest. The Gash model provided a better estimation of the modeled phenomenon (Schellekens et al., 1999). Van Dijk and Bruijnzeel (2001a) studied rainfall interception in a mixed agricultural cropping system involving maize, upland rice, and cassava in West Java, Indonesia. Three interception models were tested: (1) a simple linear regression approach, (2) the revised analytical model (Gash et al., 1995), and (3) an adapted analytical model for vegetation of variable density that used the leaf area index as a parameter. The last model showed better model efficiency than the others, indicating the importance of introducing the leaf area index as an additional parameter for the simulation of rainfall interception in tropical crop systems.

## 2.1.2. INFILTRATION

Ruy et al. (1999) developed a mechanistic model of soil deformation and water infiltration that accounts for three components of soil porosity: matric, structural and macro-cracks. Application of the simulation model to a Vertisol of Guadeloupe resulted in an inaccurate prediction of water infiltration. According to the authors, the inaccurate prediction was caused by poor modeling of water flow in the structural porosity.

The Green Ampt Mein Larson equation (GAML) (Mein and Larson, 1973) was used by Silva et al. (1994) to simulate infiltration in Brazil. In comparison to measured values from 12 rainfall events, the model overestimated infiltration by 16.4%. The authors suggested that the time step of one hour used in the simulation was not able to account for temporal variability of rainfall intensity. Silva and Kato (1998) tested the GAML equation in bare and covered infiltrometers. For the covered infiltrometers, GAML equation underestimated cumulative infiltration by an average of 0.9%. For the bare infiltrometers, GAML equation overestimated cumulative infiltration by 8.2%. The authors adapted the Green-Ampt equation to simulate superficial sealing based on the kinetic energy of rainfall. This equation improved the simulation, underestimating infiltration by 3.3%. Superficial sealing was also assessed in Brazil by Reichert et al. (1992) and Chaves et al. (1993). Reichert et al. (1992) used the Smith model modified by Cabeda (1980). The model was very efficient in describing infiltration rates of simulated rainfall, with the correlation coefficient ($R^2$) varying from 0.95 to 0.99. Chaves et al. (1993) modified the Horton equation (Horton, 1940) making the accumulated rainfall energy as independent variable. They simulated infiltration in American and Brazilian soils using the original and modified Horton equations. The changes in the model improved the simulation of infiltration in both American and Brazilian soils.

## 2.1.3. EVAPOTRANSPIRATION

Evaporation pans, like the Class A pans, probably provide the best method for obtaining an index of potential evapotranspiration. They are more accurate than formulae, especially for indicating local and short-term fluctuations under conditions of strong heat advection (Dunne and Leopold, 1978). The use of the Class A pan is very common in the tropics and has been reported by several authors (e.g. Silva et al., 1994; Mota et al., 1993).

Karongo and Sharma (1997) applied the Morton (1983) and Grindley (1970) models to evaluate monthly evapotranspiration (ET) in Kenya. Overall, the Grindley model overestimated the actual monthly evapotranspiration by 32% while the Morton model agreed more closely with the water balance analysis, overestimating ET by 8%.

Rodrigues et al. (1997) used the Ritchie method (Ritchie, 1972) to simulate evapotranspiration of irrigated bean crops (*Phaseolus vulgaris*) in Brazil. The authors observed that the model simulated ET very well in cases of high frequency irrigation, but overestimated the process in the parcels with low irrigation frequency, showing that the model is not adequate for conditions of limited water.

Equations based on air temperature work very well in the midlatitude continental climates for which they were developed, where air temperature is a fairly good index of net radiation. In the tropics, these methods often give erroneous results and may seriously underestimate the amplitude of seasonal fluctuations of water demand (Dunne and Leopold, 1978). Dagg and Blackie (1970) cited by Dunne and Leopold (1978) compared evapotranspiration simulated using the Blaney-Criddle, Thornthwaite and Penman methods with measured pan evaporation in Kenya. The Penman method, based on an energy balance model and other factors besides air temperature, estimates evaporation very well in Kenya, while the Blaney-Criddle method, which is based on air temperature, an empirical crop factor, and monthly fraction of annual hours of daylight, failed in estimating the seasonal fluctuation of evapotranspiration. The Thornthwaite method, based on air temperature, underestimated annual and monthly evapotranspiration and did not adequately represent seasonal variation.

In 1977, the Food and Agriculture Organization (FAO) published a procedure for calculating reference and crop evapotranspiration from meteorological data and crop coefficients (cited in Allen et al., 1998). The procedure was updated in the FAO Irrigation and Drainage Paper No. 56. The updated procedure, called the FAO Penman-Monteith method (Allen et al., 1998), uses standard climatological records of solar radiation, air temperature, humidity and wind speed, is now recommended as the standard method for defining and computing reference evapotranspiration, $ET_O$. The FAO Penman-Monteith method was developed by defining the reference crop that closely resembles the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered. This hypothetical crop has an assumed height of 0.12 m, with a surface resistance of 70 s $m^{-1}$ and an albedo of 0.23,. Differences in the crop canopy and aerodynamics resistance relative to the reference crop are accounted for through the use of a crop coefficient ($K_C$) (Allen et al., 1998). De Bruin (1983), analyzing data from about 60 stations lying between 23$^o$N and 23$^o$ S and below 600 m, concluded that the Penman-Monteith method is the most appropriate method for determining evapotranspiration for research purposes and diagnostic studies.

## 2.1.4. RUNOFF

Yu et al. (1997) developed the Small Scale Runoff Routing Model (SSRRM), a model for calculating runoff based on three parameters: the initial infiltration amount, a spatially averaged maximum infiltration rate, and a dimensionless routing parameter derived from the lag between rainfall and runoff and the simulation time interval. Model results were compared with measured data of rainfall and runoff from six sites located in Australia and Southeast Asia. Model parameters were estimated using data from 10 events, and the model's performance was evaluated by calculating the efficiency coefficient using data from 20 events. Considerable event-to-event variation in the estimated parameter values was observed. Model efficiency varied from 0.72 to 0.94, implying a good fit between the observed and modeled hydrograph.

The simulation of runoff through the SCS curve number (CN) method (SCS, 1972), using curve numbers documented in the literature, resulted in poor agreement between measured and simulated runoff in several studies. When CN values were determined using precipitation and runoff correlation, the agreement increased significantly. Onyando and Sharma (1995) observed this in studying runoff in two catchments in

Kenya, as did Steenhuis et al. (1995) and Dilshad and Peel (1994) in Australia, and Silva and Oliveira (1999) in Brazil. Onyando and Sharma (1995) used the SCS curve number method to estimate direct runoff volumes from the Sambret and Lagan watersheds. They used 25 rainfall-runoff events from the Sambret watershed to derive curve numbers for each storm. The derived CN values were used to calculate runoff volumes of 16 events from the Sambret watershed and 18 events from the Lagan watershed. $R^2$ between measured and simulated runoff was 0.9 for the Sambret watershed and 0.61 for the Lagan watershed. In the study by Dilshad and Peel (1994), the improved CN was able to explain 98% of variation in observed rainfall and runoff data. Silva and Oliveira (1999) analyzed precipitation and overland flow data in a 962.4 ha watershed located in central Brazil using data from 210 rainfall/runoff events. The correlation coefficient ($R^2$) between measured and predicted runoff was 0.32 when they used tabulated values of CN. When using averaged CN values calculated through rainfall and runoff data from 31 events, the correlation coefficient between measured and estimated runoff increased to 0.84, overestimating runoff by 39%. The authors suggested that the overestimation of runoff was due to inaccurate estimation of interception and that the values of CN documented for temperate conditions should be used with caution for predicting runoff in tropical watersheds under natural vegetation.

It can be concluded that the SCS curve number method is appropriate to simulate runoff in the tropics if local values of CN are used in the calculation instead of values derived for temperate conditions.

## 2.1.5. SUMMARY – HYDROLOGY

The Gash model (Gash, 1979) and the revised Gash model (Gash et al., 1995) showed very good results in the simulation of rainfall interception in tropical forests. Incorporating the leaf area index (LAI) as an additional parameter in the models improved rainfall interception simulation in both forest and crop systems.

The GAML model, the Smith model modified by Cabeda (1980), and the Horton equation showed better correlation with measured values of infiltration in the tropics when the models were modified to account for superficial sealing of soil due to the impact of rainfall.

For the calculation of evapotranspiration, the FAO Penman-Monteith method has been considered the standard method globally for defining and computing the reference evapotranspiration and has been successfully tested under tropical conditions.

The SCS curve number method simulated runoff well in the tropics, but local values of CN have to be used in the calculation instead of values derived for temperate conditions.

## 2.2. EROSION

According to Yu and Rose (1999), the most used soil erosion prediction models are the USLE (Universal Soil Loss Equation) (Wischmeier and Smith, 1978) and its revised version, RUSLE (revised USLE) (Renard et al., 1997). In recent years, a new generation of physically based models developed to predict soil loss, such as WEPP (Water Erosion Prediction Project) (Laflen et al., 1991), EUROSEM (Morgan et al., 1998), and GUEST (Misra and Rose, 1995) have received increasing use in the tropics.

### 2.2.1. THE UNIVERSAL SOIL LOSS EQUATION

The USLE is an empirical regression model based on data from the Midwest and Eastern United States. Because the equation has this specific geographical background, only by coincidence could its control variables be valid for ecological regions that differ drastically from those where the data were collected (Lal, 1990). However, despite this limitation, the USLE is the most used soil erosion model in the tropics. Several authors have adapted, tested, and modified its parameters, R, K, and C, which are related to rainfall erosivity, soil erodibility, and crop management, respectively.

#### The USLE R factor

The parameter R was originally based on the $EI_{30}$ index, the cross product of total kinetic energy and the maximum 30-min rainfall intensity (Wischmeier and Smith, 1978). Several measures of rainfall erosivity have been proposed as alternatives to the R factor of the USLE and of its successor, the RUSLE (Yu and Neil, 2000). These include Fournier's index (Fournier, 1960) and the modified Fournier index (Arnoldus, 1977), Lal's $AI_m$ index (Lal, 1976), Hudson's KE>25 index (Hudson, 1971), and Onchev's universal erosivity index (Onchev, 1985).

Lal (1990) stated that the $AI_m$ index, the product of total rainfall amount and peak storm intensity, correlates better than the USLE R factor with soil erosion on a storm basis. He reported the use of the $AI_m$ index by Arnon (1984) to prepare an isoerodent map of southeastern Nigeria. Yu and Neil (2000) tested five models to calculate rainfall erosivity in two tropical catchments. Models using a modified Fournier's index, monthly rainfall, and mean rainfall intensity generally performed more poorly than those using annual or daily rainfall data.

The relationship between rainfall intensity and kinetic energy has been expressed using power law equations (Uijlenhoet and Stricker, 1999), logarithmic functions (Wischmeier and Smith, 1978; Wagner and Massambani, 1988) and exponential equations (Van Dijk et al., 2002). Yu (1999) proposed that the RUSLE use a unit energy equation different from the original USLE logarithm equation to calculate rainfall energy. According to Yu (1999), the R-factor calculated using the unit energy equation for the USLE is, in general, greater than that derived from the unit energy equation recommended for the RUSLE. The typical difference is about 10% for the tropical region of Australia. Van Dijk et al. (2002) made a comprehensive review of rainfall intensity-kinetic energy relationships and proposed the following exponential equation:

$$e_K=e_{max}[1-a*\exp(bR)], \qquad (2.1)$$

where $e_K$ is the kinetic energy ($j.m^{-2}.mm^{-1}$), $e_{max}$ denotes maximum kinetic energy, $a$ and $b$ are empirical constants, and R is rainfall intensity ($mm.h^{-1}$). Although this equation produces curves similar to the logarithmic functions proposed by Wischmeier and Smith (1978), it is more consistent to relate rainfall intensity and kinetic energy at rainfall intensities higher than 80 mm/h, which is fairly normal in the tropics. Based on datasets from 12 previous studies that Van Dijk et al. (2002) considered to be comprehensive and reliable, values of 28.3, 0.52, and 0.042 were determined for $e_{max}$, $a$, and $b$, respectively. The rainfall erosivity factor calculated using this equation is around 8% higher than the estimate produced by the RUSLE and 5% lower than the USLE, but is much closer to measured values.

Wagner and Massambani (1988), using drop size distribution obtained by disdrometric measurement in Brazil, proposed the following equation to calculate rainfall kinetic energy:

$$E = 0.153 + 0.0645 \log I \qquad (2.2)$$

where I is rainfall intensity ($mm.h^{-1}$) and E is rainfall energy per unit rainfall depth ($J.m^{-2}.mm^{-1}$).

In studies in Brazil, Bertol (1994) cited that while Morais et al. (1988) and Dedecek (1988) found low correlation between $EI_{30}$ and soil loss, Carvalho et al. (1989) found that soil loss was more strongly correlated to $EI_{30}$ than to any other erosivity indexes. Although equations using storm runoff showed stronger correlation with soil losses in Kenya (Ulsaker and Onstad, 1984) and Northeast Brazil (Albuquerque et al., 2002), measuring runoff is not a practical option. In order to avoid measurements of runoff, Ulsaker and Onstad (1984) recommended using $EI_{30}$, while Albuquerque et al. (2002) preferred an equation including total rainfall volume and rainfall intensity ($I_{30}$). In Central Brazil, the $EI_{60}$ showed stronger correlation with soil losses than the $EI_{30}$ index, but Silva et al. (1997) recommended the $EI_{30}$ index, using the Wischmeier and Smith equation for rainfall energy in the place of the $EI_{60}$ index. In calculating erosivity, they observed no significant difference between the use of the Wischmeier and Smith equation and the use of the Wagner and Massambani (1988) equation to calculate kinetic energy.

For Dourados, in the Center West region of Brazil, Carvalho and Hernani (2001) correlated soil loss with 24 models using parameters of rainfall energy, runoff, and rainfall energy plus runoff. They found that the non-linear model:

$$SL=0.14438(Vu)^{1.0728} \qquad (2.3)$$

where SL is soil loss ($ton.ha^{-1}$) and Vu is total runoff (mm), was the best model to explain soil losses from individual rainfall events ($R^2$=0.9944). In contrast, equations using the $EI_{30}$ index had a maximum $R^2$ of 0.5737.

Lombardi Neto and Moldenhauer (1992) proposed the following equation to calculate rainfall erosivity for Campinas, Southeast region, Brazil:

$$EI = 89,823 \, (p^2/Pa)^{0.759} \qquad (2.4)$$

where p is mean monthly precipitation and Pa is mean annual precipitation.

The original USLE erosivity index has been calculated for several areas of the tropics. In Brazil it was calculated, for example, for Vicosa (Boarett et al., 1998) and Sete Lagoas (Marques et al., 1998) in the Southeast region, for Lages (Bertol, 1993) and Campos Novos (Bertol, 1994) in the South region, and for Manaus (Oliveira and Medina, 1990) in the North region. Roose (1976) presented an isoerodent map for West Africa using diurnal rainfall of 20-50 years and Lal (1990) cited several authors who developed the USLE R factor for Hawaii, South Africa, Brazil, Uruguay, Chile, West Africa, Kenya, Sri Lanka, India, Zimbabwe, Morocco, and Malaysia.

Yu (1998) computed the R factor and its seasonal distribution for 41 sites in tropical Australia with a model using daily rainfall amounts. He concluded that the daily rainfall erosivity model could be used to accurately predict the R factor and its seasonal distribution. Lu and Yu (2002) used the same methodology to compute the R factor and its monthly distribution for all of Australia and created digital maps showing the spatial and seasonal distribution of the R-factor at a $0.05^{o}$ resolution.

In summary, although several indexes have been developed to substitute for the original R factor for the USLE, the $EI_{30}$ is the most widely accepted by researchers as an appropriate way to calculate rainfall erosivity and has been extensively used to calculate the R factor in tropics.

## The USLE K factor

The USLE K factor expresses the erodibility of a soil – how susceptible it is to erosion by rainfall. The K factor is defined as the rate of erosion per unit of erosivity index R from a unit plot of that soil (Lal, 1990). The K factor can be determined by any one of three accepted methods (El-Swaify and Dangler, 1976). The first method is based on measurements of soil losses from selected natural sites over a period long enough to represent a large variety of environmental conditions. The second is based on measurements under simulated rainstorms, and the third is regression equations based on chemical, physical, and mineralogical properties of soils as independent variables. Direct measurement of the USLE K factor was carried out in several areas in the tropics, including Hawaii (El-Swaify, 1977), Brazil (e.g. Mota and Lima, 1976; Alvarenga et al., 2004), Kenya (Barber et al., 1981), Nigeria (Lal, 1984; Vaneslande et al., 1985), Malaysia (Maene et al., 1977), and Indonesia (Sudjadi, 1984). The method of using regression equations to derive soil erodibility has been attempted by several researchers in temperate and subtropical areas (e.g., Dumas, 1965; Wischmeier and Mannering, 1969; Wischmeier et al., 1971; Romkens et al., 1977). The nomograph of Wischmeier et al. (1971), which is based on percent silt, percent sand, organic matter content, structure, and permeability, is the most widely used. El-Swaify and Dangler (1976) and Henklain and Freire (1983) considered the nomograph to have limited validity for calculating the erodibility of Hawaiian and Brazilian soils. Mtakwa et al. (1987), Ngatunga et al. (1984), and Vaneslande et al. (1985) held similar views of the nomograph's applicability to soils of tropical Africa.  However, according to Lal (1990), Lindsay and Gumbs (1982) and Maene et al. (1977) concluded that the method predicted erodibility well for the soils studied in Trinidad and Malaysia, respectively.

Loch and Rosewell (1992) calculated the K factor for five Australian soils using the form of the nomograph equation described by Wischmeier et al. (1971), with modifications to the M factor (the factor related to soil texture). Two of the five models used showed a strong correlation between measured and predicted erodibility. The first accounted for particle density, while the second was based on non-dispersed particles of 0.002-0.1 mm.

Models to estimate soil erodibility have been developed in several areas of the tropics using different parameters. El-Swaify and Dangler (1976) conducted a stepwise multiple linear regression analysis between erodibility and twenty independent variables for a set of ten Hawaiian soils. The predictive capability of the derived models resulted in very high correlation coefficients between measured and calculated K values. The authors presented six equations, each using five parameters that accounted for at least ninety five percent of the variation in K values. Bertoni and Lombardi Neto (1990) proposed a model based on the percentage of natural clay, percentage of clay dispersed in water, and equivalent humidity at one atmosphere of pressure (the percentage of water retained by the soil when it is submitted to a centrifuge force of 1000 x gravity). Based on the physical and chemical parameters of 31 Brazilian soils, Denardin (1990) developed an equation to estimate erodibility using permeability, organic matter content, aluminum oxide extracted by sulfuric acid, and the fraction of sand between 0.5 and 2.0 mm as the independent variables. Using data from 19 Brazilian soils, Chaves (1994) (cited by Luppi, 2002) developed an equation based on the percentage of silt, percentage of organic carbon, and percentages of aluminum, iron, and silicon oxides extracted with sulfuric acid. Mulengera and Payton (1999) used data from 12 soils from Africa, Australia, and Asia to derive three equations for calculating the K factor using texture-related parameters and permeability. Correlation between measured and predicted erodibility ranged from 0.843 to 0.911. Silva et al. (1999) presented five equations to calculate soil erodibility of Brazilian Oxisols based on data from 19 Oxisols in several Brazilian regions. The equations included 8 to 14 soil variables and showed correlation coefficients between estimated and measured values ranging from 0.72 to 0.98. The equation with the strongest correlation used parameters linked to structure (size, degree, and type), texture (particles dispersed in NaOH 0.1 M and in water), consistency (plasticity), color (hue), and flocculation index. Marques et al. (1997) developed eight equations to predict erodibility of soils with argilic horizon based on data from 22 Brazilian soils. The number of parameters varied from 5 to 10, with $R^2$ varying from 0.79 to 0.98.

As can be seen, the USLE K factor has already been calculated for numerous soils from many tropical regions and several formulae are available to calculate the K factor using intrinsic characteristics of tropical soils. The appropriateness of the nomograph of Wischmeier et al. (1971) has been almost unanimously rejected by researchers in the tropics.

## The USLE C factor

The USLE C factor is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow land. It is the integrated effect of all variables, such as crop canopy, residue management, cropping systems, mixed cropping, tillage systems, and mulch rate (Lal, 1990). The C factor has been derived for many of the tropical crop types and management systems that are also found in temperate regions, and studies have been carried out to derive the C factor for cropping systems unique to the tropics. Elhassanin et al. (1993) used data from 17 rainfall-runoff plots in Burundi to calculate C(u), a crop-factor calculated from the USLE, C(r), a crop-factor calculated as soil loss ratio from vegetative and fallow plots, and C(p), a crop-factor related to plant cover characteristics. Statistical analysis showed that C(r) overestimated the C-factor while the other crop-factors gave more accurate estimations. Evensen et al. (2001) developed improved C sub-factors for RUSLE in a study on drip-irrigated sugarcane in Hawaii, using two varieties of sugarcane and two planting times. The authors emphasized canopy cover, surface and residue cover, and surface roughness sub-factors, and developed equations correlating residue dry weight to percent residue cover. Da Silva and Schulz (2001) developed the C factor for mulch and yard debris distributed on the surface of a sandy red-yellow Oxisol in the southeastern region of Brazil. DeMaria and Lombardi Neto (1997) used seven years of data from plots on three types of soil in the southeastern region of Brazil (Sao Paulo) to calculate the C factor for continuous corn with buried residues, continuous corn with burned residues, continuous corn with residues left on the surface, corn after soybean, and corn after pasture. Bertol et al. (2001) calculated C factors for three management systems of wheat and soybean rotation in southern Brazil: plowing followed by two diskings, chiseling plus disking, and no-tillage. Roose (1976), Bertoni and Lombardi Neto (1990), and Lal (1990) described the C factor for other tropical crop and management systems.

The efforts spent by researchers to derive the USLE C factor for specific crops and management practices in the tropics have added to the list of C factor values already derived for crops and management practices common in temperate regions, so that there is now a known C factor for most cases in the tropics.

### 2.2.2. PROCESS-BASED EROSION MODELS

The current emphasis in erosion research, both in temperate and tropical climates, has shifted from empirical models to process-based models (Amorim et al., 2001). In addition to deriving parameters and input variables to make process-based erosion models from temperate countries applicable to tropical areas, studies have also focused on developing complete models specifically for application in the tropics. The work of Favis-Mortlock and Guerra (2000), Yu et al. (2000), and Yu and Rosewell (2001) are all examples of process-based erosion models developed for temperate areas that were adapted for application to the tropics.

There are several studies on the derivation of parameters and input variables for WEPP (Flanagan and Nearing, 1995). The ability of CLIGEN (CLImate GENerator - the weather-data generator for WEPP) to generate satisfactory precipitation statistics in the tropics was tested by Elliot and Arnold (2001) in two sites in Uganda. CLIGEN was successful in modeling the annual and monthly total precipitation, the monthly probability of wet and dry days, and average storm duration, but there were differences in some of the standard deviations between observed and generated values.

Zeleke (2000) observed that WEPP overpredicted runoff and slightly underpredicted soil loss in northwestern Ethiopia. Revision of the hydrologic components, particularly those related to the Green-Ampt infiltration model, was suggested for the conditions with long duration and high intensity rainfall. In order to facilitate the input of weather data, the author developed the breakpoint climate data generator (BPCDG), a stand alone program that helps to create breakpoint climate data for WEPP from standard rain gage data and other daily weather data sets of any meteorological station. Unlike the original climate generator model (CLIGEN), BPCDG uses measured storm data rather than storm data generated by using probability functions.

Since the development of WEPP, there have been a growing number of studies to determine the parameters of rill and interrill erosion in the tropics. In the southern region of Brazil, Schafer et al. (2001) determined interrill erodibility for a Hapludalf with sandy loam surface. Cassol and Lima (2003) performed a field study to determine interrill erodibility of a sandy clay loam Palleudult soil and cited Rockenbach (1992) and Braida and Cassol (1996), who determined interrill erodibility for a sandy loam Hapludalf and a sandy Paleudult, respectively. Lima and Andrade (2001) evaluated interrill erodibility of three clayey soils located in Lavras, southeastern region of Brazil: a Typic Rhodudult, a Typic Hapludult, and a Rhodic Hapludox. In Colombia, Hincapié et al. (2001) studied interrill erodibility of a volcanic ash soil from the Colombian coffee zone using field and laboratory experimentation.

Veiga et al. (1993) developed an equation to determine interrill erodibility based on laboratory tests using seven soils from the southern region of Brazil. The equation that best estimated soil erodibility ($r^2$=0.98) has as independent variables a stability index of soil particles and a measure of the iron oxides content extracted with hydrochloric acid

(HCl). Lima and Andrade (2001) verified that the soil attributes most closely correlated with interrill erodibility were iron oxides, kaolinite, water dispersed clay, total volume of pores, bulk density, particle density, organic matter, and aggregates smaller than 0.105 mm. Amorim et al. (2001) evaluated the effect of slope and rainfall kinetic energy on interrill erosion processes of a Brazilian Red-Yellow Oxisol and observed that interrill erosion is more sensitive to rainfall energy than it is to slope. They developed an equation to simulate soil loss using slope and rainfall kinetic energy as independent variables. The correlation between measured and simulated soil losses had $r^2$ of 0.94. Braida and Cassol (1999) derived an equation to estimate the ground cover factor for wheat and corn residue, which they used to estimate interrill erosion with WEPP. In Australia, Sheridan et al. (2000) developed equations to estimate rill and interrill erodibility based on data from 17 soils and 17 overburdens from open-cut coal mines. The soil interrill erodibility equation was based solely on the percentage of organic carbon, while the equation to estimate rill erodibility was based on pH, bulk density, and percentage by weight of particles size 0.02-1mm.

The Griffith University Erosion Model Template - GUEST (Rose et al., 1997) is a process-based erosion model that was developed for tropical Australian conditions. The model considers detachment and entrainment of the original soil, re-detachment and re-entrainment of the eroded materials, the effects of variable water depth, topography and rill geometry, and the effect of high sediment concentration. Yu et al. (1999) applied GUEST to four experimental sites in China, Malaysia, and Thailand. Comparison between observed and predicted soil loss using GUEST with estimated erodibility parameters resulted in an average model efficiency of 0.68, ranging from 0.60 to 0.74 for the described sites.

## 2.2.3. SUMMARY – EROSION

The current tendency in temperate, more developed countries to concentrate efforts on studies related to process-based erosion models is also observed in tropical countries. However, given the extensive research conducted to derive accurate parameters and variables for tropical application of the USLE, its widespread use in tropical research, and the reliance researchers place on this model, it is still an appropriate tool for simulating water erosion in the tropics.

The use of the original formula to calculate rainfall erosivity (the USLE R factor) is still controversial, but most studies support its validity. For derivation of the soil erodibility factor (K factor), many studies have rejected the validity of the nomograph of Wischmeier et al. (1971) and advocated that regression equations derived in the tropics that use soil properties as independent variables are the most appropriate.

# 2.3. SOIL TEMPERATURE

Tropical soils are defined as the soils lying between the tropics of Cancer and Capricorn that have an iso-temperature regime (difference between mean winter temperature and mean summer temperature of 5$^{o}$C or less at 50 cm of soil depth) (Eswaran et al., 1992). In a conventional tillage system, in which extensive soil mobilization and residue incorporation take place, the soil surface is bare during the early stage of the crop, which can lead to significant oscillation in the humidity and temperature of the soils. Temperatures greater than 40$^{o}$C at 5 cm depth are common (Morote et al., 1990). Bare soil at the Duclos Experimental Station in Guadeloupe, French West Indies, had a mean temperature of 31$^{o}$C at 20 cm depth, with a mean maximum of 35.5$^{o}$C and mean minimum of 25.6$^{o}$C. Sierra and Marban (2000) report that a maximum daily temperature of 45 to 47$^{o}$C is frequent in this soil. Similarly, Myers (1975) reported a maximum daily temperature of 41 to 52$^{o}$C for a tropical soil in Australia.

Several studies report that the use of porous mulch promotes the reduction of soil temperature in the tropics. Lal (1978) reported a difference of 6.1$^{o}$C at soil surface between a bare soil and a soil mulched with 4 tons/ha rice straw, planted with maize near Ibadan, Nigeria. Morote et al. (1990) observed differences of up to 8$^{o}$C at 5 cm depth between treatments with zero and 6.6 tons/ha of wheat straw in a soybean experiment in southern Brazil. The author also cited Derpsch et al. (1983), who reported a difference of 13$^{o}$C at 5 cm depth between a mulched and bare soil.

The importance of soil temperature for the soil biota and the kinetics of nutrients has led to the development of soil temperature models for tropical conditions. Oliveira et al. (1979) correlated mean soil temperature at 2 cm depth with the mean air temperature the same day and the 12 previous days. They observed that measured and estimated values of soil temperature converged well for days with no rainfall, but on rainy days the measured soil temperature was always lower than the estimated value because rainwater cools the soil surface faster than it cools the air.

Manrique (1988) applied the Gupta model (Gupta et al., 1982), which was developed for temperate areas, to a clayey, kaolinitic, isohyperthermic Tropudult soil in Panama to test the accuracy of this model in predicting soil temperatures under tropical conditions. The model consistently underpredicted soil temperatures, which could be due to the relatively narrow diurnal temperature variation in the tropics. The average differences between measured and predicted temperatures were nearly the same as the soil temperature predictions at high latitudes reported by Gupta et al. (1982).

A good estimate of soil temperature is of vital importance for the simulation of nutrient kinetics. Most studies are limited to observing the effects of different conditions; consequently, modeling soil temperature in the tropics is still an open field to be explored. The Gupta model seems to be appropriate for tropical conditions, but more studies are needed to validate the model in conditions different from those described by Manrique (1998).

# 2.4. NUTRIENT KINETICS

Although most research related to nutrients in the tropics focuses on crop productivity, the role of nutrients as pollutants is a growing concern. An increasing number of studies have examined models of nutrient kinetics, transformation, and loss.

## 2.4.1. NITROGEN KINETICS

Most information on nitrogen dynamics comes from experiments carried out in temperate soils, which are usually rich in bases and in microbial populations dominated by bacteria (Sierra and Marban, 2000). Experiments with tropical soils have also been conducted to determine the kinetics and response of nitrogen to different environmental conditions. Nitrogen and carbon cycles are closely linked and usually are studied or modeled together. Although modeling of soil carbon and nitrogen has been conducted since the 1960s, it is one of the least understood areas of NPS modeling and extensive research is needed to better understand and model the variability of processes, the effect of environmental factors on carbon and nitrogen soil processes, and the role of microorganisms (Ma and Shaffer, 2001).

## Nitrogen mineralization

Nitrogen mineralization has been measured through calculating the production of nitrogen in the form of ammonium ions ($N\text{-}NH_4^+$) (Sierra and Marban, 2000), the sum of $N\text{-}NH_4^+$ and nitrate ($N\text{-}NO_3^-$) production (Sampaio and Salcedo, 1993), or the production of $CO_2$ (Grisi et al., 1998; Reis and Rodella, 2002). It has been modeled in the tropics primarily using either single-fraction, multi-fraction, or mixed first- and zero-order models.

The single-fraction approach considers the soil organic nitrogen as the only pool that degrades according to first-order kinetics (Stanford and Smith, 1972):

$$N_m=N_0(1-e^{-k1t}), \qquad (2.5)$$

where Nm is total mineralized nitrogen, No is total mineralizable nitrogen, k1 is the rate of mineralization, and t is time. Several studies found that this approach was very effective in modeling organic matter decomposition over short durations. Sierra (2002) applied the single-fraction model to study how temperature fluctuation affects mineralization in a kaolinitic dark red Oxisol (Typic Eutroperox) from Guadeloupe. Reis and Rodella (2002) used the same approach to study the decomposition of straw (*Canavalia ensiformis* D.C.), cattle manure, vinasse, sewage sludge, and peat in central Brazil. Mubarak et al. (2001), studying N mineralization in five tropical soils of Malaysia, fitted the single-fraction first order model to simulate N mineralization of soil organic matter (SOM) over 12 weeks. Correlation between simulated and measured values resulted in $R^2$ varying from 0.51 to 0.93.

In the multi-fraction approach, the mineralizable nitrogen is divided into different fractions and each one is assumed to mineralize according to first-order kinetics at different rates. The most common multi-fraction approach is the double exponential model, in which two fractions of nitrogen are assumed (Deans et al., 1986). The first fraction, the labile pool, mineralizes faster than the second pool, which is composed of more recalcitrant nitrogen and is represented as:

$$N_m = N_1(1-e^{-k1*t}) + N_2(1-e^{-k2*t}), \tag{2.6}$$

where $N_1$ is total mineralizable labile nitrogen, $N_2$ is total mineralizable recalcitrant nitrogen, k1 is the rate of mineralization for the labile nitrogen and k2 is the rate of mineralization for the recalcitrant nitrogen.

Sierra and Marban (2000) used the double exponential approach to simulate nitrogen mineralization in two Oxisols of Guadeloupe (pH=4.7 and pH=6.2), obtaining a correlation of $R^2 = 0.97$ between the simulated and measured values for both soils. Sierra et al. (2001) obtained $R^2$ of 0.99 between measured and estimated N mineralization of fresh and dry sewage sludge applied on the same Oxisols of Guadeloupe. The double exponential model was also very effective in simulating the decomposition of $^{14}C$- and $^{15}N$-labelled corn straw in an Oxisol of northeastern Brazil at depths of 10, 30, and 60 cm (Sampaio et al., 1990). Alves et al. (1999) compared the efficiency of the single exponential, double exponential, zero and first order exponential, and the Richard's equation (described by White and Marinakis, 1991) in the simulation of potential soil N and C mineralization of 20 soils from the semiarid and humid zones of northeastern Brazil over 20 weeks. The double exponential model showed the most realistic results.

The mixed first- and zero-order kinetics approach assumes the labile pool decomposes according to first-order kinetics, while the recalcitrant pool is considered to follow zero-order kinetics (Benbi and Richter, 2002):

$$N_m = N_1(1-e^{-k1t}) + k_2t \tag{2.7}$$

where $N_1$ is the potential mineralizable N, and $k_1$ and $k_2$ are the mineralization rates of the labile and the recalcitrant N pools, respectively.

Araujo et al. (2001) also compared the performance of the single exponential, double exponential and mixed first- and zero-order kinetics in the simulation of C and N mineralization in a Red-yellow Podzolic soil planted with sugarcane in northeastern Brazil. They observed a decline in the slope of the mineralization curve until the eighth week; after that, the curve showed a constant slope. The mixed first- and zero-order model showed the best fit to their experimental data.

In summary, for short-term studies (usually less than 50 days), the simulation of N mineralization using single-fraction and mixed first- and zero-order kinetics showed good agreement with measured N mineralization. For long-term studies (more than 150 days), the application of the multi-fraction model provided a more accurate simulation of N mineralization in the tropics.

## Nitrogen immobilization and remineralization

Sampaio and Salcedo (1993) observed significant immobilization of soil N during the first month following the addition of corn straw to a Red-yellow Podzolic soil in northeastern Brazil and gradual remineralization after this period. An initial immobilization of the mineralized nitrogen and its subsequent remineralization was also observed by Sierra et al. (2001) in a soil of Guadeloupe amended with fresh sewage sludge. The authors suggested adaptations to the double exponential model for N mineralization to include a term accounting for N-remineralization. The model simulates remineralization with first order kinetics:

$$N_m = N_m^* - N_i + N_i\,[1 - e^{-k(ti-t0)}] \qquad (2.8)$$

where Nm is cumulative N mineralization, Nm* is the result of the double exponential model, Ni is mineral N sink corresponding to the potential of N immobilization at t=0, and k is the mineralization rate.

## Nitrification

Sierra and Marban (2000) and Sierra et al. (2001) observed a linear relationship between time and the nitrification of organic matter and sewage sludge, respectively, in Oxisols of Guadeloupe. Sierra et al. (2001) also observed a delay period of eight days before nitrification began, which they attributed to the initial bacterial growth stage. They suggested the following model for nitrification:

$$N_{nit} = k_{nit}(t - t_{del}) \qquad (2.9)$$

where $N_{nit}$ is the cumulative nitrification, $k_{nit}$ is the rate of nitrification and $t_{del}$ is the delay period.

Sierra et al. (2003) estimated nitrification on a given day as:

$$N_{it} = F_{Nit} * C_{NH4} \qquad (2.10)$$

where Nit is nitrification on a given day, $F_{Nit}$ is nitrification rate, and $C_{NH4}$ is the $NH_4^+$ content of the soil.

## Effects of environmental conditions on nitrogen transformations

The influence of environmental factors on the chemical reactions involved in nitrogen dynamics is well recognized. Temperature, soil water content, and pH, the most influential factors, affect the dynamics of organic matter in the tropics differently than they do in temperate areas (Grisi et al., 1998; Sierra and Marban, 2000). Temperature controls the rate of soil organic transformation; if all other factors are held constant, the turnover of organic matter increases with increasing temperatures. Consequently, the generalization is made that soils in the tropics tend to contain less organic matter than temperate soils (Grisi et al., (1998). However, because of the diversity of soils and the many factors affecting organic matter dynamics, generalizations about type and rates of decomposition of the soil organic matter (SOM) in tropical soils are unlikely to have wide applicability (Greenland et al., 1992). Grisi et al. (1998) compared soil organic matter transformations of three soils from the UK and three soils from Brazil. The soils were incubated at $15^{o}$ C and $35^{o}$ C for 150 days, with periodic measurements of microbial biomass and carbon dioxide evolution. Their results showed that the organic matter of the tropical soils was more degraded than that of two of the temperate soils. The third temperate soil, a sandy loam soil, behaved, in terms of its organic matter content, much more like the tropical soils.

Differences between the partitioning and decomposition rates of SOM in temperate and tropical soils are compared in Tables 2.1 and 2.2. Table 2.1 shows the fractions of labile and recalcitrant nitrogen ($N_1$ and $N_2$, respectively) for selected soils in the tropical and temperate regions, while Table 2.2 shows the decomposition rates of labile and recalcitrant N ($k_1$ and $k_2$) for both regions.

**Table 2.1**. Values of the fraction of labile and recalcitrant N for selected soils in the tropical and temperate regions

| Source | Region | Labile N ($N_1$) (mg/kg) | Recalcitrant N ($N_2$) (mg/kg) |
|---|---|---|---|
| Cabrera and Kissel (1988)* | USA (Mollisols) | 13-36 | 160-280 |
| Nordmeyer and Richter (1985)* | Germany | 13-24 | 128-179 |
| Deans et al. (1986)** | USA | 10-95 | 65-793 |
| Sierra and Marban (2000) | Guadeloupe | 29-36 | 90-117 |
| Sampaio et al. (1990) | Brazil | 14.7-27 | 78.6-85.3 |
| Alves et al. (1999) | Northeast Brazil | 2.2-52.8 | 6.5-2379 |

*According to Sierra and Marban (2000).

**Citing several authors.

**Table 2.2**. Rates of mineralization of labile ($k_1$) and recalcitrant ($k_2$) N for selected soils in tropical and temperate regions

| Source | Region | Unit | $k_1$ | $k_2$ |
|---|---|---|---|---|
| Alves et al. (1999) | Northeast Brazil | $Week^{-1}$ | 0.18-5.24 | 0.001-0.20 |
| Sampaio et al. (1990) | Northeast Brazil | $Month^{-1}$ | 0.81-2.13 | 0.014-0.023 |
| Sierra et al. (2001)** | Guadeloupe | $Day^{-1}$ | $8x10^{-4}$ – 0.409 | $5.5x10^{-4}$ – $5.9x10^{-3}$ |
| Griffin and Laine (1983)* | Temperate | $Week^{-1}$ | 0.526-0.653 | 0.017-0.034 |
| Linderman and Cardenas (1984)* | Temperate | $Week^{-1}$ | 1.095-2.804 | 0.038-0.058 |
| Richter et al. (1989)* | Temperate | $Week^{-1}$ | 0.408-5.11 | 0.018-0.152 |
| Chae and Tabatabai (1986)* | Temperate | $Week^{-1}$ | 0.281-0.526 | 0.006-0.074 |

* According to Benbi and Richter (2002)

** Varying temperature and soil water content

As can be observed, there is great variation in the fractions of labile and recalcitrant nitrogen, as well as in their rates of decomposition in both temperate and tropical soils. Consequently, if differences in these parameters do exist between temperate and tropical soils, statistics other than the range of parameter values will be necessary to demonstrate the difference. Alves et al. (1999) showed that the mean mineralization rate of recalcitrant nitrogen in soils from the humid area of northeastern Brazil was 0.067 $week^{-1}$, whereas soils from the arid zone of the same region had a mean rate of 0.036 $week^{-1}$, suggesting that environmental changes may affect the type of SOM and cause differentiation in mineralization rates, even between contiguous areas.

Sierra and Marban (2000) compared the rates of SOM mineralization of two temperate soils and one tropical soil. They observed that the temperature response of the temperate soils is shifted left of the tropical soil response curve. At 20°C, nitrogen in the temperate soils mineralizes at a rate 14 times faster than the rate for the tropical soil. When mineralization rates were compared for both soils at their typical mean temperature (18° C for the temperate and 31° C for the tropical soil), the mineralization rate of the temperate soils was only two times greater than that of the tropical soil. The authors concluded that the soil organic matter of the tropical soil was slightly more recalcitrant than the SOM of the temperate soils and that the microorganisms responsible for N mineralization in the tropical soil are adapted to the higher temperatures of tropical soils. Myers (1975) observed that the optimum temperature for ammonification in an Australian soil was close to 50° C and the process was still observable at 60° C, while Sierra and Marban (2000) reported that N mineralization increased continuously with the increase of temperature from 0° C to 60° C.

Sierra (2002) studied the effect of soil temperature fluctuation on N mineralization in a tropical soil, observing that N mineralization in a soil incubated with temperature fluctuation that approximated a sinusoidal wave (temperature ranging from 27.1°C to 33.2°C) did not differ significantly from mineralization in soil maintained at a constant temperature of 30°C. When soils were treated with temperature fluctuations simulating the upper layer of tropical soils (20°C-30°C-40°C and 20°C-40°C, both with average temperature of 30° C), mineralization was 51% and 56% greater than occurred with a constant temperature of 30° C. This study shows the importance of understanding how temperature variation affects N mineralization when simulating nitrogen transformation in the tropics.

Sierra and Marban (2000) and Sierra (2002) used the $Q_{10}$ expression to simulate the effect of temperature on the rate of soil N mineralization. The expression is as follows:

$$k_t = A * Q_{10}^{(T/10)} \qquad (2.11)$$

where $k_t$ is the mineralization rate, A is an empirical coefficient, $Q_{10}$ is the response to a 10°C temperature change, and T is the soil temperature in (°C). For temperate soils, Sierra and Marban (2000) cited values of $Q_{10}$ varying from 1.5 to 5.0, while the soils they tested showed $Q_{10}$ values around 2.8 and 4.0 for the mineralization rates of the labile and recalcitrant N, respectively. These results indicate that the mineralization rates of different N pools diverge in their response to temperature variation.

Sierra and Marban (2000) studied the effect of soil moisture on N mineralization by incubating a tropical soil with 30, 200, and 1500 kPa of water potential. For all incubation temperatures used (20, 30, 40, and 50$^{o}$ C), they observed that N mineralization declined with increasing water potential, suggesting that the coefficient A of equation 2.11 is a function of water potential. The equations for k1 and k2 were, respectively:

$$A(k1)=B-C\Psi \quad (2.12)$$

$$A(k2)=D\Psi^{-E} \quad (2.13)$$

where B ($d^{-1}$), C( $d^{-1}kPa^{-1}$), D($d^{-1}kPa^{-1}$), and E are empirical constants and $\Psi$ (kPa) is water potential.

Birch (1958) observed a higher rate of organic matter decomposition in a tropical soil at the beginning of each wet period. The "Birch effect" was also reported by Myers (1975); he detected a faster mineralization rate in the first seven days of incubation while studying nitrogen transformation in an Australian tropical soil. Likewise, Murphy et al. (1998) observed the effect in Australia, where a large flux in $CO_2$ production and gross N mineralization occurred immediately after rewetting a dry soil. Myers (1975) adjusted two Arrhenius-type equations to simulate changes in the ammonification rate of soils at 20 to 50$^{o}$C, one equation for the first seven days and the other for the period between days 7 and 28:

$$\ln Y_1= -2982*(1/T) + 10234 \quad (2.14)$$

$$\ln Y_2= -14282*(1/T) + 44156 \quad (2.15)$$

where $Y_1$ (μgN/g.day) is the ammonification rate for days 0-7, $Y_2$ (μgN/g.day) is the ammonification rate for days 7-28, and T is the absolute temperature.

While Joergensen et al. (1990) found no nitrification at 35$^{o}$C in a grassland soil from England incubated for 240 days, Myers (1975) observed a maximum rate of nitrification at 35$^{o}$ C, with a rapid rate decline at temperatures above this value, but with measurable nitrification even at 60$^{o}$C. Sierra et al. (2001) reported 38$^{o}$ C as the optimal temperature for nitrification of sewage sludge in an Oxisol of Guadeloupe.

Myers (1975) adjusted two Arrhenius-type equations to simulate changes in the nitrification rate of an Australian Tindall soil, with one equation for temperatures between 20 and 35$^oC$ and the other for temperatures between 35 and 60$^oC$:

$$\ln Z_1 = -12342*(1/T)+41.529 \qquad (2.16)$$

$$\ln Z_2 = 10581*(1/T) -33.005 \qquad (2.17)$$

where $Z_1$ (g N/g.day) is the nitrification rate between 20 and 35$^oC$, $Z_2$ (g N/g.day) is the nitrification rate between 35 and 50$^oC$, and T is absolute temperature.

Sierra and Marban (2000) observed that the rate of nitrification ($K_{Nit}$) was described by the $Q_{10}$ function only for temperatures up to 40$^o$ C and that an inhibition of the nitrification process happened at 50$^oC$:

$$K_{nit} = F*Q_{10}^{(T/10)} \quad \text{for } T \leq 40^oC \qquad (2.18)$$

$$K_{nit} = 0 \quad \text{for } T = 50^oC \qquad (2.19)$$

The response of the nitrification rate to temperatures between 40 and 50$^oC$ was not known. They suggested that the coefficient F in equation 2.18 is function of soil moisture according to the following equation:

$$F = G - H\Psi \qquad (2.20)$$

where G and H are empirical constants. For $\Psi$=1500 kPa, F=0 and, consequently, $K_{nit}$=0.

Sierra (2002) used the following S-shaped function to model the effect of temperature on nitrification rates in an Oxisol of Guadeloupe:

$$R_{ni} = R_{opt} \exp[-\rho(1-T/T_{opt})^2] \qquad (2.21)$$

where $R_{ni}$ is the actual rate of nitrification, $R_{opt}$ ($mgNkg^{-1}d^{-1}$) is the maximum rate of nitrification, $T_{opt}$ is the optimum temperature, and $\rho$ is a parameter reflecting the temperature sensitivity of $R_{ni}$.

Sierra et al. (2003) assumed that the nitrification rate, $F_{Nit}$, (Eqn. 10) is the product of temperature, water content, and pH subfactors:

$$F_{Nit} = F_T \times F_W \times F_{pH} \qquad (2.22)$$

where $F_T$, $F_W$, and $F_{pH}$ are non-dimensional coefficients representing the effect of temperature, water content, and pH on the nitrification rate. Using data from several soils of Guadeloupe, they established a linear scale for the pH factor ($F_{pH}$), setting a value of zero for $pH_{KCl} \leq 3.0$ and a maximum value at $pH \geq 6.5$, assuming a linear interpolation for

$pH_{KCl}$ between pH 3 and 6.5. The temperature factor ($F_T$) was set to zero for daily mean soil temperatures ($T_S$) $\leq 17^o$ C , or $\geq 50^o$ C. The value of $F_T$ was set to 1 for $T_s = 45^o$ C, with a linear interpolation for $F_T$ between 17 and $45^o$ C and between 45 and $50^o$ C. The water content factor ($F_W$) was also a linear scale from zero to one, with $F_W = 0$ for soil water content less than or equal to a minimum value ($W_{min}$) and $F_W$=1 for water content at or above field capacity ($W_{max}$).

In an experiment in which samples of a Brazilian soil were treated with straw and urea and were incubated for three one-month periods, Sampaio and Salcedo (1993) found evidence that N mineralization was inhibited when total soil mineral nitrogen reached concentration around 36 mg/kg soil.

## Summary – nitrogen kinetics

For long term simulation of mineralization, studies have found the double exponential model to be the most accurate model, while the single exponential model aligns closely with measured data in short term simulations. In modeling nitrification, both the zero order model (Eqn. 2.9) and the first order model (Eqn. 2.10) produce data with strong correlation to measured data. However, the first order equation is preferred because it is a more process-based model.

The microorganisms responsible for N transformation in tropical soils are adapted to higher temperatures. Consequently, the temperature response of nitrogen transformation in tropical soils is shifted to the right (toward higher temperatures) of the response curve for temperate soils. Studies have found that the optimal temperature for mineralization is higher than the optimal temperature for nitrification and that the microorganisms responsible for nitrification are more sensitive to low pH than are the microorganisms responsible for mineralization. This may result in a build-up of $NH_4^+$ in tropical soils. The impact of buildup of $NH_4^+$, which has characteristics different from $NO_3^-$, needs to be considered in the simulation of N dynamics in tropical soil profiles.

The high rate of evaporation in the tropics causes the soil surface to dry off rapidly after a rainfall event, making the "Birch effect" (faster mineralization of organic matter after rewetting a dry material) very common in the tropics. The "Birch effect" must also be considered when simulating nitrogen transformations in tropical soils.

## 2.4.2. PHOSPHORUS KINETICS

The parent material of soil phosphorous (P) is primarily calcium phosphates. The weathering process causes bases, silicates, and carbonates to be lost from the soil, concentrates the presence of iron (Fe) and aluminum (Al), and releases phosphorous into the soil solution. Part of soil P is absorbed to the soil biomass and organic material. Through mineralization, organic P is released into the soil solution as soluble inorganic P, which can return to the organic form through the process called immobilization. Soluble P can be adsorbed to the surface of secondary minerals becoming part of the pool called labile P. Labile P can be desorbed, returning to soil solution, or it can be transformed into more thermodynamically stable forms of P (non-labile P), which are not easily returned to the labile form (Rheinheimer and Anghinoni, 2001; Novais and Smyth, 1999).

Factors influencing the concentration and distribution of P in tropical soils include type of parent material, position in the landscape, and land use. In a study of soils from Rio Grande do Sul state, Brazil, Machado et al. (1993) found total P concentrations varying from 100 to more than 1,000 $mg.dm^{-3}$ and observed that soils derived from basalt were richer in P than those derived from sedimentary rocks. Mamo and Hake (1991) found that total P ranged from 185 to 1981 μgP/gr in 32 Ethiopian soils, while Motta et al. (2002) measured a P-Mehlich range from 2 to 78 mg $P.dm^{-3}$ in 5 non-cultivated Brazilian Oxisols and a range of 7 to 63 mg $P.dm^{-3}$ in soils cultivated with annual crops, with higher concentrations of P in soil originated from gabbro rocks. The concentration of total organic phosphorus varied from 7 to 272 mg/kg, representing 13 to 47% of total P in the surface layer of the 17 tested soils from Brazil (Guerra et al., 1996) and varied from 74 to 1306 μgP/gr between 32 Ethiopian soils (Mamo and Hake, 1991). Although there is significant variation in the P content of tropical soils, a characteristic common for most of them is their large P retention capacity.

## P sorption

P is retained in soils as precipitated calcium (Ca), iron (Fe), and aluminum (Al) phosphates and by adsorption to Fe and Al hydroxides. In very weathered tropical soils, the main constituents of the colloidal fraction are organic matter, 1:1 clays (mainly kaolinite), and Fe and Al oxides and hydroxides. The oxides and hydroxides have a large capacity for P sorption and the presence of these compounds, along with the high acidity of soils, is responsible for high rates of P sorption (Jorge et al., 1985; Motta et al., 2002). Al and Fe phosphates are more stable in acidic solution, while calcium phosphates are more stable in a solution with a higher pH. P adsorption and precipitation are difficult to distinguish. Consequently, both are usually described by the same model (Novais and Smyth, 1999).

The P buffer capacity (PBC) of a soil is the amount of P sorbed by the soil when the concentration of P in the equilibrium solution is raised from 0.25 to 0.35 µgP/L. According to Bolland et al. (1996), this index is regarded as the best estimate of P sorption in western Australian soils. Bolland et al. (1996) and Burkitt et al. (2002) used data from Australian soils to relate PBC to easily measured soil characteristics. While Bolland et al. (1996) concluded that the use of ammonium oxalate soluble Fe and Al are recommended as the routine procedures to estimate P sorption by soils in southwestern Australia, Burkitt et al. (2002) concluded that an alternative form of the P buffering index (PBI), in which the initial P status is accounted for by adding Colwell or Olsen extractable P ($PBI_{+ColP}$ or $PBI_{+OlsP}$, respectively), was found to be a superior indicator of the PBC.

Sorption isotherms have been used to describe the processes responsible for the retention of P by soil colloids. The Langmuir and Freundlich isotherms are the most commonly used for tropical soils. Singh et al. (1983) applied the Freundlich equation to describe P sorption in ten soils representing the six most prevalent soil types in the Brazilian Amazon and found that between 37 and 74% of P was sorbed within 32 minutes, while 100% was considered sorbed within 6 days.

Casagrande et al. (2003) used the Langmuir isotherm to calculate the maximum soil sorption when studying the influence of pH on P sorption in soils with variable electric charge. Pereira and Farias (1998) also used the Langmuir isotherm to evaluate P sorption in 15 soils from northeastern Brazil, finding that soil sorption varied from 0.124 to 0.805 mg P/g. The more alkaline soils showed higher soil sorption while the acidic soils showed greater sorption energy. Rheinheimer et al. (2003) observed that the inclusion of pre-sorbed P in the Langmuir equation increased the constant related to the energy of sorption by 2.9 times and did not modify the maximum sorption of one soil, while the maximum sorption increased in the superficial layer of two other soils. For ten Brazilian Oxisols with percentage of clay varying from 7.7 to 54.3%, the averages for maximum soil sorption capacity and bonding energy were 1.065 $mg.g^{-1}$ and 0.146 $L.mg^{-1}$, respectively (Lopes, 1977). Five Ultisols from North Carolina had average sorption and bonding energy values of 0.419 $mg.g^{-1}$ and 0.328 $L.mg^{-1}$, respectively (Novais, 1977). These average values were 0.419 $mg.g^{-1}$ and 0.265 $L.mg^{-1}$ for 15 soils from the semiarid northeast of Brazil (Pereira and Farias, 1998). Correlation of P sorption with selected parameters of tropical soils can be found in Dolui and Banerjee (2001), Adepoju (1993), Casagrande et al. (2003), Motta et al. (2002), Singh et al (1983), and Jorge et al. (1985).

Goncalves et al. (1985) studied the kinetics of P sorption in 10 Brazilian soils using an equilibrium solution with an initial concentration of 50 μgP/mL. They adjusted the following equation to the data:

$$C= Kt^{-n} \qquad (2.23)$$

where C is the concentration of P in the solution (μgP/mL), t is the time to reach equilibrium (hours), and K and n are constants. K depends on the P concentration in soil solution and n is related to the velocity of P sorption. The authors observed that previous liming of the soils did not consistently modify the velocity and magnitude of P sorption. The equation showed very good agreement with the measured data, with $R^2$ greater than 0.9 for every soil.

## Transformation of labile P to non-labile P

Non-labile P is considered the form of P not in equilibrium with P in solution because it is strongly bonded and retained by soil particles. The most probable mechanism for the formation of non-labile P is the forming of two bonds with the adsorbent surface, which is also what makes its desorption difficult. Novais and Smyth (1999) described the transformation of labile P to non-labile P as fast when P enter in contact with soil, decreasing exponentially but still existing after several months.

Goncalves et al. (1989) used five soils, four dose amounts of P, and eight incubation periods to study the transformation of labile P to non-labile P. The following equation was fitted to the data:

$Ct=Co(KT/b)^{-b}$ (2.24)

where Ct is the concentration of labile P (mg/kg), Co is initial concentration of labile P, K is the rate of transformation of labile to non-labile P ($day^{-1}$), T is time (day), and b is a constant. The decrease in labile P (P extracted by 0.01 M $CaCl_2$, anion exchange resin, Mehlich 1, or Bray 1) was obtained by the first derivative of Equation 2.24:

$$\frac{\partial Ct}{\partial t} = \frac{Cobk^{b}t^{-b-1}}{b^{-b}} \qquad (2.25)$$

For the initial dose of 150 mg P/kg, they observed a decrease of 128.2 ppm P/day (P extracted by anion exchange resin) after 15 days of incubation, 0.127 ppm P/day after 30 days, and 0.004 ppm P/day after 300 days. The change of Ct with time ($\partial$Ct/$\partial$t) showed significant correlation with the maximum capacity of P adsorption, the energy of adsorption of P, and the constant k of the Freundlich isotherm, indicating that soils with higher soil sorption capacity more rapidly transform labile P to non-labile P (Goncalves et al., 1989).

### Summary - phosphorus kinetics

The high acidity and high concentrations of Fe and Al oxides in tropical soils play a significant role in the kinetics of P. They cause tropical soils to have higher sorption of P than temperate soils. Consequently most studies on P kinetics are focused on P sorption. The equations used to simulate P kinetics in tropical soils are essentially the same as those used for temperate soils. However, different parameters have to be used in these equations to account for the differences in soil sorption and bonding energy that are characteristic of tropical soils.

## 2.5. NUTRIENT LOSSES

Nutrient loss in the agricultural environment is a major concern because, in addition to representing economic losses, nutrient loss into water bodies causes significant environmental problems. This section discusses volatilization of nitrogen and leaching and runoff of both nitrogen and phosphorous.

## 2.5.1. AMMONIA VOLATILIZATION

Gaseous loss of ammonia ($NH_3$) from upland soils is primarily a soil surface process. It is one of the few soil nitrogen processes that is abiotic and not directly mediated by microorganisms. $NH_3$ exists in a pH-dependent chemical equilibrium with ammonium ($NH_4^+$) in soil water. Losses of nitrogen as $NH_3$ gas are enhanced by high pH levels (>8.5), wind, and high temperatures (Ma and Shaffer, 2001). While Libardi and Reichardt (1978) and Sierra et al. (2001) observed only negligible gaseous losses, other studies found significant N loss by ammonia volatilization in the tropics. Alfaia (1997) observed that N loss varied with the type of fertilizer and the position of fertilizer application. In laboratory and greenhouse experiments using two soils from northeastern Brazil, Rodrigues and Kiehl (1986) observed that 83.3% of the urea applied on the soil surface volatilized as ammonia, 88 to 91% of the loss happening in the first 8 to 10 days. Losses were reduced to 50.1% of the applied N when the urea was incorporated into the soil to 5 cm depth, 65 to 81% of the loss happening within 6 to 16 days after application. In other studies in Brazil, 11.2% and 17.5% of total urea applied to two soils cultivated with sugarcane volatilized during 17 days of incubation, (Lara Cabezas et al., 1994) and 32.8% of urea applied to a corn crop volatilized within nine days (Lara Cabezas et al., 1997).

The above studies have shown that when N is applied as urea in tropical conditions, gaseous losses of ammonia can be significant. These losses must be accounted for when modeling NPS pollution because ammonia volatilization decreases the amount of nitrogen available in the soil profile.

## 2.5.2. NUTRIENT LEACHING

Nitrate leaching below the crop root zone can be a significant mechanism for nitrogen loss due to the high rainfall typical of the tropics. However, the percentage of N lost by leaching varies greatly between experiments. Lilienfein et al. (2000) studied the effects of conventional till and no-till on soil solution N concentration in Brazilian Oxisols planted with soybean. 43 days after planting, they found no difference in the nutrient concentrations of the two management systems at 15 cm depth but observed that the concentration of nitrate ($NO_3^-$) at 2 m depth was five times higher under no-till than under conventional till. Meireles et al. (1980) observed that only 1.35% of the N (in the form of ammonium sulfate) applied to an Oxic Paleudalf planted with bean (*Phaseolus vulgaris*) leached in the year following application. In contrast, in a field experiment conducted by Chotte et al. (1998) in the Lesser Antilles, 40 to 45% of the N applied as urea to corn crop plots was lost during the growing season. For an Alfisol from Venezuela, where yearly rainfall is 1700 mm, Hetier et al. (1989) found that only 2% of fertilizer N was lost by leaching, whereas total N losses amounted to 30%. They suggested that N losses were mainly from denitrification. Oliveira et al. (2001) observed that the application of sewage sludge on soils based on the maximum annual heavy metal load might lead to significant nitrate leaching and Sierra et al. (2001) observed leaching of 355-435 kg N/ha 210 days after the application of 630 kg N/ha sludge.

Nitrate is highly soluble and moves quickly with the soil water in temperate soils because it is not usually adsorbed to soil particles (Ma and Shaffer, 2001). In the tropics, however, soils with net positive charges are very common, and the adsorption of nitrate in these soils plays an important role by retarding its movement to deeper soil layers. Seyfried and Rao (1990) used a piston displacement model to simulate solute movement in two contrasting cropping systems in Costa Rica, with very good agreement between simulated and observed values of the profile water content. Libardi and Reichardt (1978) estimated N losses during a bean crop cultivation by multiplying N concentration by the water flow. However, Kinjo et al. (1978) calculated that the volume of water required to leach all nitrate from an Oxisol amended with $NaNO_3$ is four times the pore volume. Wong and Rowell (1994) observed that for three Nigerian soils, an average water flow of 2.4 times the pore volume was sufficient to leach the nitrate.

Sierra et al. (2003) asserted that the piston displacement model overestimates nitrogen leaching in tropical Oxisols due to intrinsic characteristics of these soils. Firstly, nitrifiers are very sensitive to low soil pH. A significant amount of the N in Oxisols is in the form of $NH_4^+$, which moves through the soil more slowly than $NO_3^-$. Secondly, the high anion exchange capacity of some soils contributes to $NO_3^-$ retention, delaying N leaching. Sierra et al. (2003) found that nitrate transport occurs when its concentration is higher than a critical value. This retardation factor represents $NO_3^-$ adsorbed to the positively-charged sites of the clay particles. Observations made at the beginning of the rainy period revealed that not considering the retention factor caused an overestimation of nitrate transport.

For three soils monitored by Wong and Rowell (1994), the delay of nitrate leaching correlated to how positively charged the soil column was. Oliveira et al. (2000) found the best agreement between the nitrate adsorbed to organic matter and the amount of extracted sulfate for a positively charged Brazilian Dark-Red Oxisol. They observed that nitrate adsorption increased with soil depth and suggested that the increased adsorption is caused by the decreased amount of organic matter at greater depths, with a consequent reduction in charge repulsion. Black and Waring (1979) verified that nitrate adsorption is strongly correlated with specific surface area, organic matter content, and pH in water. Nitrate adsorption correlated with $\Delta$pH only when soils from different depths at the same location were used (Black and Waring, 1976; Oliveira et al., 2000).

Leaching of P is more significant in sandy soils, but it has also been reported in soils with higher clay content. In tropical soils, studies on nutrient leaching do not usually include P as a leachable nutrient due to its low mobility (Seyfried and Rao, 1990; Wong and Rowell, 1994). However, Soprano and Alvarez (1989) conducted a greenhouse experiment using a Dark-red Oxisol from southeastern Brazil in which pots were irrigated with the same amount of rainfall as occurred outside the greenhouse. They detected P leaching corresponding to 75-196 gr P/ha. Faria and Pereira (1993), studying P movement in four Brazilian Oxisols over 75 days, found that P moved until reaching a depth of 6-8 cm in a clayey soil, while moving to a depth of 14-16 cm in a sandy soil. Araujo et al. (2003) quantified leaching of phosphorus in columns of aggregates of a Brazilian Oxisol (Rodhic Haplustox). They evaluated different sizes of aggregates using ten pore volumes of distilled water, Mehlich-1 extractor, and solution of ammonium acetate at pH 7.0 as eluates. Distilled water eluted more phosphorus from the columns of smaller aggregates and eluted more P if elution time was increased. Mehlich-1 leached three to sixty times more P than distilled water did, while P leached with the ammonium acetate solution did not reach the minimum concentration required for detection. In a laboratory experiment with a Brazilian Oxisol, Lessa and Anderson (1996) observed that leaching of organic P was ten times greater than leaching of inorganic P in a laboratory experiment with a Brazilian Oxisol. They concluded that leaching of organic P may add significantly to the P contained in ground water and contribute to overall loss of P in areas where Oxisols predominate.

## 2.5.3. NUTRIENTS IN RUNOFF

Runoff water removes phosphorus and nitrogen from the upper horizon in both sediment-bound and dissolved forms. Several studies have qualified and quantified the impact of land use and crop management on nutrient losses from runoff in the tropics. Bertol and Miquelluti (1993) compared runoff losses of P in bare plots and plots planted with corn in southern Brazil, finding that losses were equivalent to 0.95 kgP/ha in bare plots and 0.36 kgP/ha in planted plots. In Oxisols from the center-west region of Brazil, Hernani et al. (1999) found that losses of dissolved P were 2.8 to 5.8 times greater than losses of sediment-bound P. In the Andean hillsides of Colombia, Ruppenthal et al. (1997) observed that in bare soils 80% of lost P was sediment bound, while sediment-bound P was only 20 to 65% of total P losses for several cassava (*Manihot esculenta*) cropping systems. Average total P losses in bare soils were 7.3 times greater than losses from soils cropped with cassava (Ruppenthal et al., 1997).

Guadagnin (2003) studied plots under natural rainfall in southern Brazil to see how different management systems affect P loss by erosion. Overall, P concentrations were higher in sediments than in runoff water. Less sediment-bound P was lost in no-till plots than in the plots with disturbed soil. The no-till plots lost more soluble P than sediment-bound P. Tilled soil cropped with soybean in southern Brazil lost three times more organic matter and five times more P than no-till soils with the same crop (Vieira et al., 1978). Hernani et al. (1999) observed a higher concentration of dissolved P in runoff from no-till soils and asserted that this result may be linked to the higher concentrations of this nutrient in the upper horizon (0-0.05m depth). On a Typic Hapludox in southern Brazil losses of N from water erosion were 2.6, 3.5, 6.2, and 10.4 times greater for conventional tillage than for bare soil, reduced tillage, no tillage in desiccated and burned field, and no tillage in desiccated field, respectively (Bertol et al., 2003).

Nutrient enrichment ratio (Er) is highly variable in the tropics due to the high variability in soils. P enrichment ratio was found to be 5.8 in Alfisols of West Africa (Lal, 1976), 5.09 for no-till and 1.58 to 2.89 for other crop management systems in

Oxisols of Center-West Brazil (Hernani et al., 1999), close to or slightly below unity in a loam soil in Australia planted with pineapple (Palis et al., 1997), and 1.07 for Bray-II P in Oxic Dystropept and Oxic Humitropept soils from the Andean hillsides of Colombia (Ruppenthal et al., 1997). According to the authors, the low enrichment ratios of the Andean soils (0.99 for organic matter, 1.03 for total N, 1.07 for Bray-II P) were the result of good aggregation. A study carried out in a Palleudult soil located in southeastern Brazil showed that losses of nutrients (P, K, Ca, and Mg) had a strong correlation with organic matter and a weak, negative correlation with the clay content of sediments, indicating that the low CEC of these soils causes mineral colloids to have a low contribution to the binding of nutrients (Schaefer et al., 2002).

In Australia, Palis et al. (1990a) observed that when Er is greater than one, its value declines proportionally to the amount of soil eroded, because as the erosion event progresses, the size distribution of transported sediments tends to approach that of the original soil. The following logarithmic function was developed to relate enrichment ratio to total soil loss (SL) (Palis et al., 1997):

$$\ln Er = a - b \ln SL, \qquad (2.24)$$

where SL is total soil loss and *a* and *b* are fitted constants. The effects of surface cover on soil loss and Er were investigated by Palis et al. (1990b) who observed that the more covered the soil, the finer the sediments, particularly in the beginning of a rainfall event.

## 2.5.4. SUMMARY — NUTRIENT LOSSES

There are two points to be highlighted regarding nitrogen loss under tropical conditions. The high acidity of tropical soils should make the equilibrium between ammonia and the ammonium ion favor the formation of ammonium, making loss of gaseous ammonia negligible. However, ammonia volatilization was significant in several studies carried out in Brazil, both in laboratory and field conditions when urea was the applied source of nitrogen. These losses must be accounted for when modeling NPS pollution because they decrease the amount of nitrogen available to enter water bodies.

The other point to be highlighted is that tropical soils retain more N than temperate soils. This greater retention may occur because nitrifiers are very sensitive to low soil pH, and a large amount of the $NH_4^+$ may accumulate in acidic soil and be attracted to the negative charges of the soil particles. $NO_3^-$ may also accumulate in the soil profile due to its attraction to the positive charges of soils.

Because of its low mobility, phosphorus leaching has been considered only in some NPS pollution models, but not universally. However, the high porosity of Oxisols makes possible high rates of water infiltration, leading to loss of P, especially organic P. These losses may be significant and should also be accounted for in conditions with high rates of water infiltration.

## 2.6. CONCLUSIONS

Predicting the delivery of sediment and agrochemicals to waterbodies requires a model that includes components for hydrology, erosion, nutrient, and pesticide variables, integrated by the user interface and the input and output systems. The components of NPS models have been studied intensively in the tropics. However, many of these studies have been published as theses or dissertations, or in proceedings of national meetings or journals of restricted circulation, making access difficult. A review of these studies was carried out with the primary objective of presenting a framework for the development of a NPS model appropriate to simulate loadings of sediments, nitrogen, and phosphorus in leachate and overland flow from agricultural fields under tropical conditions.

The Gash model (Gash, 1979) and the revised Gash model (Gash et al., 1995) showed very good results in the simulation of rainfall interception in tropical forests. Incorporating the LAI as an additional parameter in the models improved rainfall interception simulation in both forest and crop systems.

The SCS curve number method simulates runoff well in the tropics if local values of CN are used in the calculation instead of values derived for temperate conditions. Evapotranspiration under tropical conditions can best be modeled by the Penman-Monteith equation. Simulations of infiltration show better agreement with measured data when they account for the superficial sealing caused by the impact of rainfall.

The current tendency in temperate, more developed countries to concentrate efforts in studies related to process-based erosion models is also observed in tropical countries. However, given the extensive research conducted to derive accurate parameters and variables for tropical application of the USLE, its widespread use in tropical research, and the reliance researchers place on this model, it is still an appropriate tool for simulating water erosion in the tropics. The use of the original formula to calculate rainfall erosivity (the USLE R factor) is still controversial, but most studies support its validity. Many studies reject use of the nomograph of Wischmeier et al. (1971) for deriving the soil erodibility factor (K factor) and advocate that regression equations derived in the tropics that use soil properties as independent variables are the most appropriate

For long term simulation of nitrogen mineralization, studies have found the double exponential model to be the most accurate, while the single exponential model aligns closely with measured data in short term simulations. The zero order model for nitrification shows good agreement with measured data, but the first order model is preferred because it is more process-based.

The temperature response of nitrogen transformation in the tropics is shifted to higher temperatures than are observed in temperate soils because the microorganisms responsible for N transformation in tropical soils have adapted to the higher soil temperatures. Because the optimal temperature for mineralization is higher than the optimal temperature for nitrification and the microorganisms responsible for nitrification are more sensitive to low pH than those responsible for mineralization, $NH_4^+$ is more likely to build up in tropical soils.

The high rate of evaporation in the tropics causes the soil surface to dry rapidly after a rainfall event, making the “Birch effect” (faster mineralization of organic matter after rewetting a dry material) very common in the tropics. The “Birch effect” must also be considered when simulating nitrogen transformations in tropical soils.

Phosphorus kinetics are significantly affected by the high concentrations of Fe and Al oxides and the high acidity of tropical soils, which cause greater sorption of P than occurs in temperate soils. Although the equations used to simulate the P kinetics in the tropics are essentially the same as those used in temperate soils, different parameters have to be used to account for the different soil sorption and bonding energy characteristics of tropical soils.

Regarding nitrogen losses, the high acidity of tropical soils should make the equilibrium between ammonia and the ammonium ion favor the formation of ammonium, consequently making gaseous losses of ammonia negligible. However, several studies found that when urea was the source of nitrogen application, nitrogen loss from ammonia volatilization was significant and should be accounted for in models.

Tropical soils have greater retention of nitrogen than temperate soils, which may be the result of multiple factors. Nitrifiers are very sensitive to low pH; $NH_4^+$, which is attracted to negative charges of soil particles, accumulates in acidic soil. Nitrate can also accumulate in the soil profile because of its attraction to the positive charge of some tropical soils.

The high porosity of Oxisols enables high rates of water infiltration, leading to losses of P from these soils, especially organic P. These losses may be significant and should also be accounted for in conditions with high rates of water infiltration.

As a final conclusion, the knowledge described above provides the framework for developing a more representative and comprehensive model for NPS assessment in the tropics. The incorporation of specific parameters and relationships for components and processes specifically adapted for the tropics should provide an improved model appropriate to simulate loadings of sediments, nitrogen, and phosphorus in leachate and overland flow from agricultural fields under tropical conditions.

# CHAPTER III
# MODEL DEVELOPMENT

## 3.1. MODEL SELECTION

A number of nonpoint pollution models were evaluated to assess their suitability for adaptation to simulate nutrient transformations and losses under tropical conditions. The desired characteristics of the model were that it would: represent field-scale processes of nitrogen and phosphorus dynamics in the soil profile, predict nutrient losses in surface runoff and in leachate, and have modifiable source code available.

The Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984) was developed to assess the effect of soil erosion on soil productivity. According to Meinardus et al. (1998), EPIC simulates hydrology, weather, erosion, irrigation, nutrient (nitrogen and phosphorus) transformation and losses by percolation and surface runoff, pesticide fate, soil temperature, tillage, plant environment control, and economics. EPIC was already tested in several environmental conditions and recently received improvements that extend its capabilities to deal with a wide variety of agricultural management problems. However, EPIC is not appropriate for the simulation of complex fields because it assumes that weather, soils, and management systems are homogeneous in each simulation (Meinardus et al., 1998).

The Root Zone Water Quality Model (RZWQM) is a one-dimensional (vertical in the soil profile) process-based model that simulates the growth of plants and the movement of water, nutrients and agro-chemicals over, within and below the crop root zone.  It can represent agricultural cropping system under a range of common management practices, including the simulation of a tile drainage system.  RZWQM was created to be used primarily as a tool for assessing the environmental impact of alternative agricultural management strategies on the subsurface environment. The model does not incorporate the transformation and transport of phosphorus, but focuses on carbon, nitrogen, and pesticide processes. In addition, it does not simulate erosion and the crops parameterized are limited to corn, soybean and wheat (USDA/ARS, 2003).

The Nitrate Leaching and Economic Analysis Package (NLEAP) (Shaffer et al., 1991) is a field-scale computer model developed to determine the potential nitrate leaching associated with agricultural practices. The model does not simulate losses by erosion or transformation and transport of phosphorus (Brodahl et al., 1991).

Opus (Smith, 2004) is a continuous simulation model that estimates the vertical movement and transport of water in the root zone soil profile and also predicts surface water movement and transport of material during rainfall runoff on small catchments. Simulated soil processes include unsaturated soil water flow, plant growth and transpiration, soil evaporation, soil water transport and decomposition of adsorbed chemicals, soil C, N and P cycling and residue decomposition. It is an integrated field scale model developed for studying the effects of management and weather inputs on the movement of water and potential pollutants within and from small watersheds (Zacharias, 1998; Smith, 2004). Opus is available publically and its documentation can be obtained upon request, but its source code is not distributed.

The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Knisel and Davis, 1999) is a continuous simulation, field-scale functional model developed to simulate edge-of-field and bottom-of-root-zone loadings of water, sediment, pesticides, and plant nutrients from the complex climate-soil-management interactions. The model can provide estimates of the impacts that management systems such as planting dates, cropping systems, irrigation scheduling, and tillage operations have on chemical movement. Erosion is calculated through USLE-based equations, while runoff calculation is based on the SCS-CN method, both extensively tested in tropical conditions. The nutrient module includes transformation and transport of nitrogen and phosphorus (Knisel and Davis, 1999). Furthermore, the model is well documented, has been applied and evaluated in many environments, and its source code is readily available. GLEAMS was the model chosen to be adapted for tropical conditions.

## 3.2. CHANGES TO THE GLEAMS CODE

The source code of GLEAMS was written in FORTRAN and is composed of eleven files. The files were downloaded from the GLEAMS homepage (http://sacs.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm) in August 2004. FORTRAN Developer Studio was used to modify the code, compile files and build the modified model, which is called TROPGLEAMS. The changes made to GLEAMS were related to initial and default parameter values and algorithms that affect nutrient transformations, nitrate movement in the soil profile, and evapotranspiration. An input parameter called TROPI was added to GLEAMS so that the user can choose to run the original or the modified model. Setting TROPI = 0, the original model is executed. Setting TROPI = 1, the model is executed using parameters and algorithms that represent tropical conditions as implemented in the model code in this study. The simulation of subsurface organic fertilizer application was included in TROPGLEAMS and is discussed in Appendix A.

## 3.2.1. INITIAL VALUES

GLEAMS considers the following pools of nitrogen: total nitrogen (TN), which includes all forms of N except $NO_3$-N, potentially mineralizable nitrogen (POTMN), stable organic nitrogen (SORGN), fresh organic nitrogen (FON) from crop residue, organic nitrogen from animal waste (ORGNW), nitrate nitrogen (CNIT), and ammonium nitrogen (AMON). The following pools are considered for phosphorus: fresh organic P in crop residue (FOP), organic humus P (SORGP), organic P from animal waste (ORGPW), labile P (CLAB), active mineral P (PMINP), and total P (TP), which comprises all forms of P except CLAB.

The nutrient editor of GLEAMS is comprised of 19 lines (cards), in which up to 51 variables and parameters have to be input when NPS pollution is simulated in a field with a one-horizon soil. A common limitation of model application is the lack of detailed parameter data on physical, chemical, and biological properties of the soil, as well as on crop and tillage information and terrain characteristics. Model input for nitrogen is composed of crop residue in soil surface (RESDW), TN, CNIT, POTMN, and ORGNW. For phosphorus, the inputs are TP, CLAB, and ORGPW. With these values, GLEAMS calculates all N and P pools for model initialization.

If input values of N and/or P are left blank, the subroutine INITNT sets default values or calculates their values using equations derived from soil data. Total nitrogen

(TN) is calculated by dividing soil organic matter (SOM) by 1.724 g OM/g OC, then dividing the result by the average carbon:nitrogen (C:N) ratio, which is set at 10:1. The default for nitrate concentration is 5µg $NO_3$-N/g soil in all horizons. Potentially mineralizable nitrogen (N0) is set as 17% of total nitrogen, based on the data presented by Stanford and Smith (1978). Ammonium is estimated internally in the model as 2 µg/g soil.

For the superficial horizon of highly weathered soils, soil organic P (SORGP) is calculated based on total nitrogen (TN) through the following equation:

$$SORGP = 44.4 + 1130\ TN \quad (3.1)$$

where SORGP is soil organic humus P (mg/kg). For the other horizons, the relation is given by:

$$SORGP = 1464\ TN \quad (3.2)$$

where TN is total nitrogen (percent). Labile P (CLAB) is estimated as 10% of SORGP for calcareous soils, 8.7% of SORGP for slightly weathered soils, and 5.6% of SORGP for highly weathered soils.

The phosphorus sorption coefficient or P availability index is a variable that estimates the fraction of fertilizer P that remains in the labile form after a 6-month incubation. It is used by GLEAMS to calculate active mineral P (PMINP) using values of labile P. Soil sorption (PSP) is calculated as follows:

$$PSP = 0.46 - 0.0916 * \ln(CLAYPCT) \quad (3.3)$$

where CLAYPCT is the clay content of each soil layer, in percent. Stable mineral P (SOILP) is calculated as four times the value of active mineral P.

The use of measured soil data to represent initial conditions increases the accuracy of model results, and thus is always preferred over default values. The relationships and default values described above were developed for temperate soils. The appropriateness of their use in the tropics was evaluated and is described in the next sections.

## The C:N Ratio

The value of the C:N ratio in tropical soils was evaluated using published data from 13 studies. Data of organic C and total nitrogen from Brazil (Araujo et al., 2001; D'Andrea et al., 2004; Sampaio et al., 1990; Van Wambeke, 2003), Dominica, Guadeloupe and Santa Lucia (Chotte et al., 1998), Malaysia (Mubarak et al., 2001), Hawaii (Neff et al., 2000), Thailand, Sudan, and Zambia (Van Wambeke, 2003), Australia (O'Connel and Rance, 1999), Venezuela (San Jose et al., 2003), Nigeria (Wong et al., 1987), Martinique (Neff et al., 2000), Colombia (Phiri et al., 2001), Ethiopia (Solomon et al., 2002), and Kenya (Warren and Kihanda, 2001) were included in this analysis. First, a mean value for each soil order was calculated, and then the overall mean was calculated based on the area covered by each soil in the tropics. The result was compared with values of other datasets and a C:N value considered more appropriate for tropical conditions was selected.

The mean C:N ratio and total area of different soil orders in the tropics are summarized in Table 3.1. The area-weighted C:N ratio, based on the mean value of C:N for each soil order and the area of each soil order, was 13.26. Tognon et al. (1998) presented soil data from 78 sites with Yellow Oxisols and 184 sites with Red-yellow Oxisols in the Amazonian region and 123 sites with Red-yellow Oxisols and 121 sites with Dark-red Oxisols in the central savannah region of Brazil. Their dataset resulted in a C:N ratio of 12.37. Post and Pastor (1985) reported mean C:N ratios in soils from tropical thorn woodland, tropical very dry forest, tropical dry forest, tropical moist forest, and tropical wet forest as 9.2, 13.7, 13.3, 14.9, and 30.2, respectively. Sanchez et al. (1982) conducted a study using sixty five soil profiles from the tropics (19 Oxisols, 18 Ultisols, 13 Alfisols, and 11 Mollisols) and 45 soil profiles from a temperate region (8 Ultisols, 16 Alfisols, and 21 Mollisols). For the tropical soils, they found C:N ratios of 13.7, 11.3, and 9.6 for the 0-15, 0-50, and 0-100 cm layers, respectively, and found ratios of 13.6, 11.3, and 10.0 for the same layers in temperate soils, suggesting the orders Oxisols, Ultisols, Alfisols, and Mollisols have no major differences in C:N ratio between tropical and temperate regions.

**Table 3.1**. Area and mean C:N ratio for different soil orders in the tropics.

| Soil | Total area in the tropics* | | Mean C:N |
|---|---|---|---|
| | ($10^6$ ha) | ( % ) | Ratio** |
| Oxisols | 525 | 35.3 | 13.0 |
| Ultisols | 413 | 27.7 | 13.3 |
| Inceptisols | 226 | 15.2 | 12.3 |
| Alfisols | 53 | 3.6 | 8.0 |
| Spodosols | 19 | 1.3 | 44.7 |
| Vertisols | 5 | 0.3 | 12.3 |
| Andisols | 2 | 0.1 | 15.2 |

*Based on Lal (1995).

**Based on data from: Araujo et al. (2001), D'Andrea et al. (2004), Sampaio et al. (1990), Van Wambeke (2003), Chotte et al. (1998), Mubarak et al. (2001), Neff et al. (2000), O'Connel and Rance (1999), San Jose et al. (2003), Wong et al. (1987), Phiri et al. (2001), Solomon et al. (2002), and Warren and Kihanda (2001).

The ISRIC-WISE Global soil profile dataset (ISRIC, 2003) was also used to calculate the C:N ratio. Data from Angola, Australia, Burundi, Benin, Brazil, Central African Republic, Congo, Cote D'Ivoire, Cameroon, Colombia, Costa Rica, Cuba, Ecuador, Gabon, Ghana, Guatemala, Guyana, Honduras, Jamaica, Kenya, Malawi, Mexico, Malaysia, Mozambique, Nicaragua, Panama, Philippines, Sudan, Sierra Leone, Suriname, El Salvador, Togo, Thailand, and Venezuela were used. The dataset used in this analysis comprises 3576 samples from 888 soil profiles with 1 to 9 horizons. The results are shown in Table 3.2.

**Table 3.2.** Mean, standard deviation, number of samples, and confidence value of C:N ratio for the first 6 soil layers of 888 profiles of tropical soils (ISRIC, 2003).

| Statistics | Horizons | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **All** |
| Mean | 14.14 | 13.25 | 12.58 | 11.80 | 11.95 | 11.57 | 12.95 |
| Stand. Dev. | 7.54 | 8.55 | 9.83 | 10.79 | 9.26 | 9.07 | 9.07 |
| Number of samples | 888 | 857 | 727 | 494 | 367 | 186 | 3576 |
| Confidence* | 0.50 | 0.57 | 0.71 | 0.95 | 0.95 | 1.30 | 0.30 |

*Statistic used to calculate the confidence interval, which is the mean value + or – the confidence value.

Mean values varied from 14.14 for the first soil horizon to 11.57 for the 6th soil horizon. The overall mean for this dataset was 12.95 ± 0.30, which encompasses the mean value (13.26) of the data shown in table 4.1. Based on these data, a C:N ratio of 13.0 was selected as being representative of tropical soils and is the value used in TROPGLEAMS.

## Potentially Mineralizable Nitrogen

Stanford and Smith (1978) used data of 62 soils from 8 soil orders (Alfisols, Aridisols, Entisols, Inceptisols, Mollisols, Spodosols, Ultisols, and Vertisols), all from sites located in the USA, and observed an average ratio of $N_0$/total nitrogen of 0.165 ± 0.068. This relationship was used for calculating the default value of potentially mineralizable N in GLEAMS.

The average ratio of $N_0$/total nitrogen for tropical soils was calculated in this study by using 27 data values from soils in Venezuela (San Jose et al., 2003), Colombia, Brazil, Costa Rica, Peru (Motavalli et al., 1995), and Australia (Campbell et al., 1981). The dataset included data from an Ultisol from Venezuela with four different land uses (woodland savanna fallow, pasture, cowpea, and native savanna), two Vertisols and one Andisol from Colombia, one Vertisol and two Andisols from Costa Rica, one Mollisol and four Oxisols from Brazil, and five non-classified soils from Australia. All data were from samples collected to a depth of 30 cm.

Table 3.3 shows the mean, standard deviation, minimum, and maximum values of the ratio $N_0$/total nitrogen. The high variation of this dataset, evidenced by the high values of range and standard deviation (0.24 and 0.06, respectively), was also observed in the data of Stanford and Smith (1978). The confidence interval of the mean was calculated as 0.14±0.022 ($\alpha$=0.05). This interval is very close to the mean value of Stanford and Smith (1978), whose analysis included Ultisols, Inceptisols, and Alfisols, which together comprise 46.5% of tropical soils. Consequently, the original value of the N0/total nitrogen ratio used in GLEAMS was considered appropriate for tropical soils and was not changed.

**Table 3.3**. Mean, standard deviation, minimum, and maximum values of No/total nitrogen ratio of tropical soils (n = 27)*.

| Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|
| 0.14 | 0.059 | 0.062 | 0.303 |

*Data from San Jose et al. (2003), Motavalli et al. (1995), and Campbell et al. (1981).

## Nitrate and Ammonium

Nine studies with measurements of nitrate and five with measurements of ammonium in different depths and locations were used to calculate the value that best represents the initial concentration of nitrate and ammonium in the tropics. The nine studies for nitrate were D'Andrea et al. (2004) with a Brazilian savanna Oxisol under native savanna, Phiri et al. (2001) with a Colombian Inceptisol, Deare et al. (1995) with a Ultisol of Trinidad, Mekonnen et al. (1997) with a very fine kaolinitic Oxisol with anion sorption located in the highlands of western Kenya, Arora and Juo (1982) with a strongly acidic kaolinitic Ultisol in Nigeria, Shepherd et al. (2001) with three Oxisols and 3 Alfisols planted with corn in 96 smallholder farms in the highlands of western Kenya, Wild (1972) with an Alfisol under bare fallow in northern Nigeria, Hartemink et al. (1996) with an Oxisol and an Alfisol in the subhumid highlands of Kenya, and Strong et al. (1998) with a red earth of New South Wales, Australia. The five studies with ammonium data were D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Arora and Juo (1982), and Strong et al. (1998).

Values of $NO_3$-N and $NH_4^+$-N were separated for each soil order and the mean value for each soil order was calculated. The overall mean was estimated based on the area covered by each soil order in the tropics. Table 3.4 shows the mean concentration of $NO_3$-N and the total area of tropical soils by soil order. The area-weighted mean based on soil distribution in the tropics was 10.34 μg $NO_3$-N/g soil. In order to evaluate variation of $NO_3$-N concentration in the soil profile, the dataset was grouped according to the depth of samples. Mean, standard deviation, minimum, and maximum value for each layer were calculated (Table 3.5).

**Table 3.4.** Area and mean $NO_3$-N concentration for some soil orders in the tropics*.

| Soil | Total area in the tropics | | Mean conc. |
|---|---|---|---|
| | ($10^6$ ha) | (%) | (μg $NO_3$-N/g soil) |
| Oxisols | 525 | 35.3 | 12.5 |
| Ultisols | 413 | 27.7 | 8.6 |
| Inceptisols | 226 | 15.2 | 7.7 |
| Alfisols | 53 | 3.6 | 14.1 |

*Data from D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Mekonnen et al. (1997), Arora and Juo (1982), Shepherd (2001), Wild (1972), Hartemink et al. (1996), and Strong et al. (1998).

**Table 3.5.** Number of samples, mean, standard deviation, minimum, and maximum values of $NO_3$-N concentration in tropical soils.*

| Depth | Number of samples | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| (cm) | | ———————————μg $NO_3$-N/g soil-------------------- | | | |
| 0-15 | 88 | 12.81 | 11.29 | 0.00 | 50.00 |
| 15-30 | 77 | 11.44 | 9.43 | 0.00 | 56.67 |
| 30-50 | 77 | 11.18 | 11.08 | 0.45 | 66.67 |
| 50-100 | 143 | 12.08 | 11.07 | 0.46 | 78.33 |
| 100-150 | 53 | 9.02 | 9.97 | 0.83 | 63.33 |
| 150-200 | 19 | 5.41 | 7.14 | 1.25 | 33.33 |

*Data from D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Mekonnen et al. (1997), Arora and Juo (1982), Shepherd (2001), Wild (1972), Hartemink et al. (1996), and Strong et al. (1998).

The large range of values and standard deviation in Table 3.5 show that there is high variation in the $NO_3$-N concentration in every soil layer. This variation was expected because the dataset came from multiple studies involving different soil types, land use, fertilization rates, and lengths of time from fertilization. Despite the variation, the dataset does show a tendency toward lower concentrations of nitrate in deeper layers, which can be explained by the distribution of organic matter in the soil profile, the adsorption of nitrate to the positively charged tropical soils, gaseous losses, and plant uptake.

The overall mean $NO_3$-N concentration for the entire dataset shown in Table 3.5 is $11.33 \pm 1.07$ ($\alpha=0.05$), with an area-weighted mean of 10.34 μg $NO_3$-N/g soil. Based on this data, the value of 10 μg $NO_3$-N/ g soil was adopted as the default value for $NO_3$-N for all layers of tropical soils.

An area-weighted overall mean was also calculated for $NH_4^+$-N. Table 3.6 shows the total area and mean concentration of $NH_4^+$-N for the soil orders used in the studies.

**Table 3.6.** Area and mean $NH_4^+$-N concentration for some soil orders in the tropics*.

| Soil | Total area in the tropics | | Mean concentration |
|---|---|---|---|
| | $10^6$ ha | % | μg $NH_4^+$-N /g soil |
| Oxisols | 525 | 35.30 | 18.8 |
| Ultisols | 413 | 27.70 | 19.1 |
| Inceptisols | 226 | 15.20 | 19.2 |

*Data from D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Arora and Juo (1982), and Strong et al. (1998).

The overall mean based on soil distribution in the tropics was 19.0 μg $NH_4^+$-N/g soil. In order to evaluate the variation of $NH_4^+$-N concentration in the soil profile, the dataset was grouped according to the depth from which the samples were taken. Mean, standard deviation, minimum, and maximum values for each layer were calculated; the results are shown in Table 3.7.

**Table 3.7.** Number of samples, mean, standard deviation, minimum, and maximum values of $NH_4^+$-N concentration in tropical soils*.

| Depth | Count | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| (cm) | | ( μg $NH_4^+$-N /g soil ) | | | |
| 1-10 | 60 | 25.81 | 30.54 | 0.00 | 156.00 |
| 10-20 | 12 | 18.39 | 9.42 | 8.93 | 42.86 |
| 20-40 | 42 | 14.55 | 14.63 | 4.00 | 99.00 |
| 40-80 | 24 | 9.62 | 6.44 | 3.00 | 33.93 |
| 80-100 | 6 | 17.26 | 2.63 | 15.18 | 21.43 |

*Data from D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Arora and Juo (1982), and Strong et al. (1998).

Although high variation in the dataset was observed in every soil layer, values significantly higher than 2 μg $NH_4^+$-N /g soil, the value adopted as default in the original GLEAMS, were observed in every layer of the soils used in this analysis. The mean values varied from 25.81 μg $NH_4^+$-N /g soil in the 1-10 cm layer to 9.62 μg $NH_4^+$-N /g soil in the 40-80 cm layer depth. Silva and Vale (2000) also found higher values of $NH_4^+$-N than are typical for temperate conditions. They observed values of ammonium concentration ranging from 10 to 23 μg $NH_4^+$-N /g soil in the superficial layer of five soils from the southeastern region of Brazil.

One of the main reasons for the higher concentration of ammonium in tropical soils is the inhibition of nitrification in acidic soils. Sierra et al. (2003) considered the nitrification rate to be a result of factors related to soil moisture, pH, and temperature. They quantified the pH factor as ranging from 0 at $pH_{KCl} = 3.0$ to a maximum value of one at $pH_{KCl} = 6.5$, with linear interpolation between them. Silva et al. (1994) suggested that soil pH is the main factor limiting nitrification, noting that nitrification rates decrease sharply at a pH lower than 6.0 and are very low in soils with pH lower than 5.0. In addition to reducing the nitrification rate, low pH also favors the formation of the cation ammonium in its equilibrium reaction with ammonium. Because low pH is a characteristic of tropical soils and was also observed in the samples used in this analysis, a build up of $NH_4^+$-N may be expected in those soils, accounting for the higher values of $NH_4^+$-N in tropical soils than in temperate ones.

The overall mean $NH_4^+$-N concentration for the entire dataset was $18.9 \pm 3.67$ ($\alpha$=0.05). The value of 19 μg $NO_3$-N/ g soil was adopted as the default value for $NH_4^+$-N for all layers of tropical soils.

## Phosphorus

The equations originally used in GLEAMS for calculating initial values of phosphorus were based on Sharpley et al. (1984). They were derived from regression analysis of data from 78 soils from the continental U.S. and Puerto Rico, 23 of them considered highly weathered (Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and acidic Ochrepts).

Sharpley et al. (1989) used data from 32 highly weathered soils (5 Alfisols, 2 Inceptisols, 3 Oxisols, 3 Spodosols, and 19 Ultisols), all with aluminum (Al) saturation greater than 30, to derive other equations with the same forms as those from Sharpley et al. (1984). For soil sorption, Sharpley et al. (1989) suggested the following equation:

$$PSP = 0.7 - 0.19 \log (CLAYPCT) \quad (3.4)$$

where CLAYPCT is soil clay content. Equations derived by Sharpley et al. (1989) for calculating initial values of organic phosphorus were as follows:

$$SORGP = 1109\ TN + 42.2 \quad (3.5)$$

$$SORGP = 62.1\ OC + 63.4 \quad (3.6)$$

where SORGP is organic phosphorus in mg/kg, OC is organic carbon (%), and TN is total nitrogen in g/kg.

Three datasets were used for the development of five equations for calculating SORGP based on organic carbon (OC) and total nitrogen (TN). The first dataset is comprised of 15 soils from sites in northeastern Brazil and Ghana (Condron et al., 1990), the second is comprised of 13 soils from Brazil (Guerra et al., 1996), and the third, of 16 soils from northern Nigeria (Ipinmidun, 1973). The five new models were derived by linear regression and are shown in table 3.8.

**Table 3.8.** Models to calculate SORGP derived from the datasets of Condron et al. (1990), Guerra et al. (1996) and Ipinmidun (1973).

| Model | Dataset | $R^2$ | Equation |
|---|---|---|---|
| SORGP = 2.5405 OC + 8.7765 | Ipinmidun (1973) | 0.61 | (3.7) |
| SORGP = 6.9038 OC – 14.305 | Condron et al. (1990) | 0.52 | (3.8) |
| SORGP = 0.0777 TN + 5.9978 | Condron et al. (1990) | 0.35 | (3.9) |
| SORGP = 3.0256 OC + 23.75 | Guerra et al. (1996) | 0.28 | (3.10) |
| SORGP = 0.0428 TN + 2.5543 | Guerra et al. (1996) | 0.51 | (3.11) |

Equations 3.1, 3.5, 3.6, and the five new ones (equations 3.7 to 3.11) were tested using the datasets of Condron et al. (1990), Guerra et al. (1996), and Ipinmidun (1973), which have measured data of SORGP, TN, and OC. SORGP values were calculated and the mean square error (MSE) between measured and calculated values for each equation was calculated.

$$MSE = \frac{\sum_{i=1}^{n} (ri)^2}{n} \quad (3.12)$$

where $r_i$ is the difference between measured and simulated values and *n* is the number of observations. The result is shown in table 3.9.

**Table 3.9.** Goodness-of-fit of eight models predicting soil organic P (SORG) using values of total nitrogen and total carbon applied to three datasets, measured through their mean square error (MSE).

| Model* | Ref. | Dataset | | |
|---|---|---|---|---|
| | | Condron et al. (1990) | Guerra et al. (1996) | Ipinmidun (1973) |
| | | --------------------MSE-------------------- | | |
| SORGP = 44.4 + 1130 TN | Eqn. 3.1 | 7,529 | 24,874 | |
| SORGP = 1109 TN + 42.2 | Eqn. 3.5 | 1,183,820 | 3,234,676 | |
| SORGP = 62.1 OC + 63.4 | Eqn. 3.6 | 774,854 | 972,396 | 144,172 |
| SORGP = 2.5405 OC + 8.7765 | Eqn. 3.7 | 3,612 | 1,358 | 37 |
| SORGP = 6.9038 OC – 14.305 | Eqn. 3.8 | 1,681 | 1,974 | 210 |
| SORGP = 0.0777 TN + 5.9978 | Eqn. 3.9 | 2,270 | 2,427 | |
| SORGP = 3.0256 OC + 23.75 | Eqn.3.10 | 2,427 | 857 | 337 |
| SORGP = 0.0428 TN + 2.5543 | Eqn. 3.11 | 3,777 | 581 | |

* SORG is soil organic P (mgP/kg soil), TN is total nitrogen (gN/kg soil), and OC is organic carbon (gC/kg soil)

The last five models (equations 3.7 to 3.11) showed better goodness-of-fit than the models derived by Sharpley et al. (1984) (equation 3.1) and Sharpley et al. (1989) (equations 3.5 and 3.6). The equations using OC as an independent variable (equations 3.5, 3.7, 3.8, and 3.10), overall, showed smaller MSE than the equations using TN. When the user does not input the value of TN in GLEAMS, the model automatically calculates its value using the value of OC. In this case, the calculation of SORGP using TN could be subject to two approximations. Bearing these conditions in mind, Equations 3.8 and 3.10

were considered the most appropriate for calculating organic phosphorus in highly weathered tropical soils; the model derived from the dataset of Condron et al. (1990) (Equation 3.8) was chosen for use in TROPGLEAMS.

Labile P (CLAB) is estimated in GLEAMS as 10% of SORGP for calcareous soils, 8.7% of SORGP for slightly weathered soils, and 5.6% of SORGP for highly weathered soils. Most studies that reported different pools of phosphorus in tropical soils considered residual P as one pool, in which organic and inorganic recalcitrant P were measured together (e.g. Tokura et al., 2002; Silva et al., 2003), making it impossible to calculate total organic P. The studies of Guerra et al. (1996), Oberson et al. (2001), and Cardoso et al. (2003) show values of P that enable the calculation of the relationships between labile P and total organic P. Their data were used to assess if the relationship between CLAB and SORGP used in the original GLEAMS is appropriate for tropical soils. The studies comprise 29 values from different soils and land uses, most from Brazil. Using this dataset, the percentage of CLAB in relation to total organic P was calculated. The average and the median values for these datasets were 5.25 and 3.47, respectively. Based on these data, the relationship between both P pools used in GLEAMS for highly weathered soils (CLAB = 5.6% SORGP) was considered appropriate for use in TROPGLEAMS.

The phosphorus sorption coefficient, or P availability index (PSP), is used in the INITNT subroutine to calculate active mineral P (PMINP) using values of labile P. The equation derived by Sharpley et al. (1989) (equation 3.4) was the only one found that was derived using tropical soils. It was assessed observing the resulting value of PSP using several values of soil clay content. With clay values equal to or greater than 40%, the equation resulted in negative values of PSP. Because clay content greater than 40% is very common in tropical soils, the model of Sharpley et al. (1989) was not considered appropriate for being used in TROPGLEAMS.

The appropriateness of using equation 3.3 to calculate P availability index of tropical soils was assessed using the datasets from the studies of Goncalves et al. (1989), Lopez et al. (2001), and Cardoso et al. (2003). The first two studies were composed of 18 soil samples and were used to define the real values of PSP. Different amounts of fertilizer P were added to soil samples, which were incubated over 180 days. The following equation was used:

$$PSP = (P_{lf} - P_{li})/P_f \quad (3.13)$$

where $P_{lf}$ is mg/kg labile P after 180 days of incubation, $P_{li}$ is mg/kg labile P in the control (when no P is added to the soil sample), and $P_f$ is mg/kg labile P added as fertilizer. The mean value of PSP for the two datasets was 0.14, with standard deviation of 0.07. The appropriateness of using the mean value of PSP in the place of values calculated using equation 3.3 was evaluated using the dataset of Cardoso et al. (2003), which contains measured values of CLAB and PMINP. For this evaluation, values of PMINP were calculated as:

$$PMINP = PLAB / (PSP / (1 - PSP)) \quad (3.14)$$

PMIMP was calculated both by using the PSP value from equation 3.3 and by using the mean value of 0.14. The mean square error (MSE) between measured and calculated values of PMINP was calculated. MSE was 1046 when PMIMP was calculated using PSP = 0.14 and 1566 when PSP was calculated by using equation 3.3. These results showed that the use of 0.14 as the value of PSP for highly weathered tropical soils is more appropriate than using values calculated by equation 3.3. The value of PSP was set as 0.14 in TROPGLEAMS.

Cardoso et al. (2003) presented values of active mineral P (PMINP) as P extracted with 0.1 M NaOH and values of stable P (SOILP) as the sum of P extracted with 1 M HCl and with a concentrated solution of HCl. The mean value of the ratio between these two P pools (SOILP/PMINP) for this database was 5.9, with standard deviation of 7.24. The size of this dataset (limited to one soil with three land uses in three depths) was not considered appropriate to represent the variability of the tropical soils. Since this was the only study presenting these two values in tropical soils that was found, the relationship between PMINP and SOILP of the original GLEAMS was not modified.

## 3.2.2. NUTRIENT TRANSFORMATIONS

## Carbon, nitrogen, and phosphorus mineralization

In the original GLEAMS, the calculations of the decay rates of residue and animal waste, as well as the mineralization of N and P from these organic materials are determined from:

DCR = CNP * CKOR * ((SWF4 * TK4) **0.5) (3.15)

where DCR is the daily decay rate of vegetal residue or animal waste (or the quantity of mineral N or P formed daily), CNP is the limitation imposed by C:N and C:P ratios, SWF4 and TK4 are soil moisture and temperature factors, and CKOR is the basic decay rate that is set as 0.8, 0.05, and 0.0095 depending on the rate between current and initial values of residue.

The mineralization of soil organic P and soil organic N is calculated as:

CMIN = 0.0001 * POTMN * ((SWF4 * TK4) **0.5) (3.16a)

CMINP = 0.0001 * POTMP * ((SWF4 * TK4) **0.5) (3.16b)

where CMIN and CMINP are, respectively, the quantity of N and P mineralized from soil organic matter during one day, POTMN and POTMP are potentially mineralizable N and P, and SWF4 and TK4 are soil moisture and soil temperature factors, respectively.

As discussed in section 2.4.1, the decay of organic matter in long-term studies is better explained by the two compartment model, in which the organic material is divided in two pools (labile and recalcitrant), which degrade following first order kinetics with different rates of degradation ($k_1$ for the labile and $k_2$ for the recalcitrant organic matter). The two compartment model was incorporated in TROPGLEAMS to simulate the degradation of vegetal residue, animal waste, and soil organic matter. For each material, basic rates of decomposition $k_1$ and $k_2$ were defined based on previous studies. The basic rates are modified in TROPGLEAMS by factors reflecting the effects of temperature, soil water content, C:N and C:P ratios, and the occurrence of the Birch effect.

For the definition of the basic rates and the proportion of the labile and recalcitrant pools of vegetal residue, the studies of Aita and Giacomini (2003) and Sampaio et al. (1990) were used. They include long-term decomposition of corn, oat, common vetch, and oilseed radish residues under tropical conditions. Mean temperature in these studies varied from 24 to 40°C. The rates of decomposition at the mean temperature of the experiments were transformed to the rates of decomposition at 50°C using equation 3.17. The mean value of decomposition rates of the labile and recalcitrant pools at 50°C ($k_1$ and $k_2$) were, respectively, 0.317 and 0.01. The mean proportions of the labile and recalcitrant pools were 42 and 58% of the total carbon, nitrogen, and phosphorus in decomposition.

The definitions of $k_1$ and $k_2$ and the proportions of the labile and recalcitrant pools for animal waste were based on the study by Sierra et al. (2001), which included a long-term decomposition of sewage sludge in Guadeloupe. The decomposition rates of the labile and recalcitrant pools were 0.717 and 0.011, respectively, at 50°C and the proportion of the labile and recalcitrant pools were 13 and 87% of the total organic carbon, nitrogen, and phosphorus in decomposition.

The studies of Sierra and Marban (2000) and Motavalli et al. (1995) were used to define the proportions of labile and recalcitrant soil organic matter. They include incubation of soils from Brazil, Costa Rica, Peru, Colombia, and Guadeloupe during 57 or 342 days at different temperatures. The mean proportions of the labile and recalcitrant pools were 20% and 80% of the potentially mineralizable nitrogen and P. The rates of decomposition of SOM were set as 10% the rates of degradation of vegetal residue, as suggested by Jenkinson and Ayanaba (1997). The rates of degradation were set as 0.03 and 0.001 for the labile and recalcitrant SOM, which are values very close to those derived by Sierra and Marban (2000) for an Oxisol from Guadeloupe.

The effect of temperature on the rates of degradation was represented in the temperature factor (Ftemp), which was based on the studies of Myers (1975) and Campbell et al. (1981). Myers (1975) showed that maximum rate of SOM degradation occurred at 50°C in an Australian soil, with a decrease in rate above this temperature. Campbell et al. (1981) derived equations based on laboratory incubation of five Australian soils in constant temperature from 5 to 40°C. A sharp increase of $k_1$ was observed with increasing temperature. Equations 3.17 to 3.19 were derived based on the result of Campbell et al. (1981) and show the relationship between temperature and degradation rate. The maximum rate of decomposition was set as 50°C, according to Myers (1975):

$$Ftemp = 10^{7.07} \Big/ 10^{2285/(t+273)} \qquad \text{(if t > 5°C)} \qquad (3.17)$$

$$Ftemp = t*0.0144 \qquad \text{(if } 0^{o}C < t \leq 5^{o}C) \qquad (3.18)$$

$$Ftemp = 0 \qquad \text{(if } t \leq 0^{o}C) \qquad (3.19)$$

where t is temperature in degrees centigrade. This temperature factor was incorporated in TROPGLEAMS to calculate the effect of temperature on the degradation rates of the soil organic matter, vegetal residue, and animal waste.

The calculation of the factor related to the influence of water content on mineralization (SWF) had a small change. The original GLEAMS sets the value of SWF to zero for days when some percolation occurs. This value was modified to 1 in TROPGLEAMS. This change was made because most tropical soils are highly porous and maintain good conditions for mineralization even on days when there is excess water.

The effect of C:N and C:P ratios on the mineralization of vegetal residue is the same in TROPGLEAMS as in GLEAMS.

According to Birch (1959) a flux of soil organic decomposition after rewetting a dry soil needs a certain degree of drying, which is approximated to the air-dry state. he also observed that for a soil with 7% organic carbon, the magnitude of decomposition and nitrogen mineralization that occurs upon moistening soil after drying it for different lengths of time is a direct function of the time the soil was dried. Birch (1959) observed that the rate of N mineralization in the first week was about three times the rate of the second week after a dry period. Murphy et al. (1998) studied microbial respiration (measured as $CO_2$ production) after multiple rewettings of a dry soil and found that in the first week the microbial respiration is around 2.7 times the rate in the second week (mean of two soils used). However, the gross N mineralization during the second week was basically the same as during the first week.. The equations derived by Myers (1975) resulted in daily ammonification during the first week after rewetting a dry soil around 100 times the value of the daily ammonification during the second week using incubation temperature of $20^{o}$C and around 3 times higher than the second rate using temperatures of $50\,^{o}$C.

In order to account for the Birch effect, the basic rate of mineralization of organic material in TROPGLEAMS is multiplied by a factor of three during the first week after a dry period. A dry period for each soil layer is considered as three weeks in which its soil water content is less than or equal to the wilting point.

The calculation of $k_1$ and $k_2$ for vegetal residue and animal waste is made in TROPGLEAMS using equations 3.20 and 3.21. Similar equations are used for calculating $k_1$ and $k_2$ for soil organic matter, but with no use of the CNP factor.

$$k_1 = Birch * Bk_1 * TK_4 * SWF_4 * CNP \tag{3.20}$$

$$k_2 = Birch * Bk_2 * TK_4 * SWF_4 * CNP \tag{3.21}$$

where Birch is a multiplication factor equal to 1 or 3 depending on conditions as described above, $Bk_1$ is the basic value of $k_1$ (0.717, 0.317, and 0.03 for animal waste, vegetal residue, and soil organic matter, respectively), $Bk_2$ is the basic value of $k_2$ (0.011, 0.01, and 0.001 for animal waste, vegetal residue, and soil organic matter, respectively), TK4 is the temperature factor, SWF4 is the soil water factor, and CNP is the factor for the ratios C:N and C:P.

The degradation of organic carbon, nitrogen, and phosphorus from vegetal residue, animal waste, and soil water matter, respectively, is calculated using the following equations:

$$Cres = Cores*0.42(1-e^{k1}) + Cores*0.68(1-e^{k2}) \tag{3.22}$$

$$Canwst = Coanwst*0.13(1- e^{k1}) + Co*0.87(1- e^{k2}) \tag{3.23}$$

$$Cmin = POTMNP*0.20(1- e^{k1}) + POTMNP*0.80(1- e^{k2}) \tag{3.24}$$

where Cres, Canwst, and Cmin are the quantity of nutrients mineralized during one day from vegetal residue, animal waste, and soil organic matter, respectively, Cores and Coanwst are the quantity of C, N, or P on vegetal residue and animal waste, respectively, and POTMNP is potentially mineralizable N or P in SOM.

## Nitrification

In the original GLEAMS, nitrification rate is calculated based on factors for soil water and temperature, with a maximum limit calculated as:

Cknit = 0.01429 * SOILMS (3.25)

where Cknit is the maximum daily rate of nitrification and SOILMS is the soil mass of each layer.

The model for nitrification used in TROPGLEAMS was based on Sierra et al. (2003), where the rate of nitrification is recognized to be affected by soil pH and a microbial temperature response, in addition to constraints due to soil water content. Following Sierra et al. (2003), the nitrification rate is calculated in TROPGLEAMS as:

Cknit = SWF * FTEMP * FpH (3.26)

where FTEMP, SWF, and FpH are non-dimensional coefficients representing the effect of temperature, water content, and pH KCl, with 0≤( SWF and FTEMP) ≤1 and $0 \leq FpH \leq FpH_{max}$. $FpH_{max}$ represents the maximum value for FpH as well as for Cknit. SWF is calculated as it is for mineralization. FpH was derived from the results from several Oxisols of Guadeloupe. It was considered zero for pH KCl≤3.0, with a maximum value at pH KCl≥6.5, and a linear interpolation between these two values. Sierra et al. (2003) reported a maximum value for FpH of 0.5, which was also used in TROPGLEAMS.

The temperature factor is based on the studies of Myers (1975), Sierra and Marban (2000), and Sierra et al. (2003). The pattern of the temperature factor of these three studies is shown in figure 3.1. Maximum nitrification is observed at 35$^{o}$C in the model of Myers (1975) and at 45$^{o}$C in the model of Sierra et al. (2003), with a sharp decrease in nitrification at temperatures above the oprimum. In the model of Sierra and Marban (2000), no limit on nitrification is defined at high temperatures. Sierra et al. (2003) set zero nitrification for temperatures lower than 17$^{o}$C, while in the other studies, no lower limit is specified. No nitrification is observed in Sierra et al. (2003) after 50$^{o}$C, while Myers (1975) observed nitrification even at 60$^{o}$C.

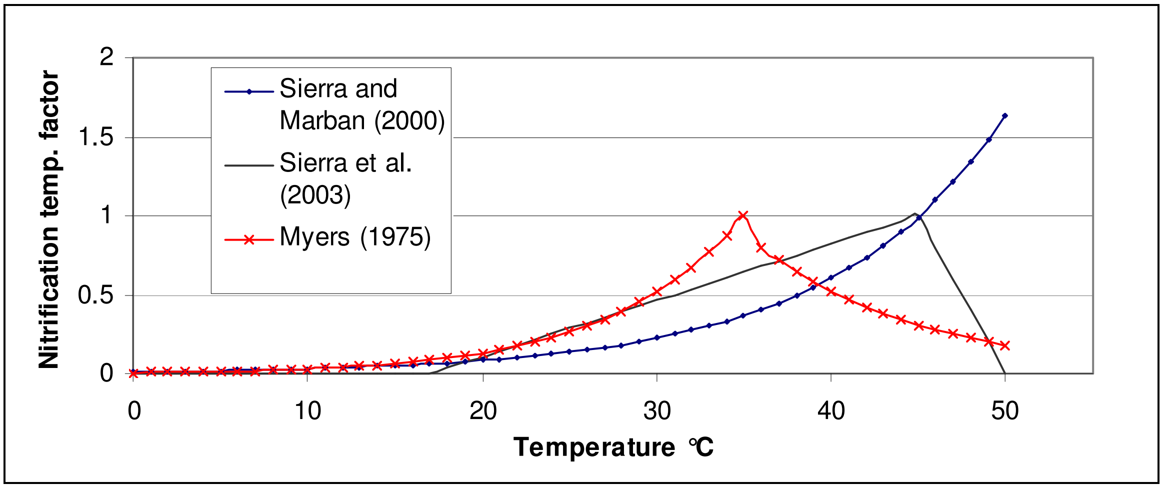


**Figure 3.1.** Pattern of the temperature factor of nitrification based on Myers (1975), Sierra and Marban (2000), and Sierra et al. (2003).

In TROPGLEAMS, the temperature factor for nitrification is a combination of the models from the three studies cited above. The factor is given a value of one at 40°C and zero at 0°C and 60°C, with linear interpolation between 40°C and 60°C and a Q10 function between 0°C and 40°C. The Q10 value is 2.7, the value found in the study by Sierra and Marban (2000). Equations 3.27 to 3.30 were used to calculate FTEMP.

FTEMP = 0 (if temp = 0°C or 60°C) (3.27)

FTEMP = 1 (if temp = 40°C) (3.28)

FTEMP = 0.018817 * (2.7 ** (temp(k)/10.0)) (if 0°C< t<40°C) (3.29)

FTEMP = (60 - temp(k))/20.0 (if 40 °C < temp<60°C) (3.30)

## Nitrogen and phosphorus immobilization

The subroutine IMMOBL, responsible for the immobilization of N and P, was changed to better predict the mineralization of residue. The quantity of nitrogen and phosphorus immobilized in one day depends on the quantity of fresh organic matter mineralized on that day. The calculation of mineralization was modified according to the equations 3.15 through 3.21 described in the section on nitrogen mineralization. When immobilized N is more than 95% of $NO_3$-N and $NH_4^+$-N in a soil layer or immobilized P is greater than 95% of labile P in a soil layer, the original GLEAMS recalculates the rate of residue degradation. In TROPGLEAMS, the same rate of degradation continues to be used, except when there is no N or P in soil layers. In this case, mineralization is set to zero.

## Mineral Phosphorus transformations

The Phosphorus sorption coefficient (or P availability index (PSP)) is used in GLEAMS and TROPGLEAMS to calculate the transformations between labile P and active mineral P and between active mineral P and stable mineral P. Soil sorption of weathered soils is calculated in GLEAMS by equation 3.3. As described earlier, 0.14 was considered the value of PSP of tropical soils in TROPGLEAMS.

The changes made to GLEAMS related to mineral P transformations were the new value for PSP and the model that simulates the transformations between labile and active mineral P (PMINP). The study by Goncalves et al. (1989) was used to derive an equation to simulate the transformation of labile P to PMINP after the second day of mineral P application:

$$Ct = Co * (K*t/b)^{-b} \qquad (3.31)$$

where Ct is labile P (mg/kg), Co is labile P at day zero (mg/kg), K is the rate of transformation of labile P to PMINP ($day^{-1}$), t is time (day), and b is a non-dimensional constant. The mean values of K and b for the dataset of Goncalves et al. (1989), which was composed of five Brazilian Oxisols, were 83.48 and 0.077, respectively. These values were used in equation 3.31 and included in TROPGLEAMS. According to Novais and Smyth (1999) when a source of soluble P is applied to a tropical soil, frequently more than 90% of the applied P is sorbed in the first hour. Goncalves et al. (1989) showed the transformation of labile to active mineral P on the day of application varying according to the amount of applied P. Based on their data, the following expression was derived to calculate Co as the amount of P that is not sorbed in the day of application:

$$Co = 0.4323 * AP \qquad (3.32)$$

where AP is applied P. This relationship is incorporated in TROPGLEAMS and the difference between the applied P and Co is transferred to the active mineral P pool on the day of P application.

The results of equations 3.31 and 3.32 differ from the results of the model used in the original GLEAMS only in the first days after mineral P application. After some days, the results are very similar, and there is advantage in using the original model, which takes into account an equilibrium between labile and active mineral P (sorption and desorption) whereas the model of Goncalves et al. (1985) calculates only sorption. In addition, the model of Goncalves et al. (1985) was derived for sorption of mineral P and is not appropriate for applied organic P. Bearing this in mind, TROPGLEAMS uses equations 3.31 and 3.32 to simulate the transformation of labile to active mineral P up to 60 days after mineral P application. After 60 days of mineral P application, after application of animal waste and when no fertilizer is added to the field, this transformation is simulated using the equations of the original model.

In the original GLEAMS, the transformation between PLAB and PMINP is the result of their difference multiplied by soil water, temperature, and sorption factors. The temperature factor has values less than 1 for temperatures below 25$^{o}$C, but shows a sharp increase for temperatures above 25$^{o}$C (1.75 and 5.5 at temperatures of 30 and 40$^{o}$C, respectively). Since soil temperatures in the top soil layer of tropical soils reach 40$^{o}$C very frequently, this model may overestimate the rate of transformation between PLAB and PMINP. Further assessment of this relationship is suggested for future study.

If the field is tilled after mineral P application, P is redistributed to all layers reached by the tillage implement. Equation 3.31 is applied in each soil layer with $C_0$ as the P concentration after redistribution. If a soil layer receives labile P through tillage caused by the mixing of labile P from other layers, the number of days after P application is reset for that layer and equation 3.31 is used to transform labile to active mineral P. If the layer had already received mineral P before tillage, the number of days after P application continues to be counted as it was before tillage and the transformation of P continues to be simulated by equation 3.31 or by the equations of the original GLEAMS, depending on the number of days after P application.

## 3.2.3. NITRATE MOVEMENT IN SOIL LAYERS

The subroutine RTNUT, responsible for routing nutrients through the soil profile, and the subroutine UPTAKE, responsible for the uptake of N and P by plants and for the upward movement of N and P caused by soil water evaporation, were changed in TROPGLEAMS to account for $NO_3^-$ retention in variably charged tropical soils. The calculation was based on Sierra et al. (2003). Nitrate transport occurs when its concentration in each soil layer is higher than a critical value, Ncrit ($kg\ NO_3^-$-N $ha^{-1} mm^{-1}$water $cm^{-1}$ soil depth). Ncrit is a retardation factor and represents $NO_3^-$-N adsorbed by the soil positive charges. The amount of nitrate above Ncrit is mixed with the water in the soil layer. The water above field capacity in the layer drains to the next layer with its nitrate. In cases of upward movement of soil water, only nitrate concentration above Ncrit is mixed with water and ascends to the upper layer. TROPGLEAMS prompts the user to enter the value of Ncrit when tropical simulation is chosen.

## 3.2.4. EVAPOTRANSPIRATION

GLEAMS has two options for simulating potential evapotranspiration (PET): the Priestly-Taylor and the Penman-Monteith models. As discussed earlier, a panel of experts organized by FAO in May 1990 adopted the Penman-Monteith model as the recommended procedure for calculating reference evapotranspiration, which resulted in the development of the FAO Penman-Monteith method. One of the reasons that GLEAMS was chosen as the model to be modified for simulating NPS pollution under tropical conditions was the possibility of using the Penman-Monteith model to calculate evapotranspiration.

During the evaluation of the hydrology component of the original GLEAMS under tropical conditions, a significant instability was observed in the values of evapotranspiration using a climatic dataset from Piracicaba, Brazil, including negative values of PET and actual evapotranspiration (ET) on certain dates. Figure 3.2 shows values of ET simulated in a field planted with sugarcane in Piracicaba using the GLEAMS Penman-Monteith model. On the 515$^{th}$ day of simulation, a high value of ET is observed, followed by a negative value on the 517$^{th}$ day. A negative value of ET is also observed on day 868. Between the 623$^{rd}$ and 645$^{th}$ days, very high values of ET are followed by very low values; this pattern occurs again between days 985 and 1027. This instability in the value of ET originates in the subroutine SETONE, which is responsible for the calculation of PET. Daily values of PET are used in other subroutines to calculate daily values of ET. A high value of PET in one day results in a high value of ET, which results in a drastic reduction of the soil water content, thus constraining ET in the following day and causing the observed variation.

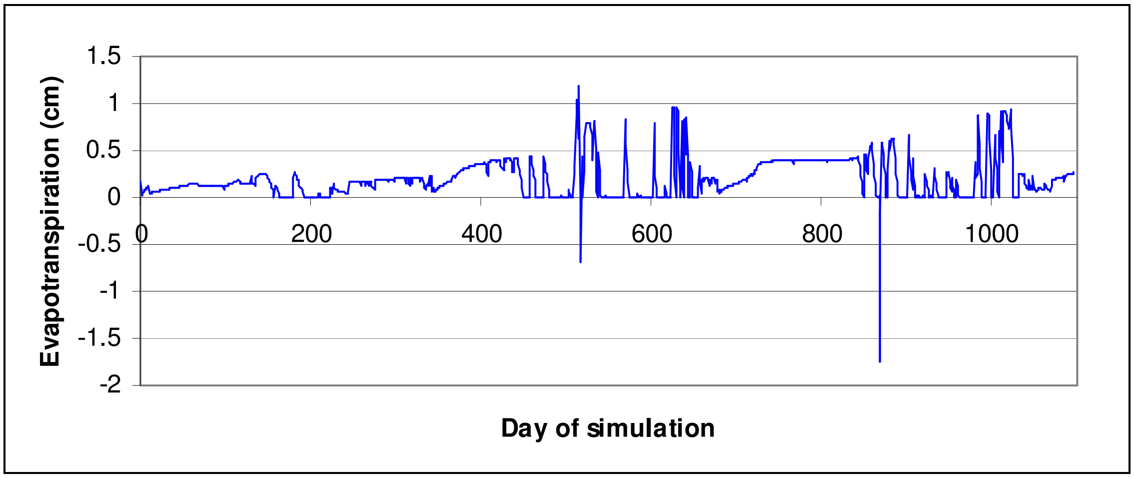


**Figure 3.2.** Result of a 3-year simulation of evapotranspiration in a field planted with sugarcane in Piracicaba, SP, Brazil, using the GLEAMS Penman-Monteith model (Day 1 is Jan. 1).

To further evaluate the PET routines, GLEAMS was also applied to a field located in Rockingham County, Virginia, with a 30-year simulation of a corn-winter wheat rotation. Figures 3.3 and 3.4 show ET for 1500 days as simulated by GLEAMS using the Penman-Monteith and Priestly-Taylor models. During the 30-year simulation, both models predicted similar trends. The Penman-Monteith model predicted higher peaks than did the Priestly-Taylor model, suggesting that the model instability observed in the subroutine SETONE when simulating in tropical conditions also occurs under temperate conditions, though the instability was not as dramatic as was observed in the Piracicaba field. It should be highlighted that no negative values were observed in the climatic conditions of Rockingham County.

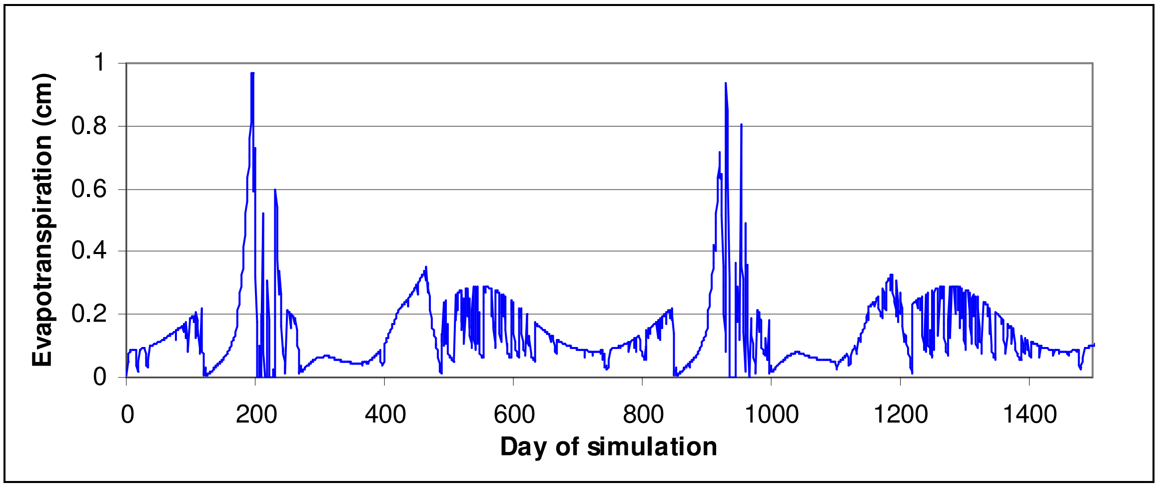


**Figure 3.3.** Evapotranspiration in a field located in Rockingham County, Virginia, planted with a corn-winter wheat rotation, as simulated by GLEAMS using the Penman-Monteith model (Day 1 is Jan. 1).

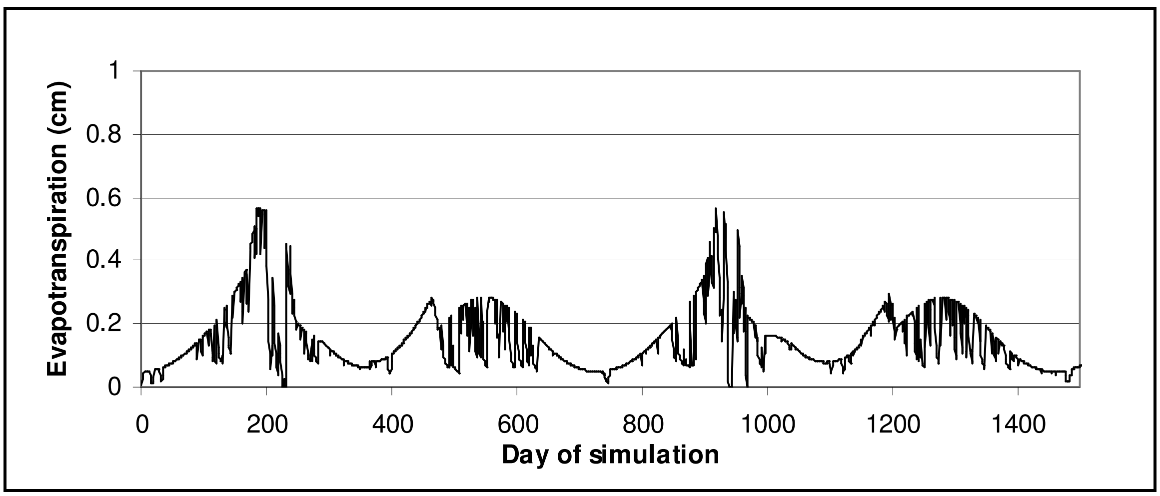


**Figure 3.4.** Evapotranspiration in a field located in Rockingham County, Virginia, planted with a corn-winter wheat rotation, as simulated by GLEAMS using the Priestly-Taylor model (Day 1 is Jan. 1).

In order to fix the instability observed in the calculation of potential evapotranspiration, the subroutine SETONE was modified and the FAO Penman-Monteith method described by Allen et al. (1998) was added as a method to calculate potential evapotranspiration in TROPGLEAMS. Routines used to calculate actual ET were not changed. To assess the performance of the new version, both GLEAMS and TROPGLEAMS were applied to the same climatic dataset of Piracicaba and the results were compared. In addition, both models were applied to the field in Rockingham

County. Evapotranspiration was calculated by the Penman-Monteith and Priestly-Taylor models using the original GLEAMS and by the FAO Penman-Monteith model using TROPGLEAMS and the results are shown in Figure 3.5. Values of ET calculated by the original and modified models show good agreement in some periods, but major differences most of the time. The instability and negative values of PET that resulted from applying the original model to the climatic dataset of Piracicaba is not observed when the new version of the FAO Penman-Monteith model is used.

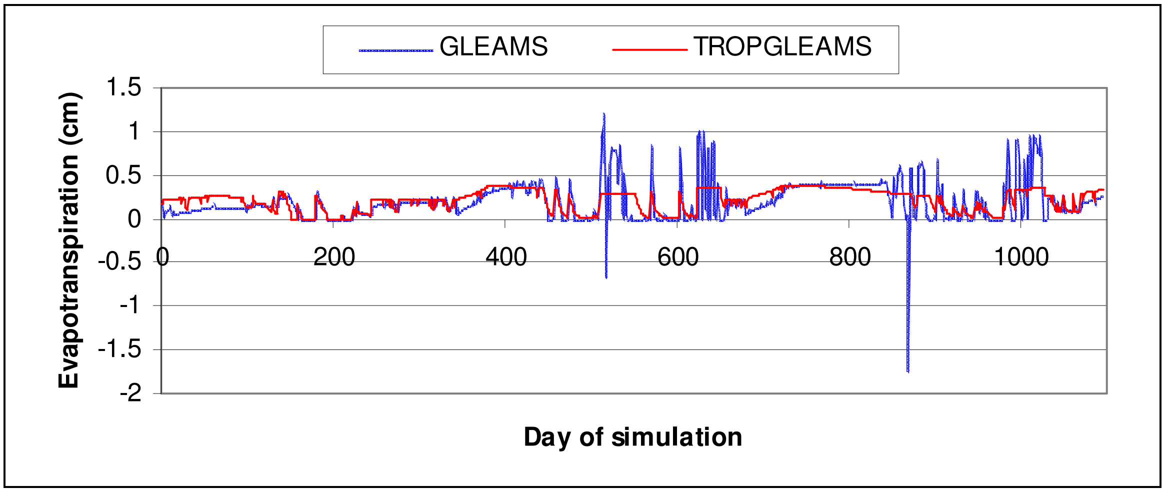


**Figure 3.5.** Result of a 3-year simulation of evapotranspiration in a field planted with sugarcane in Piracicaba, Brazil, using the GLEAMS Penman-Monteith and TROPGLEAMS FAO Penman-Monteith models.

Figure 3.6 shows values of ET calculated by the Penman-Monteith and Priestly-Taylor models using GLEAMS, and by the FAO Penman-Monteith model using TROPGLEAMS under temperate conditions. Over the 30-year simulation of the climatic dataset of Rockingham County, VA, values of evapotranspiration from the three models followed a similar trend in seasonal variation. As can be seen in Figure 3.5, for the first 400 days of simulation, values of actual ET from the Priestly-Taylor model are closer to those using the TROPGLEAMS FAO Penman-Monteith model than to those using the GLEAMS Penman-Monteith. The sum of square residual (SSR) calculated between the original Penman-Monteith and Priestly-Taylor for the 30-year simulation was 15.3, while SSR calculated between the modified Penman-Monteith and Priestly-Taylor models was 2.91. Because the Priestly-Taylor model is considered adequate to calculate evapotranspiration under temperate conditions, the lower value of SSR and the similarities observed in Figure 3.5 indicate that the FAO Penman-Monteith model performed better in the conditions of Rockingham County than the original Penman-Monteith model.

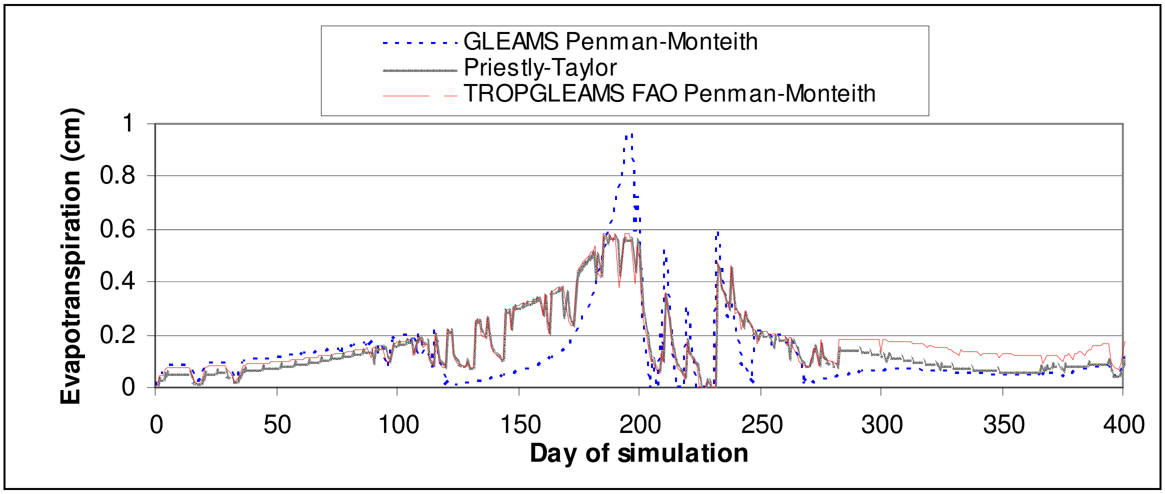


**Figure 3.6.** Evapotranspiration in a field located in Rockingham County, Virginia, planted with a corn-winter wheat rotation,simulated by GLEAMS using Penman-Monteith and Priestly-Taylor models, and by TROPGLEAMS using the FAO Penman-Monteith model.

The better performance of TROPGLEAMS in the temperate and tropical fields suggest that incorporating the FAO Penman-Monteith ET model improved the accuracy for simulating ET under tropical conditions.

# CHAPTER IV
# MODEL EVALUATION

## 4.1. MODEL VERIFICATION

Verifying that the intended changes in the model code were correctly implemented was achieved through a general analysis of the model, analysis of nutrient mass balance, and inspection of the variation of selected output variables over time. For a general analysis, input parameter files were created for a 100 $m^2$ plot planted with sugarcane, using site conditions and climate data for Piracicaba, Sao Paulo, Brazil. The model was run several times for general evaluation to identify any run time errors, unexpected values of output variables and unstable values of model results. Different types, quantity, and timing of fertilizer application were simulated. Output variables were examined using graphical and tabular summaries, facilitating the comparison of results of different output variables in different layers and time. These simulations were used to confirm that the changes made to the model resulted in model predictions that followed expected behavior.

### 4.1.1. MASS BALANCE OF NUTRIENTS

The mass balance of both nutrients is created automatically by GLEAMS and TROPGLEAMS when nutrients are simulated. The result is sent to the nutrient output file for observation and analysis. To calculate the mass balance of N, GLEAMS and TROPGLEAMS sum the concentration of all pools of N in the beginning of each year with total input of N and compare the result with the sum of the concentration of all pools of N in the end of each year with total losses of N. The same procedure is used to calculate the mass balance of P. A zero mass balance of nutrients is expected for every year of simulation, meaning that initial mass plus total input has to be equal to final mass plus losses.

A mass balance of nitrogen and phosphorus for GLEAMS and TROPGLEAMS was assessed through a three year simulation of a field planted with sugarcane in Piracicaba. . The models were run three times, each time with a different fertilization scenario. The field characteristics are described in section 4.2.2 and the three schemes of fertilization (quantity of N and P applied and day of application) are shown in tables 4.1, 4.2, and 4.3.

**Table 4.1.** Fertilization scenario one (mineral fertilization) used for evaluating the mass balance of nutrients over a three year simulation in a field planted with sugarcane in Piracicaba, Brazil.

| Day* | $NH_4^+$-N | $NO_3^-$-N | $P_2O_5$ |
|---|---|---|---|
| | ------------------------Kg/ha | ----------------------- | |
| 1342 | 30 | 0 | 180 |
| 2036 | 40 | 0 | 0 |
| 2333 | 30 | 0 | 120 |

*Day 1342 means the 342$^{th}$ day of year 1, day 2036 is the 36$^{th}$ day of year 2.

**Table 4.2.** Fertilization scenario two (sewage sludge) used for evaluating the mass balance of nutrients over a three year simulation in a field planted with sugarcane in Piracicaba, Brazil.

| Day | Sewage sludge |
|---|---|
| | Tons/ha |
| 1271 | 33 |
| 2308 | 37 |

**Table 4.3.** Fertilization scenario three (sewage sludge and mineral fertilization) used for evaluating the mass balance of nutrients over a three year simulation in a field planted with sugarcane in Piracicaba, Brazil.

| Day | Sewage sludge | $NH_4^+$-N | $NO_3^-$-N | $P_2O_5$ |
|---|---|---|---|---|
| | Tons/ha | ---------------------Kg/ha | ------------------- | |
| 1271 | 33 | -- | -- | -- |
| 2333 | -- | 30.00 | 0.00 | 120.00 |

The mass balance of both N and P for GLEAMS and TROPGLEAMS was assessed for each year for each fertilization scheme. Summary tables of the outputs for the three years of the first scheme of fertilization are shown in Appendix B. The tables show initial and final concentration of plant N and P, N and P pools in soil and in the soil surface, along with values of losses and input of N and P.

The mass balance of N and P for GLEAMS and TROPGLEAMS for the first scheme of fertilization, in which only mineral fertilization was used, resulted in values of 0.00 kg/ha for all three years of simulation. For the second scheme of fertilization, in which two applications of sewage sludge were used, the balance of nitrogen for GLEAMS resulted in values of 0.00, -17.99, and 0.00 kg N/ha for the first, second, and third years and 0.00 kg P/ha for phosphorus each year. . For TROPGLEAMS, the values were 0.00, -11.10, and 0.00 kg N/ha and 0.00, 0.00, and 0.00 kg P/ha. For the third scheme of fertilization, in which sewage sludge was applied to the soil in the first year and mineral fertilizer in the second, balances of N and P resulted in values of 0.00 kg/ha for all three years of simulation.

The modified model is accurate in terms of mass balance of P, since it resulted in values equal to zero in all years and all fertilization schemes. For nitrogen, a negative value for the second year of the second scheme was observed in both GLEAMS and TROPGLEAMS, suggesting that the origin of this error is in a subroutine common to both models that was not modified for this study.

## 4.1.2. VARIATION OF VARIABLE VALUES IN TIME

TROPGLEAMS was applied to a sugarcane field in Piracicaba using several scenarios of fertilization and different values of pH and Ncrit. For the analysis of fresh organic nitrogen (nitrogen from crop residue), nitrate, ammonium, fresh organic P, and labile P, the model was run using values of pH and Ncrit as 4.1 and 0.05, respectively. From the results of this simulation, graphics were created with values of FON, nitrate, ammonium, soil water content, fresh organic P, and labile P versus time.

GLEAMS and TROPGLEAMS have default values for fresh organic nitrogen (FON) of 40 kg/ha and 20 kg/ha, respectively, distributed in soil layers according to a weighting factor. Figure 4.1 shows the quantity of FON and water content of layer 2 during the first 600 days of simulation in the Piracicaba field. For this soil, water content at field capacity and wilting point was set as 0.22 cm/cm and 0.13 cm/cm, respectively, corresponding to 1.995 and 1.425 cm of water in layer 2, respectively.

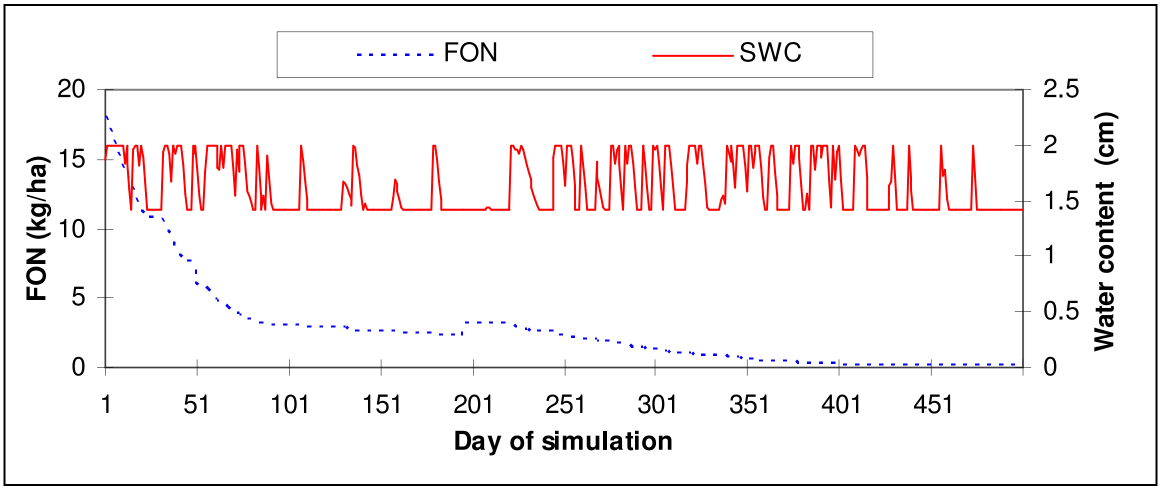


**Figure 4.1.** Fresh organic nitrogen and soil water content of layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342.

Sugarcane was planted on day 342 and, prior to that, weeds covered the field until day 197. TROPGLEAMS incorporates FON into the soil only on the day of harvest, which explains the increase in FON on day 197. The decay of FON is consistent with the decomposition rate, the quantity of nitrogen, and the moisture status of the soil layer. Variations in the FON content is related to the water content of the layer. When the layer is at the wilting point (1.425 cm), no decomposition occurs and the line flattens.

The concentration of ammonium and nitrate and the water content of layer 2 are shown in Figure 4.2. The field received 30 kg/ha of urea on day 342, applied to the depth of 20 cm, and 40 kg/ha applied on the soil surface on day 401. For this simulation, values of 4.1 and 0.05 were used for pH and the nitrate retardation factor (Ncrit), respectively.

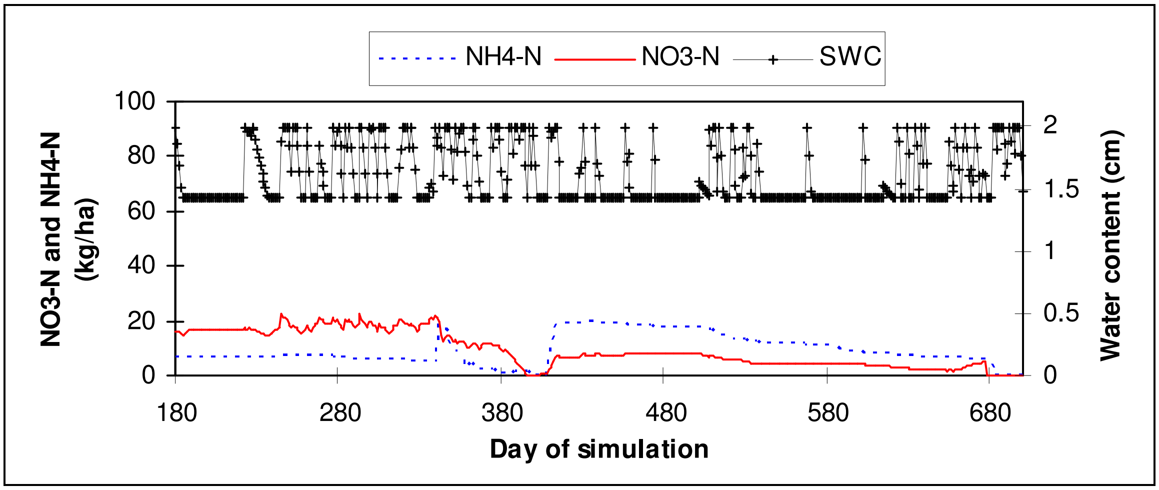


**Figure 4.2.** Values of $NO_3^-$-N, $NH_4^+$-N, and soil water content (SWC) of layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342, using values of pH and Ncrit as 4.1 and 0.05

The effect of water content on ammonium and nitrate kinetics and transport is observed in figure 4.2. During dry periods, no transformations or transport are observed and the lines representing $NO_3^-$-N and $NH_4^+$-N flatten. The lower mobility of ammonium explains why its quantity in the soil layer changes less significantly than nitrate. The change in the quantity of nitrate in soil layers at the end of each day is the result of nitrification, plant uptake, leaching, and denitrification, which are higher during rainy periods. This explains why the decay of ammonium is not followed by an increase of nitrate in most days.

Figure 4.3 shows the concentrations of ammonium and nitrate and the water content of layer 2 with values of pH and Ncrit changed to 6.0 and 0.08, respectively. The calculation of nitrification in TROPGLEAMS depends on ammonium concentration, temperature, soil water content, and pH. With higher pH, nitrification increases and a significant reduction in ammonium concentration is observed. Besides the increased production of nitrate due to greater nitrification, more nitrate is retained in soil layers due to the greater value of Ncrit. These factors explain the greater values of nitrate observed in Figure 4.3 than that observed in figure 4.2.

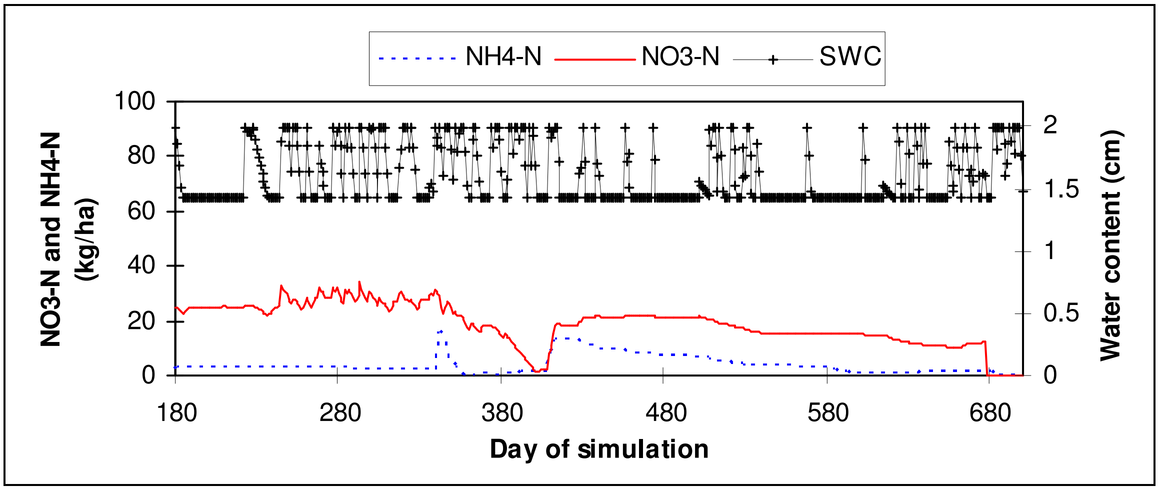


**Figure 4.3.** Values of $NO_3^-$-N, $NH_4^+$-N, and soil water content of layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342, using values of pH and Ncrit as 6.0 and 0.08, respectively.

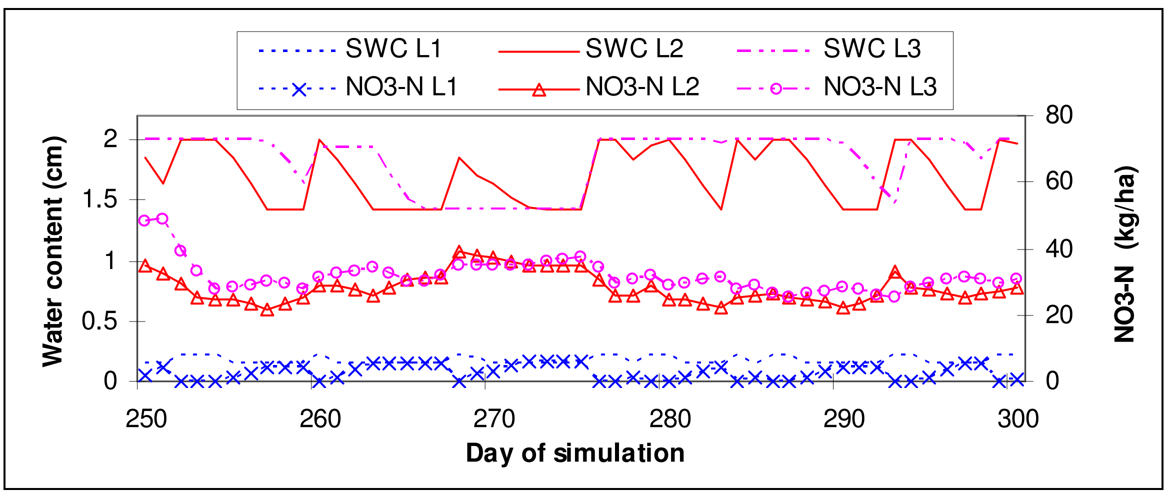


**Figure 4.4.** Values of $NO_3^-$-N and soil water content of layers 1, 2, and 3 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342, using values of pH and Ncrit as 6.0 and 0.08, respectively.

The interaction of nitrate with soil water content between linked layers is shown in Figure 4.4. The value of 0.08 for Ncrit allows significant movement of nitrate in the soil profile. Since layer 1 is only 1-cm depth, its capacity to retain water is very limited and field capacity is reached very easily, allowing for nitrate leaching to occur on several days in the period of simulation shown above. During the period in which the SWC of layer 1 is at the upper limit, water percolation takes place and nitrate is transported to layer 2, promoting an immediate increase of nitrate in layer 2. During certain periods of decreasing concentration of nitrate in layer 2, a corresponding increase was observed in layer 3, indicating that leaching occurred. In certain periods, decreasing soil water content of layers 2 and 3 is accompanied by a decrease in nitrate concentration, which is attributed to plant uptake. In the period following day 290, layer 2 soil water content is at wilting point and an increase of nitrate is observed. This increase on days 291 and 292 is caused by the upward movement of nitrate from layer 3 to layer 2. On day 293, the increase in layer 2 is due to leaching from layer 1.

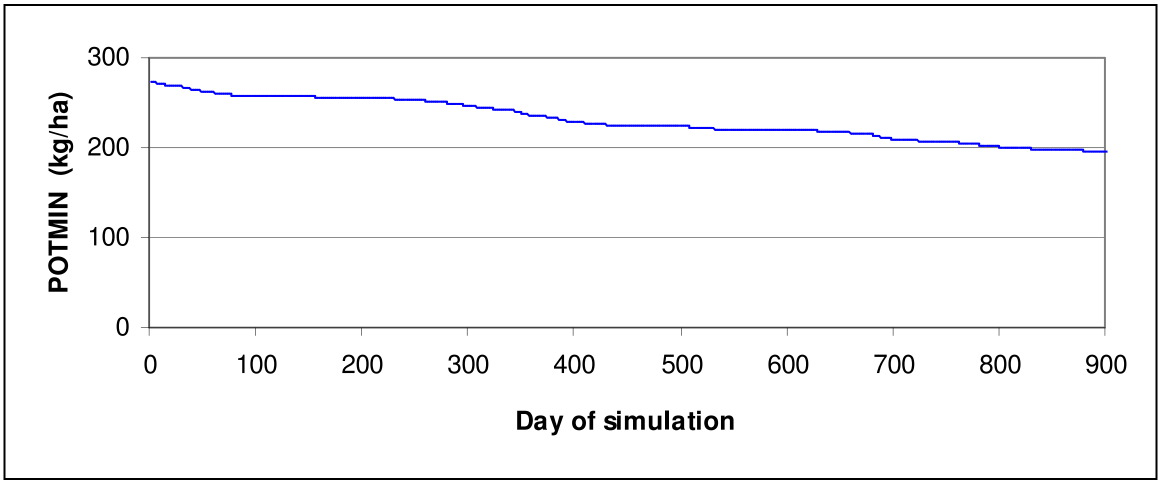


**Figure 4.5.** Values of potentially mineralizable nitrogen of layer 2 during 900 days simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342.

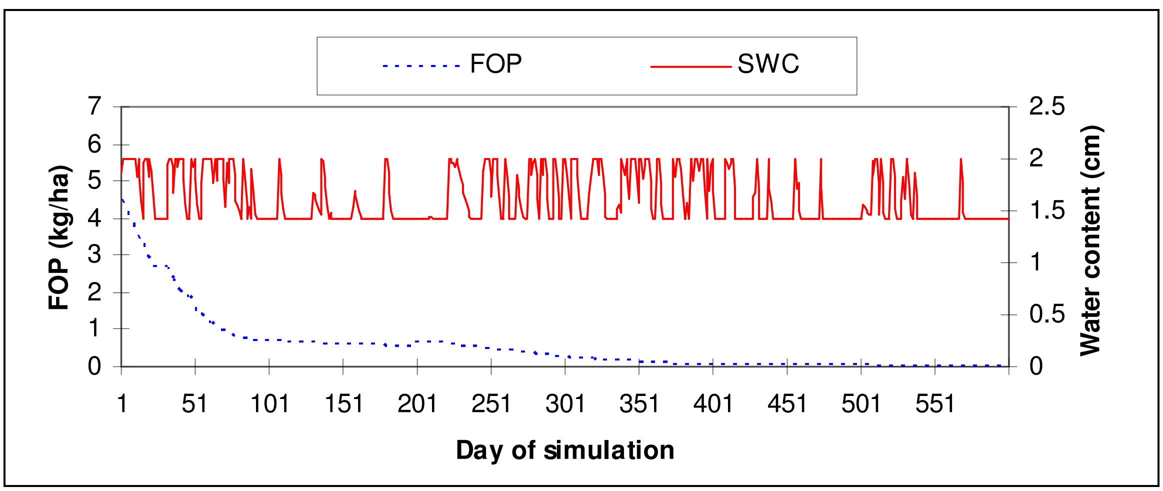


**Figure 4.6.** Values of FOP and soil water content of layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342.

Figure 4.5 shows the decay of nitrogen from the potentially mineralizable soil organic nitrogen (POTMIN) pool. It can be seen that 92 kg N/ha was mineralized during the 900-day simulation. This is consistent with the mineralization rate selected in implementing this model component. The influence of environmental factors is observed in the simulation: faster decay during the warm rainy season (days 1-100, 250-450, and 615-800) and slow decay during the dry and cold season (days 100-250, 450-615, and 800-900). Tropical forest soils tend to mineralize soil organic nitrogen faster than continuously cropped soils (Motovalli et al., 1995). A fast decrease in organic matter is observed in tropical soils in the years following forest cutting and the decay is fast enough to inhibit profitable production after five years of agricultural use in certain dystrophic soils. Erosion contributes to the decrease in productivity, but the fast mineralization and consequent leaching of nitrate contributes significantly. The decay of POTMIN in the sugarcane field of Piracicaba shown in figure 4.4 is in accordance with observations in tropical fields, showing the appropriateness of the equations incorporated in TROPGLEAMS to simulate the decay of soil nitrogen.

Figure 4.6 shows the decay of organic P from vegetal residue during the first 600 days of the Piracicaba field simulation. FOP follows the same trend as was observed for FON. The sharp decline of FOP in the first days of simulation is due to the higher quantity of material available for mineralization, sufficient soil water content, and higher temperatures. During the dry, colder period, between days 100 and 250, mineralization of FOP decreases and several days of zero mineralization occur due to the lack of water in the soil layer. On day 197, the increase of FOP is caused by the incorporation of weeds that covered the area during the antecedent period. With the beginning of the rainy season after day 251, the rate of mineralization increases with soil moisture and higher temperatures. The decline of FOP in this period is not as great as it is at the beginning of simulation because less material is available for mineralization.

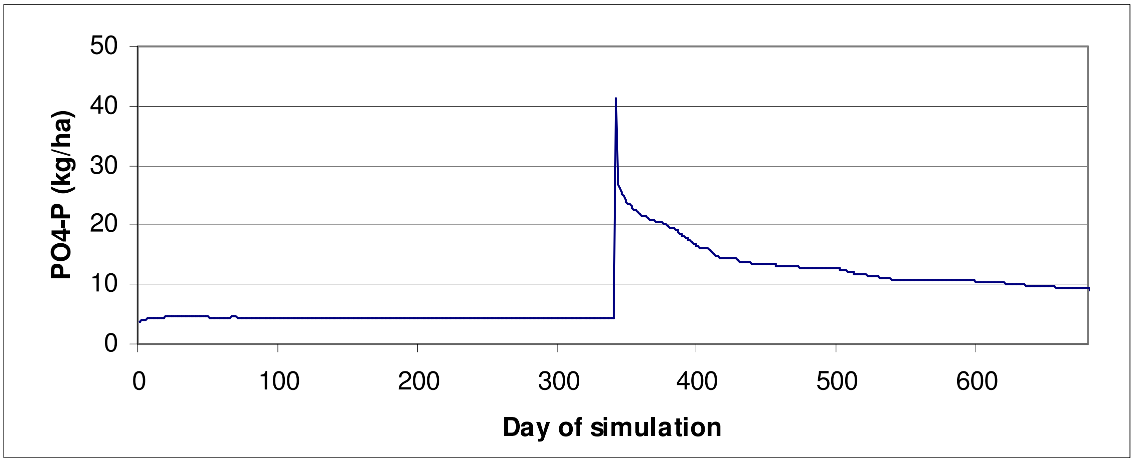


**Figure 4.7.** Values of labile P in layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, planted with sugarcane on day 342, with application of 180 kg $P_2O5$/ha on day 342, incorporated to 20 cm depth.

Figure 4.7 shows labile P in soil layer 2. In this simulation, 180 kg $P_2O_5$/ha were applied on day 342, incorporated to 20 cm depth. At the beginning of the simulation, the sources of labile P are a function of its initial concentration, specified as 5.6% of soil organic P, and due to the mineralization of existing FOP. During the first year, around 4 kg/ha of FOP was mineralized, as shown in Figure 4.6. However, the mineralization did not result in an increase of labile P. As described in section 3.2.2, the equation that calculates transformations between labile and active mineral P may overestimate the rate of transformations, since its calculation includes a temperature factor that has large values for temperatures above 25$^oC$ (1.75 and 5.5 at temperatures of 30 and 40$^oC$, respectively). Soil temperatures of layer 2 during the simulation ranged from 10.43 to 34.76$^oC$ with an average of 21.20 $^oC$. Although the average temperature was inside the range of values in which the soil temperature factor is below one, during warmer periods, the temperature factor certainly reached values well above one, possibly overestimating the quantity of labile P transformed to PMINP. This fact, along with the uptake of P by the weeds covering the soil during the beginning of simulation, are the likely reasons making the value of labile P almost constant despite the formation of PLAB by FOP mineralization.

On day 342, 180 kg $P_2O_5$/ha was applied to the field and incorporated to a depth of 20 cm. The fast decline in the quantity of labile P was caused by its transformation to

PMINP. Goncalves et al. (1985) observed the expected fast decline in labile P in the study from which the equations for simulating P transformations in the period of 60 days after mineral P application were derived. As discussed in section 3.1.2, after 60 days of mineral P application, transformations of PLAB and PMINP revert to the equations of the original GLEAMS. Figure 4.8 shows values of labile P in the period that includes the 60$^{th}$ day after mineral P application. The line representing values of labile P has no breakpoints on day 402, showing that the 60$^{th}$ day after mineral P application provides a smooth transition for the calculation of mineral P transformation from the equation based on Goncalves et al. (1985) to the equations in the original GLEAMS.

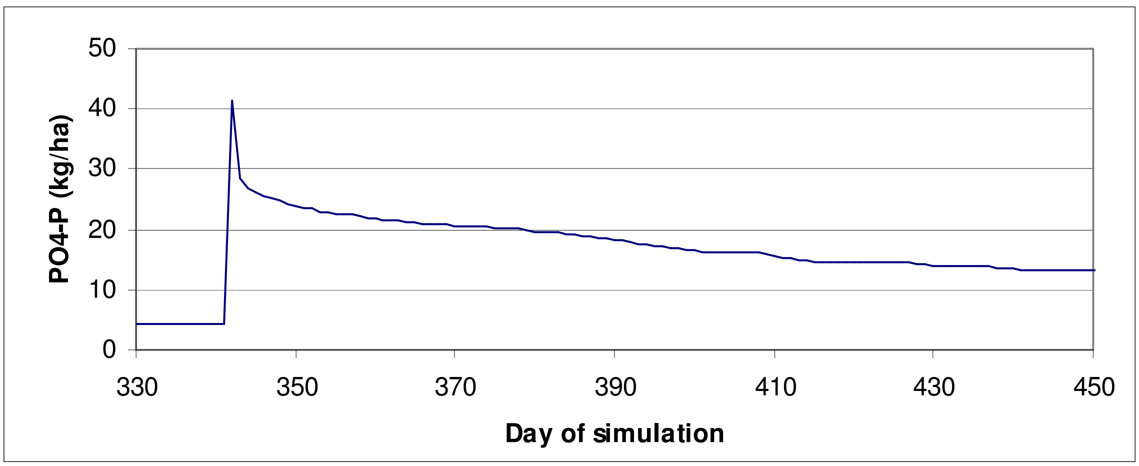


**Figure 4.8.** Values of labile P in layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, after application of 180 kg/ha of mineral P.

Figures 4.8 and 4.9 show values of organic P from animal waste (ORGP) in a simulation in which 10 tons/ha of bovine manure were applied to soil on day 50 and 180 kg $P_2O_5$/ha were applied on day 150 (both to 20 cm depth). It can be observed that, although the basic rates of degradation of ORGP are greater than those of fresh organic P (0.717 and 0.011 versus 0.317 and 0.01) the decay of ORGP is less accentuated than that of FON shown in Figure 4.1 due to constraints imposed by low soil moisture after day 90. A large quantity of ORGP, allied with high temperatures and soil water content, promoted the accentuated decay observed during the first 45 days after manure application. After day 100, the lack of water during several days, allied with lower temperatures, caused a reduction of SORGP degradation. In the periods in which the line flattens between days 100 and 250, the soil water content reached the wilting point and the soil water factor was zero. The decay of ORGP increased again after day 250 when the rainy period started. The temperature factor was 0.17, 0.167, and 0.173, on days 218, 232, 234, respectively (month of July) and 0.25, 0.24, 1.26, and 0.22 on days 317, 318, 362, and 377, respectively (months of December and January). This shows that the TROPGLEAMS simulation of ORGP decay is also influenced by differences in soil temperatures.

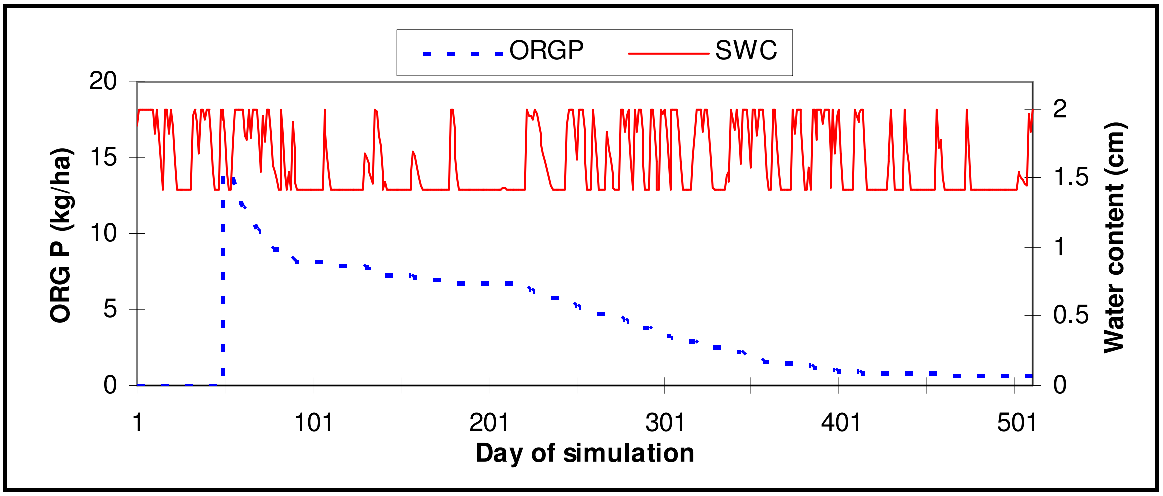


**Figure 4.9.** Values of organic P from animal waste (ORGP) and water content in layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, after application of 10 tons/ha of dairy cattle manure on day 50 and 180 kg $P_2O_5$/ha on day 150.

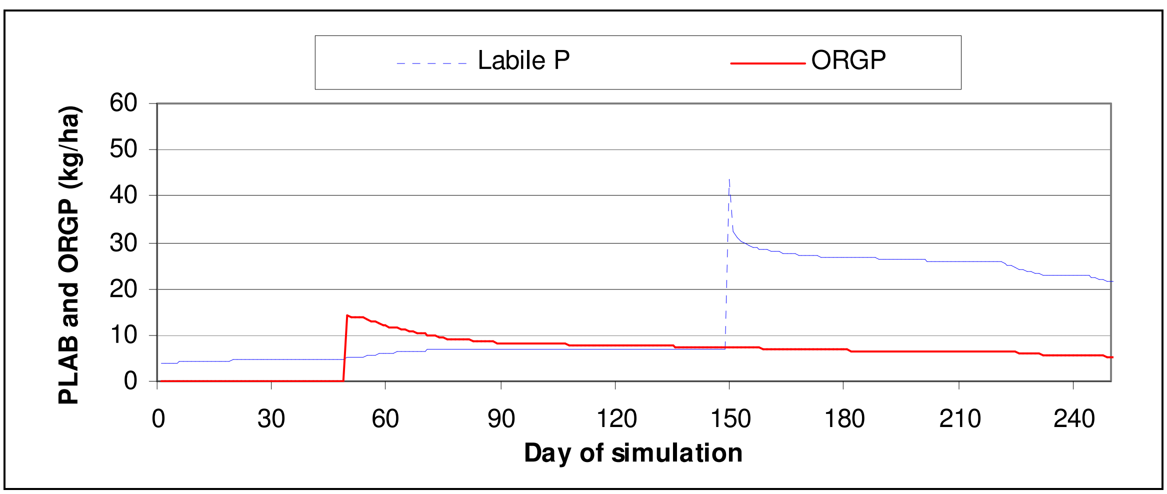


**Figure 4.10.** Values of organic P from animal waste (ORGP) and labile P in layer 2 simulated using TROPGLEAMS applied to a field located in Piracicaba, Brazil, after application of 10 tons/ha of dairy cattle manure on day 50 and 180 kg $P_2O_5$/ha on day 150.

Figure 4.10 shows values of labile P and ORGP from the same simulation. During the first 50 days, values of labile P primarily reflect the default initial values and the mineralization of FOP. After manure application, the mineralization of ORGP promoted an increase in labile P. The highest value occurs on the day of mineral P application. After that day, TROPGLEAMS uses the models responsible for calculating mineralization of FOP and ORGP, transformations between labile and PMINP, plant uptake and leaching to generate the final daily value of labile P. The stability of the predicted values of labile P indicates that the component models are functioning consistently under tropical conditions.

# 4.2. MODEL VALIDATION

Three field studies from Brazil provided the basis for independent comparison of model predictions with observed data.  For each of the monitoring studies, described below, model parameters were defined from measured data or from default or descriptive values.  Both TROPGLEAMS and GLEAMS were run to provide a comparison with the observed data and between models to assess the improvement of TROPGLEAMS in modeling tropical conditions.

## 4.2.1. PIRACICABA LYSIMETER STUDY

This study was described by Oliveira et al. (2002) and Oliveira (1999).  It was carried out in Piracicaba, Sao Paulo (Latitude: S 22°41'00"), from January to November 1996 and consisted of 16 treatments with 3 replicates each. Each experimental unit was composed of a lysimeter (polyethylene barrel) of 90 cm height and 60 cm diameter with about 250 kg of soil. The soil used to fill the lysimeters was a sandy yellow-red Podzolic taken from an area planted with sugarcane. Before soil collection, sugarcane residue and rootstalks were separated and were used during the mounting of the lysimeters. Chemical and physical characteristics of the soil used in the lysimeters are shown in table 4.4. Climatic data of Piracicaba for 1996 that was used as model input is shown in table 4.5.

**Table 4.4.** Chemical and physical characteristics of the soil used in the lysimeters.

| Parameter | Value |
|---|---|
| pH in $CaCl_2$ | 4.4 |
| Organic matter ( g $kg^{-1}$) | 19.0 |
| P (µg $cm^{-3}$) | 10.0 |
| Porosity (cm3/cm3) | 0.5 |
| Field capacity (cm3/cm3) | 0.22 |
| Wilting point (cm3/cm3) | 0.05 |
| Effective saturated conductivity (cm/h) | 1.27 |
| Total sand (%) | 84 |
| Silt (%) | 6 |
| Total clay(%) | 10 |

**Table 4.5.** Climatic data for the year of 1996 used as model input in the simulation of the Piracicaba lysimeter study.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean monthly maximum temperature $^oC$ | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 31.2 | 31.8 | 30.5 | 29.5 | 26.2 | 25.6 | 25.1 | 28.6 | 27.1 | 29.4 | 29.1 | 30.6 |
| Mean monthly minimum temperature $^oC$ | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 20.3 | 20.1 | 19.4 | 16.7 | 12.8 | 11.0 | 9.5 | 11.3 | 15.0 | 16.8 | 17.8 | 19.8 |
| Mean monthly solar radiation $MJ/m^2$.day | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 18.4 | 17.5 | 16.0 | 15.0 | 12.6 | 11.7 | 12.6 | 15.6 | 15.0 | 17.1 | 17.1 | 17.2 |
| Mean monthly wind movement km/day | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 122 | 138 | 131 | 142 | 114 | 141 | 145 | 152 | 168 | 158 | 169 | 125 |
| Mean monthly dew point temperature $^oC$ | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 22.2 | 23.1 | 22.2 | 19.1 | 16.1 | 14.0 | 12.7 | 13.9 | 16.6 | 19.4 | 19.7 | 22.5 |

Sugarcane was planted on January 6, 1996 and harvested on December 9, 1996. The lysimeters received both natural rainfall and irrigation and were fertilized with different doses of $^{15}N$ urea and crop residue. In eight treatments, percolated water was collected whenever significant percolation was observed, with measurement of volume and analysis of total mineral nitrogen ($NO_3^-$- N + $NH_4^+$-N). Measurements took place on the following dates: January 1, 16, and 23; February 8 and 29; March 6; September 13; October 28; and November 19. After harvesting, plant material was weighted, dried, chopped and analyzed. Soil samples were collected and also analyzed. Cumulative percolated water and mineral nitrogen in leachate from the eight treatments with measured percolation were used in this model validation. The quantity of N and crop residue applied to each treatment is shown in table 4.6.

**Table 4.6.** Applied nitrogen and crop residue in each treatment of the Piracicaba lysimeter study , Brazil (Oliveira et al., 2002).

| Treatment | Applied nitrogen as urea (kg ha$^{-1}$)** | Crop residue* (t ha$^{-1}$) | | | C:N ratio** |
|---|---|---|---|---|---|
| | | DL | T + S | Rt | |
| T1 | 0 | 7.0 | 8.2 | 10.0 | 73 |
| T2 | 30 ($^{15}$N) | 7.0 | 8.2 | 10.0 | 73 |
| T3 | 60 ($^{15}$N) | 7.0 | 8.2 | 10.0 | 73 |
| T4 | 90 ($^{15}$N) | 7.0 | 8.2 | 10.0 | 73 |
| T5 | 0 | 0 | 8.2 | 10.0 | 65 |
| T6 | 30 ($^{15}$N) | 0 | 8.2 | 10.0 | 65 |
| T7 | 60 ($^{15}$N) | 0 | 8.2 | 10.0 | 65 |
| T8 | 90 ($^{15}$N) | 0 | 8.2 | 10.0 | 65 |

* DL= Dry leaves; T + S= Tips + stalks; Rt = Roots.

** C:N ratio= C:N ratio of the incorporated crop residue.

Treatment T1 was used in initial model simulations for model verification and for limited calibration of selected parameters: initial nitrate concentration, potentially mineralizable nitrogen, and nitrate retardation factor (Ncrit). The following additional adjustments to the models and parameterization were made based on comparison with percolation and nitrate leaching:

- Rainfall values in the rainfall input file were reduced by 25% after LAI reaches 2m$^2$/m$^2$. This was done in order to account for intercepted rainfall retained on the canopy and for rainfall that is shed from the canopy to outside the 60 cm lysimeter. Table D1 of Appendix D shows data of precipitation + irrigation used as input by each lysimeter.

- Initial nitrate concentration, potentially mineralizable nitrogen, and nitrate retardation factor (Ncrit) were set to 3 ppm, 100 kg/ha, and 0.03, respectively. The first two parameters are inputs used in both models, while Ncrit is an input used only in TROPGLEAMS. Since field-measured values were not reported, these parameters were adjusted by comparison of predicted and measured values of percolated mineral nitrogen. The range of values considered in the calibration were 0 to 12 ppm (with step 3 ppm) for initial nitrate concentration, 50, 100, and 150 kg/ha for potentially mineralizable nitrogen, and 0 to 0.05 (with step of 0.01) for Ncrit.
- The default initial value of ammonium (19 ppm $NH_4^+$-N) defined in TROPGLEAMS appeared to be too high for the conditions of the lysimeters and was changed to a value of 4 ppm for both models for simulations related to this study.
- The default value of C:N ratio of residue in the beginning of simulation in GLEAMS and TROPGLEAMS is 1:30. This value in both models was changed to 1:70 to correspond to measured values reported by Oliveira (1999).
- The default value of fresh organic nitrogen in GLEAMS and TROPGLEAMS is 40 and 20 kg/ha, respectively, distributed to each soil layer based on a weighting factor. This value in GLEAMS was changed to 20 kg/ha.

Input parameter files were created for each treatment using the above parameter values and unique parameters for each treatment as described in the field data. Model results were compared with measured data through graphical presentation and the result of the calculation of root mean square error (RMSE). Daily values of simulated and measured percolated water and cumulative N in leachate were used in the calculation of the RMSE for each treatment.

Measured and simulated values of accumulated percolated water from the lysimeters composing treatment 1 (10 kgN/ha + 25.2 ton crop residue/ha) are shown in figure 4.11. The Penman-Monteith option was chosen as the evapotranspiration model for the GLEAMS simulations.

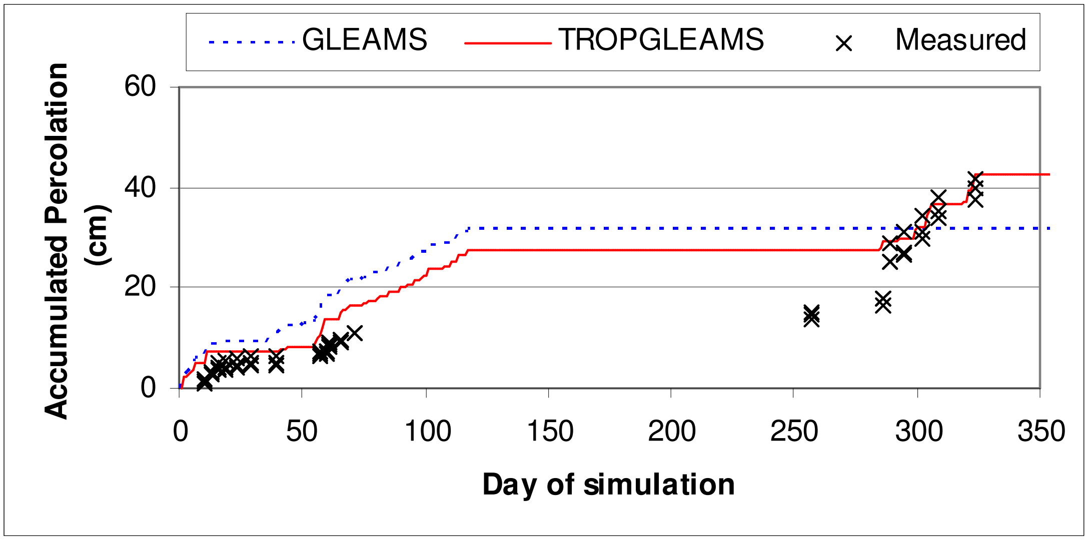


**Figure 4.11**. Simulated and measured values of cumulative percolated water from a lysimeter located in Piracicaba, Brazil, calculated by the original and modified GLEAMS. Evapotranspiration of the original GLEAMS was calculated using the Penman-Monteith model.

Both models reasonably follow the percolation of water from the lysimeters at the beginning of the simulation. In this period, an overprediction of values is observed in the results from both models, with the modified model resulting in values closer to the measured ones. Between days 71 and 257, water percolation from the lysimeters was negligible and no water was collected, but both models continued predicting losses of water until day 118, resulting in greater differences between measured and simulated values in the second period of measurement after day 257. For the second period, the results of TROPGLEAMS followed the trend of the measured values, while GLEAMS reported no further leaching until the end of the period. As discussed previously, the inconsistent results shown by the original Penman-Monteith model were assumed to be the reason for the constant values of accumulated percolation observed, since the evapotranspiration model was the only hydrology-related model that was changed in the development of TROPGLEAMS. The root mean square error between simulated and measured values of cumulative percolation for GLEAMS was 8.10, while for TROPGLEAMS it was 4.97.

GLEAMS was run again using the Priestly-Taylor model, and the result is shown in Figure 4.12. Using the Priestly-Taylor model, the performance of GLEAMS improved in the first part of the simulation as well as in the beginning of the second period of percolation measurements. However, GLEAMS again did not simulate the increase of percolated water in the end of the period. The RMSE for GLEAMS for this simulation was 7.7, smaller than the 8.10 resulted when the Penman-Monteith model was used.

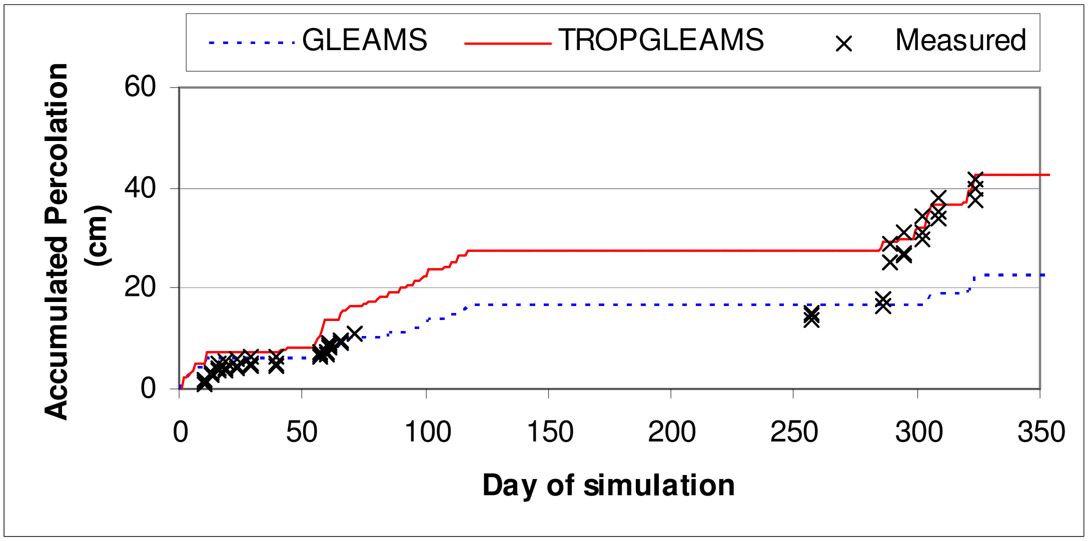


**Figure 4.12.** Measured and simulated accumulated percolated water from Piracicaba lysimeter study, treatment 1calculated by GLEAMS and TROPGLEAMS. Evapotranspiration of GLEAMS was calculated using the Priestly-Taylor model.

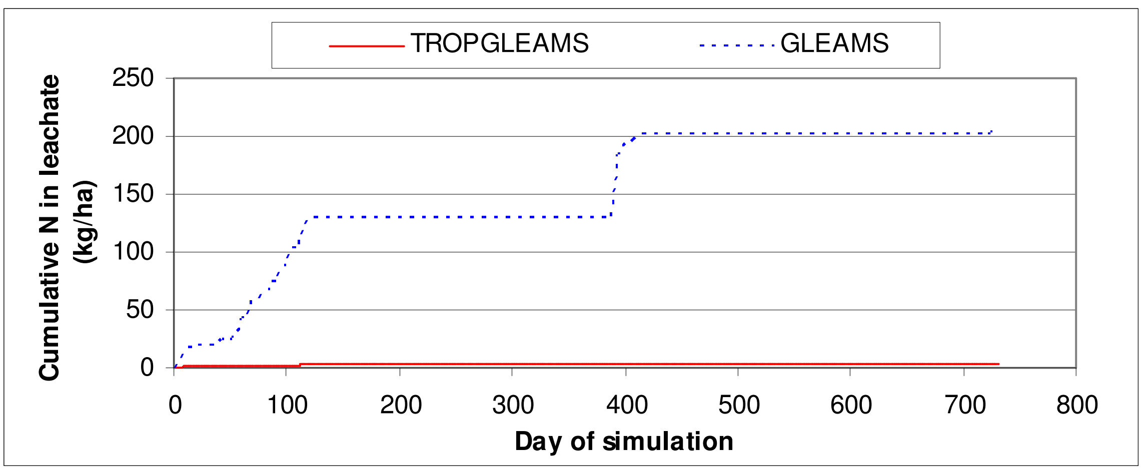


**Figure 4.13.** Simulated values of N in leachate calculated by GLEAMS and TROPGLEAMS applied to Piracicaba lysimeter study, treatment 1 (Oliveira, 1999). GLEAMS was run with default initial conditions.

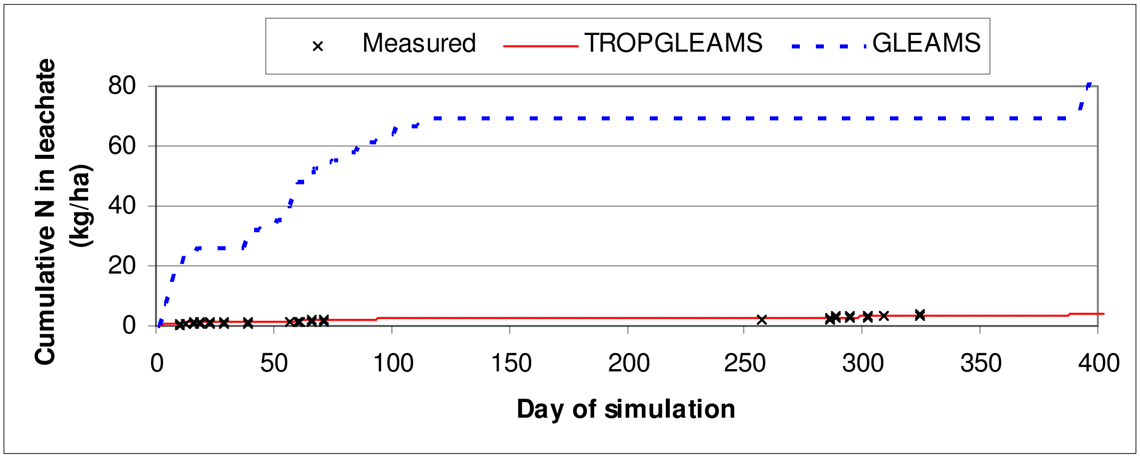


**Figure 4.14.** Measured and simulated values of N in leachate calculated by GLEAMS and TROPGLEAMS applied to Piracicaba lysimeter study, treatment 1 (Oliveira, 1999). Both modified and original models were run with the same initial conditions.

Figure 4.13 shows values of N in leachate from GLEAMS and TROPGLEAMS simulating treatment 1. The differences in the values of the initial/default conditions of N were certainly one factor that contributed to the observed differences in model results. Figure 4.14 shows measured and simulated values of N in leachate after changing the initial/default conditions for GLEAMS to be the same as those implemented in TROPGLEAMS. Changes were made to the initial values of FON, ammonium and the C:N ratio of crop residue on soil surface, which were modified from 40 kg/ha, 2 ppm, and 25 to 20 kg/ha, 4 ppm, and 70, respectively. While these initial/default parameters reduced the overprediction by a factor of 2, the remaining difference of a factor of 10 must be attributed to the changes in the model algorithms. There was a significant amount of nitrogen in the soil and on the surface of the lysimeters when the simulation began - 20 kgN/ha as FON in soil layers, 365 kg/ha in the 25.2 ton/ha of crop residue, 3 ppm of $NO_3^-$-N, and 4 ppm of $NH_4^+$-N. The algorithms responsible for the transformations of nitrogen in the original model overpredicted the rates of transformation, resulting in the high values of N in leachate observed in Figure 4.14. The modified model, however, showed better performance, with results very close to the measured values. The RMSE between measured and simulated values was 49.00 for GLEAMS and 0.35 for TROPGLEAMS.

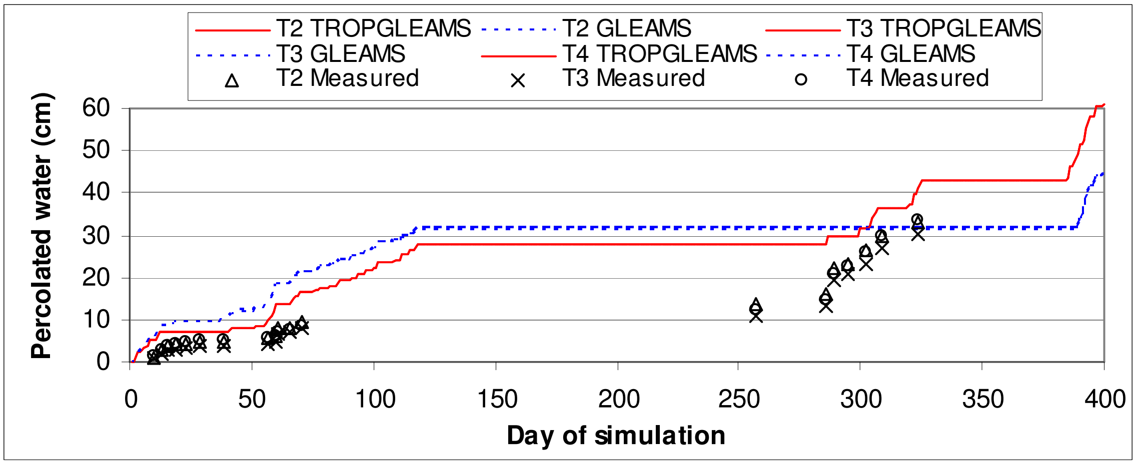


**Figure 4.15.** Measured and simulated values of accumulated percolated water from the Piracicaba lysimeter study, treatments 2, 3, and 4. Measured values are averages of three replicates.

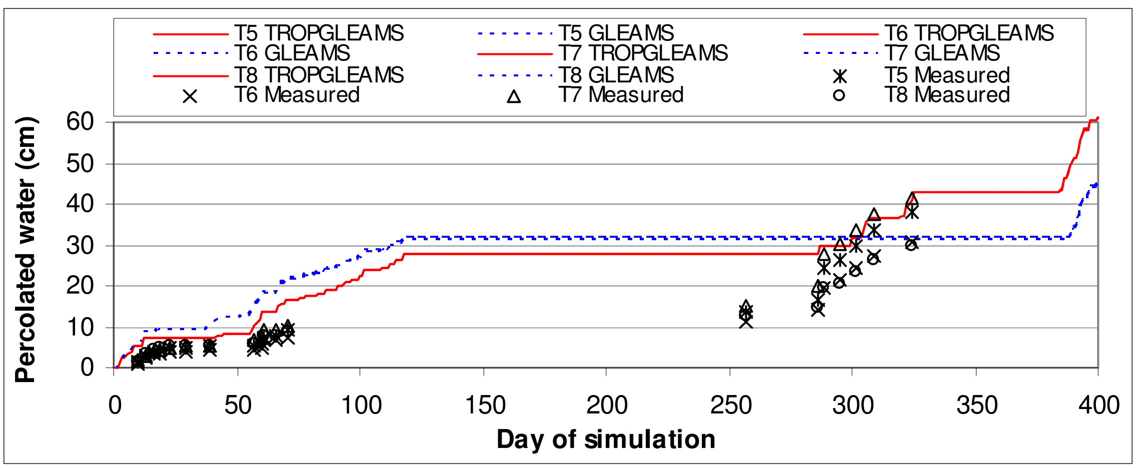


**Figure 4.16.** Measured and simulated values of accumulated percolated water from the Piracicaba lysimeter study, treatments 5, 6, 7, and 8. Measured values are average of three replicates.

Figures 4.15 and 4.16 show measured and simulated values of percolated water from the lysimeters of treatments 2 through 8. Both models predicted percolation independent of the input level of nitrogen and crop residue. Greater nutrient availability should increase plant growth and LAI, increasing evapotranspiration and, consequently, potentially reducing the quantity of water available for percolation. However, GLEAMS (and TROPGLEAMS) do not simulate these interactions; consequently every treatment yielded the same prediction for percolation as seen in Figures 4.15 and 4.16.

**Table 4.7.** RMSE between measured* and simulated values of percolated water from treatments 2-8 of the Piracicaba lysimeter study.

| Treatment | GLEAMS | TROPGLEAMS |
|---|---|---|
| T2 | 8.89 | 6.59 |
| T3 | 10.48 | 8.46 |
| T4 | 9.35 | 7.07 |
| T5 | 8.88 | 5.80 |
| T6 | 10.29 | 8.10 |
| T7 | 7.92 | 4.63 |
| T8 | 9.55 | 7.73 |

* mean value of 3 replicates used in calculating the statistic

Table 4.7 shows the RMSE values between daily measured and simulated values of percolated water using GLEAMS and TROPGLEAMS. It can be seen that TROPGLEAMS had lower values of RMSE for all treatments, indicating better performance in simulating soil hydrology compared to the original model. This difference is due to improvements in the calculation of evapotranspiration.

Figures 4.17 and 4.18 show values of cumulative mineral nitrogen in leachate simulated by the original and modified GLEAMS from the lysimeters of treatments 2 to 8. Both models reflected the quantity of applied N in their results. Treatments 2, 3, and 4 received 25.2 tons of crop residue per hectare, while treatments 5, 6, 7, and 8 received 18.2 tons/ha. Both models simulated greater values of cumulative N in leachate for the treatments that received more organic matter. Different mineral N application also resulted in different quantities of cumulative N in leachate. For the same quantity of crop residue applied to the soil, the treatments that received more mineral nitrogen resulted in greater values of simulated leachate.

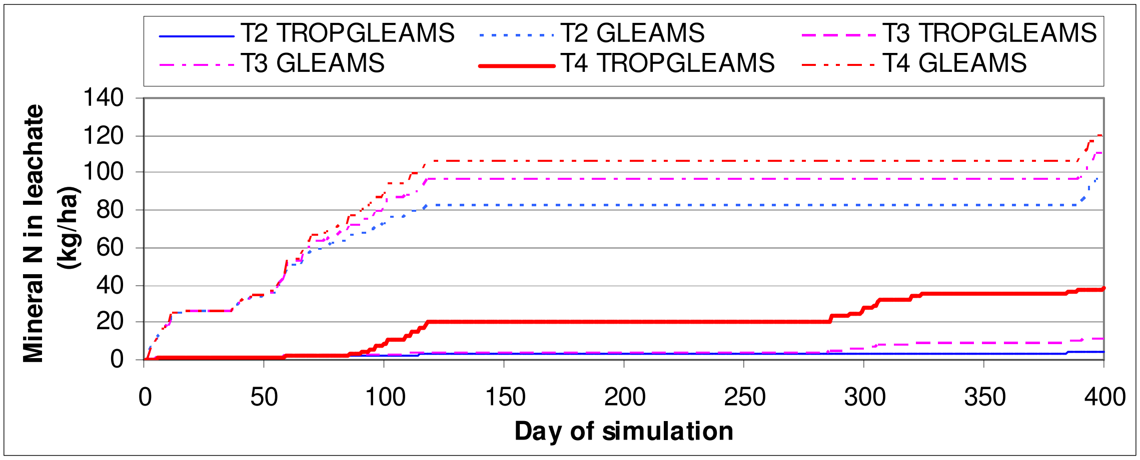


**Figure 4.17.** Values of cumulative mineral N in leachate from the Piracicaba lysimeter study, treatments 2, 3, and 4, simulated using GLEAMS and TROPGLEAMS.

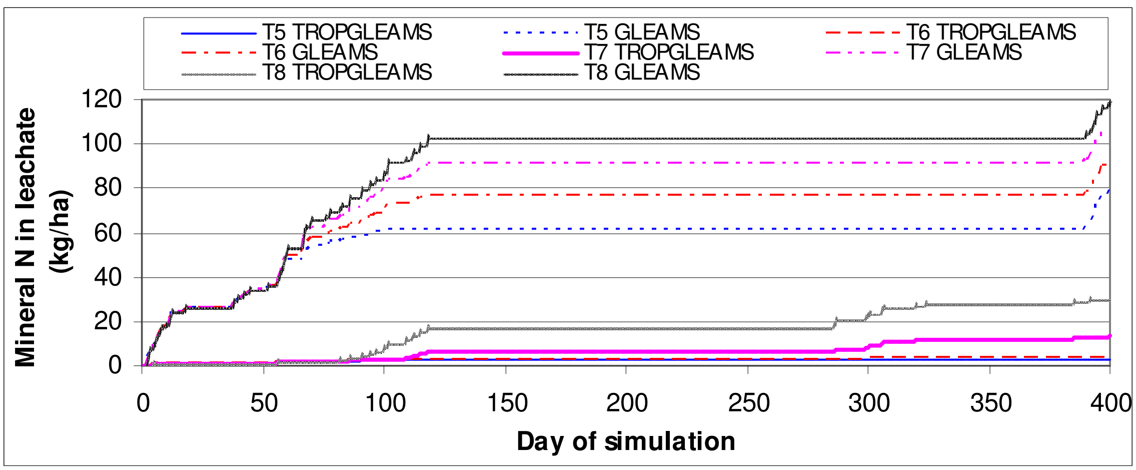


**Figure 4.18.** Values of cumulative mineral N in leachate from the Piracicaba lysimeter study, treatments 5, 6, 7, and 8, simulated using GLEAMS and TROPGLEAMS.

Table 4.8 shows values of RMSE between measured and simulated values of daily cumulative mineral N in leachate using GLEAMS and TROPGLEAMS, while figures 4.19, 4.20, and 4.21 show measured and simulated values using TROPGLEAMS. These values show that TROPGLEAMS performed better than GLEAMS in the simulation of nitrogen fate and transport in the tropical condition where the lysimeters were installed.

**Table 4.8.** RMSE between measured and simulated values of daily cumulative mineral N in leachate from lysimeters of treatments 2-8 of the Piracicaba lysimeter study.

| Treatment | GLEAMS | TROPGLEAMS |
|---|---|---|
| T2 | 54.61 | 1.60 |
| T3 | 62.82 | 1.82 |
| T4 | 68.64 | 13.92 |
| T5 | 42.95 | 2.44 |
| T6 | 51.45 | 1.65 |
| T7 | 60.98 | 3.09 |
| T8 | 67.73 | 11.79 |

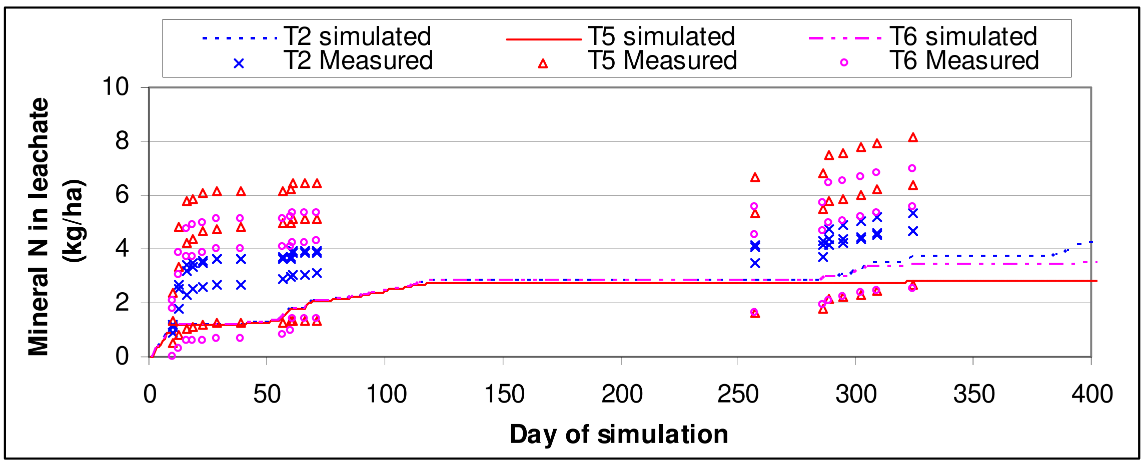


**Figure 4.19.** Measured values of cumulative mineral N in leachate from the lysimeters of treatments 2, 5 and 6 and values simulated using TROPGLEAMS. (Individual values of the 3 replicates for each treatment are shown.)

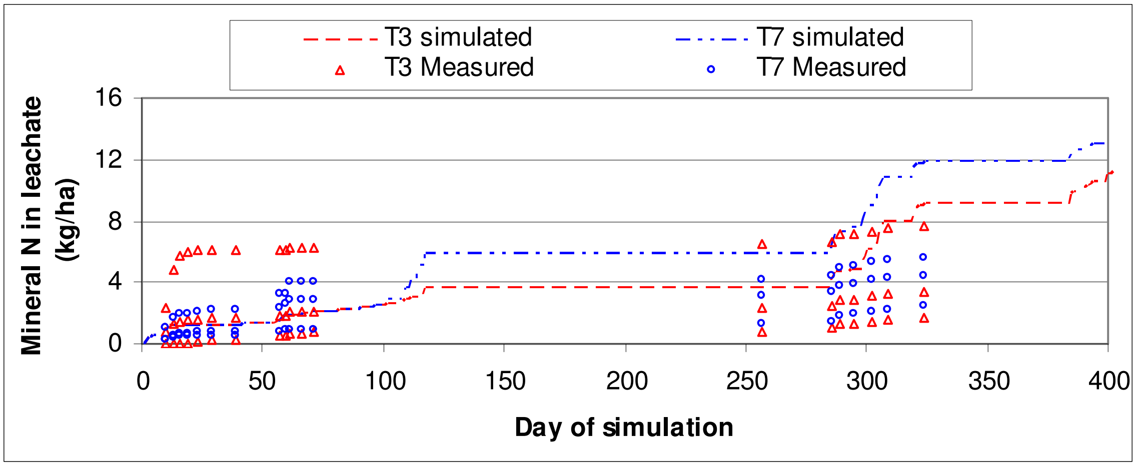


**Figure 4.20**. Measured values of cumulative mineral N in leachate from the lysimeters of treatments 3 and 7 and values simulated using TROPGLEAMS. (Individual values of the 3 replicates for each treatment are shown.)

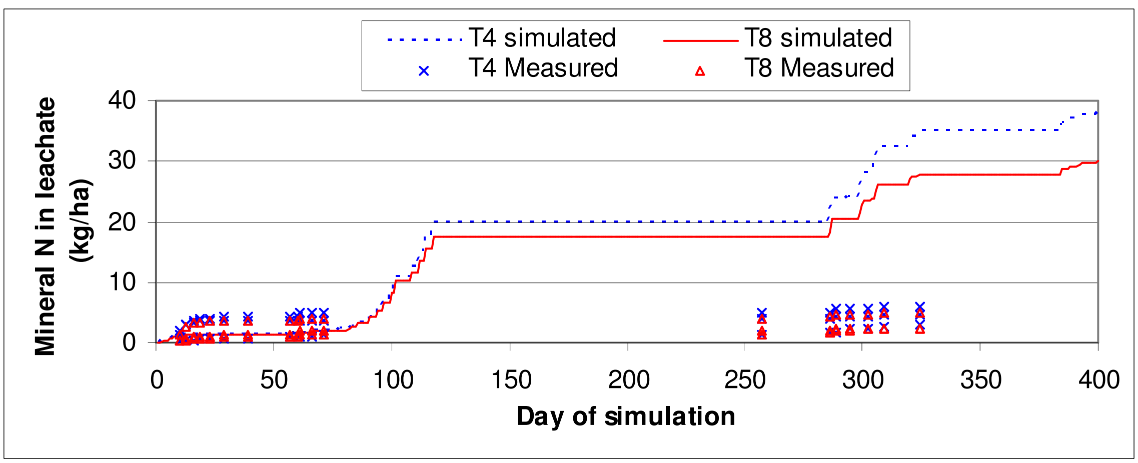


**Figure 4.21.** Measured values of cumulative mineral N in leachate from the lysimeters of treatments 4 and 8 and values simulated using TROPGLEAMS. (Individual values of the 3 replicates for each treatment are shown.)

Figures 4.19 to 4.21 enable a close observation of measured values and those simulated by TROPGLEAMS. It can be seen that measured values are not significantly different between treatments, while the model predicted higher values for treatments where more nitrogen was applied. For treatments T2, T5, and T6, which received 30, 0, and 30 kgN/ha, respectively, TROPGLEAMS underpredicted values of N in leachate in both periods of measurements. For treatments T3 and T7, where 60 kgN/ha were applied, measured values were scattered around the values predicted by the model in the first period (between days 1 and 71). In the second period (days 257 to 324), the model overpredicted N leachate, although the difference is not great. For treatments T4 and T8, where 90 kgN/ha were applied, measured and simulated values were very close in the first period, but significantly different in the second period, which is why these treatments had larger RMSE values.

For the first period, the model simulated higher percolation and lower total leached nitrogen than measured values. This fact suggests that the simulated concentration of nitrogen in leachate was lower than real values.

According to Oliveira (1999), other studies using $^{15}N$ indicated no losses or low losses of N from the fertilizer in leachate (Ng Kee Kwong and Deville, 1987; Padovese, 1988; Salcedo et al., 1988, Rivera and Treto, 1988; Coelho, 1987), while Camargo (1989) verified leaching of 28.2% of N applied as urea in a very sandy soil.

All mineral N applied in the lysimeters was $^{15}N$, making it possible to follow the route of the applied N. According to Oliveira (1999), "11 months after planting sugarcane, 90% of the $^{15}N$ in fertilizer was retained in the soil-plant system and no leaching of $^{15}N$ was observed". While the results of the statistical analysis did not show any effect of the quantity of applied N on the quantity of nitrogen in leachate, the accumulation of plant organic matter and nitrogen was closely related to the amount of applied mineral and organic N. For treatments 2, 3, and 4, in which 30, 60, and 90 kg N/ha were applied, GLEAMS simulated the same value of plant uptake (205.63 kgN/ha), while the average of accumulated N in the plant (root + aerial part) was 6782, 7778, and 9583 mgN/Lysimeter. Simplifications in the plant uptake model may be the main reason for the differences between measured values of N in leachate and those simulated by TROPGLEAMS.

## 4.2.2. PIRACICABA PLOT STUDY

This study was also conducted in Piracicaba, Sao Paulo, and was described by Marciano (1999), Oliveira (2000), and Oliveira et al. (2001). The study consisted of 27 areas of 100 $m^2$ each fertilized with chemical fertilizer and different doses of sewage sludge and municipal solid residue. The treatments in which sugarcane was fertilized with chemical fertilization and sewage sludge were used in this model validation and the fertilization of each treatment is described in table 4.9. Physical and chemical characteristics of the soil of the areas are described in table 4.10. Climatic data used as model input is shown in table 4.11 and daily rainfall is shown in table C.2 of Appendix C.

**Table 4.9.** Applied mineral nitrogen and sewage sludge to each treatment of the Piracicaba plot study.

| Treatment | Sewage sludge (Mg/ha dry sludge) | | Mineral N | |
|---|---|---|---|---|
| | 1996 | 1997 | 1996 | 1997 |
| FertMin | | | 70 | 120 |
| Sludge dose A | 33 | 37 | | |
| Sludge dose B | 66 | 74 | | |
| Sludge dose C | 99 | 110 | | |

**Table 4.10.** Soil chemical and physical characteristics used as model input in the simulations for the Piracicaba plot study.

| Depth | pH $CaCl_2$ | Org. C | sand | Silt | Clay |
|---|---|---|---|---|---|
| m | | ---------------------------g $kg^{-1}$ | ------------------------------------ | | |
| 0-0.20 | 4.1 | 9.29 | 524 | 141 | 335 |
| 0.20-0.40 | 4.1 | 8.13 | 442 | 116 | 442 |
| 0.40-0.60 | 4.1 | 6.38 | 429 | 90 | 481 |

| Depth | Effective sat. conductivity | Porosity | Field capacity | Wilting point | P |
|---|---|---|---|---|---|
| (m) | cm/h | $cm^3/cm^3$ | cm/cm | cm/cm | mg $dm^{-3}$ |
| 0-0.20 | 23 | 0.5 | 0.22 | 0.13 | 3 |
| 0.20-0.40 | 23 | 0.5 | 0.2 | 0.13 | 2 |
| 0.40-0.60 | 23 | 0.5 | 0.2 | 0.13 | 1 |

**Table 4.11.** Climatic data used as model input in the simulations of the Piracicaba plot study.

| Year | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean monthly maximum temperature $^{o}C$ | | | | | | | | | | | |
| 1996 | 31.2 | 31.8 | 30.5 | 29.5 | 26.2 | 25.6 | 25.1 | 28.6 | 27.1 | 29.4 | 29.1 | 30.6 |
| 1997 | 29.7 | 31.7 | 29.9 | 28.7 | 25.7 | 23.5 | 26.1 | 27.8 | 29.4 | 29.4 | 30.3 | 31.1 |
| 1998 | 31.7 | 30.0 | 31.0 | 28.4 | 25.0 | 24.1 | 25.9 | 27.4 | 27.7 | 27.1 | 30.0 | 30.0 |
| | Mean monthly minimum temperature $^{o}C$ | | | | | | | | | | | |
| 1996 | 20.3 | 20.1 | 19.4 | 16.7 | 12.8 | 11.0 | 9.5 | 11.3 | 15.0 | 16.8 | 17.8 | 19.8 |
| 1997 | 20.1 | 19.5 | 17.5 | 15.0 | 12.6 | 11.4 | 11.3 | 11.2 | 15.3 | 17.3 | 19.5 | 19.7 |
| 1998 | 20.6 | 20.5 | 19.8 | 17.0 | 12.8 | 9.9 | 10.8 | 14.4 | 15.3 | 16.3 | 16.5 | 19.2 |
| | Mean monthly solar radiation $MJ/m^2$.day | | | | | | | | | | | |
| 1996 | 18.4 | 17.5 | 16.0 | 15.0 | 12.6 | 11.7 | 12.6 | 15.6 | 15.0 | 17.1 | 17.1 | 17.2 |
| 1997 | 15.1 | 17.8 | 15.9 | 14.9 | 12.8 | 10.5 | 12.9 | 15.2 | 14.3 | 17.1 | 17.9 | 20.1 |
| 1998 | 19.2 | 17.4 | 15.9 | 14.9 | 12.3 | 11.7 | 12.5 | 13.0 | 14.0 | 15.5 | 19.9 | 18.5 |
| | Mean monthly wind velocity km/day | | | | | | | | | | | |
| 1996 | 122 | 138 | 131 | 142 | 114 | 142 | 145 | 153 | 168 | 158 | 169 | 125 |
| 1997 | 122 | 120 | 147 | 122 | 118 | 110 | 98 | 127 | 142 | 165 | 138 | 126 |
| 1998 | 117 | 88 | 104 | 122 | 110 | 117 | 120 | 129 | 147 | 165 | 167 | 113 |
| | Mean monthly dew point temperature $^{o}C$ | | | | | | | | | | | |
| 1996 | 22.2 | 23.1 | 22.2 | 19.1 | 16.1 | 14.0 | 12.7 | 13.9 | 16.6 | 19.4 | 19.7 | 22.5 |
| 1997 | 22.6 | 20.9 | 18.7 | 16.8 | 15.3 | 14.7 | 14.6 | 14.1 | 16.9 | 18.9 | 21.6 | 21.6 |
| 1998 | 22.2 | 23.5 | 22.8 | 19.3 | 15.6 | 14.7 | 15.0 | 16.7 | 17.1 | 18.8 | 18.9 | 21.3 |

Sugarcane was planted in December of 1996 and harvested in October of 1997 and October of 1998. Soil water suction extractors were installed at 30 and 60 cm soil depth and seven composite soil water samples were collected and taken to laboratory for analysis of total Kjeldahl nitrogen (TKN), nitrate, and ammonium. The dates of extraction were December 16, 17 and 28, 1997 and February 12 and 17, May 6 and 7, June 9 and 10, September 21 and 22, October 20 and 21, and December 14 and 15 of 1998. In addition, soil samples were collected at depths 0-30 and 30-60 cm on November 1, 1997 and December 22-23, 1998 for analysis of TKN, nitrate, and ammonium.

TROPGLEAMS was run simulating treatment Sludge dose A in order to choose the best value for NCrit and maximum rate of nitrification. Default values for nutrient initial conditions were used, since they were not considered important for model comparison. Values of pH, clay and silt content, field capacity, wilting point, and porosity were taken from Marciano (1999) and Oliveira (2000) and are shown in table 4.10. Concentrations of nitrate and ammonium in soil solution are not output variables in GLEAMS. In order to compare model results with measured concentration of solution extracted from the soil, a common part of GLEAMS and TROPGLEAMS code was modified and two new user-selected output variables were included. They are nitrate and ammonium concentration in soil solution (mg/L), with code numbers 952 and 954. These code numbers were included in the hydrology input files for these simulations in order to include nitrate and ammonium concentration in the output files.

Both GLEAMS and TROPGLEAMS were run simulating all treatments described in table 4.9. Model results of nitrate and ammonium concentrations in soil solution (mg/L) and concentrations of TKN and ammonium + nitrate in soil (mg/kg) at 30 and 60 cm depths were graphed along with their respective measured values. Measured concentrations of soil solution extracted at 30 cm soil depth were compared with averaged values simulated for the fourth and fifth layers (20-30 and 30-40 cm depth, respectively), while those extracted at 60 cm soil depth were compared with values simulated for the seventh layer (50-60 cm depth). RMSE between measured and simulated values of nitrate and ammonium concentrations in soil solution was calculated for each treatment. In this case, each measured value was compared with the average daily concentration of $NH_4^+$-N or $NO_3^-$-N over the period of sampling. No statistic was calculated for concentrations of TKN and ammonium + nitrate in soil because only two measured values of each variable were available.

The best performance of TROPGLEAMS simulating the treatment Sludge dose A was using 0.01 as the Ncrit value and 0.7 as the maximum value of the nitrification pH-factor. Figures 4.22 and 4.23 show measured and simulated concentrations of ammonium in soil solution at 30 and 60 cm depth for treatment Sludge dose A. Measured values are averaged for different sampling periods and are shown as lines covering the sampling periods.

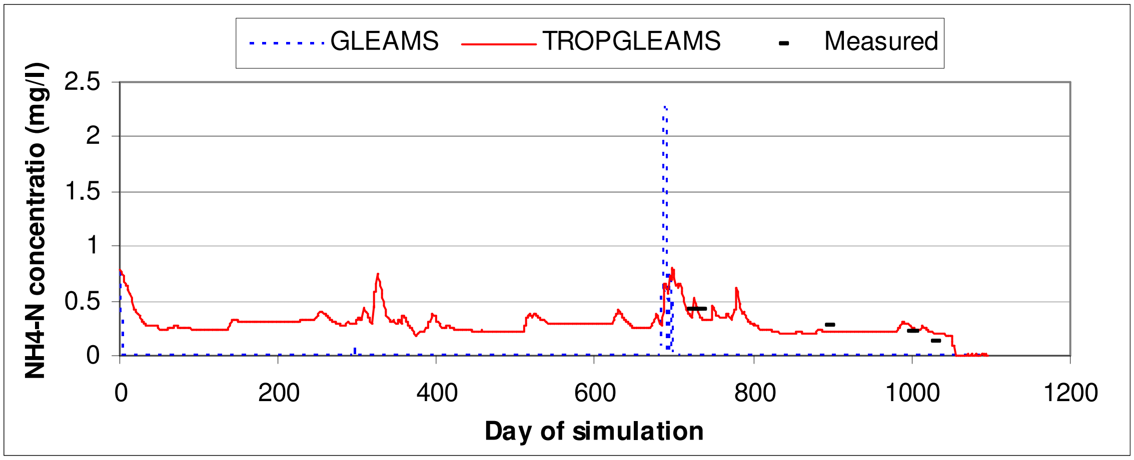


**Figure 4.22.** Measured and simulated values of $NH_4^+$-N in soil solution at 30 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

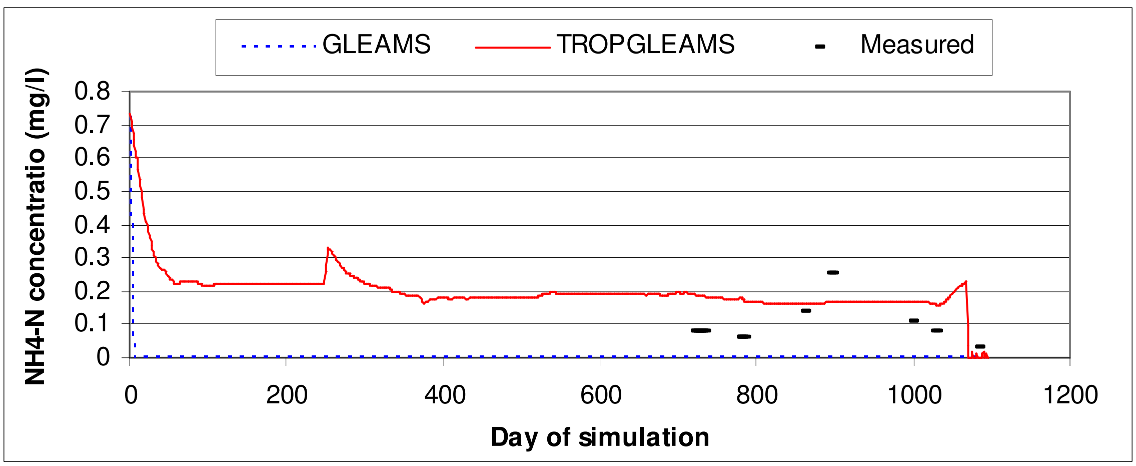


**Figure 4.23.** Measured and simulated values of $NH_4^+$-N in soil solution at 60 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

It can be observed that, while TROPGLEAMS kept some concentration of $NH_4^+$-N in both soil depths during the whole period of simulation, GLEAMS simulated three peaks of ammonium (in the beginning, due to the initial concentration of ammonium, and after sludge applications) and concentration zero in the rest of the simulation at 30 cm depth. At 60 cm depth, values are all zero, except in the first three days of simulation. The high rate of nitrification in GLEAMS made all mineralized nitrogen be transformed to nitrate in the same day, while in TROPGLEAMS nitrification was limited by a maximum rate, set as 0.7 for this soil, as commented above. RMSE between measured and simulated values was 0.28 for TROPGLEAMS and 0.06 for GLEAMS.

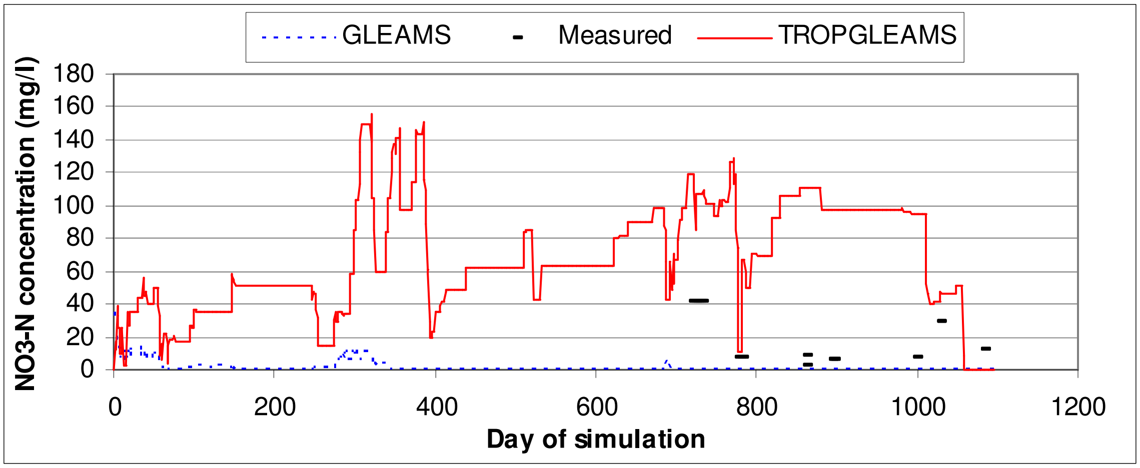


**Figure 4.24.** Measured and simulated values of $NO_3^-$-N in soil solution at 30 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

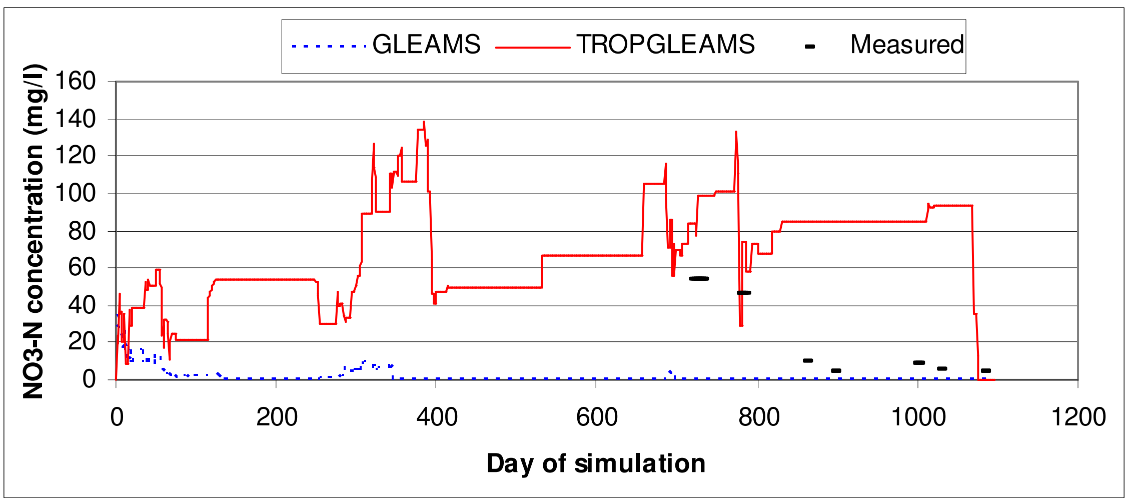


**Figure 4.25.** Measured and simulated values of $NO_3^-$-N in soil solution at 60 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

Figures 4.24 and 4.25 show observed and measured values of nitrate concentration in soil solution at depths of 30 and 60 cm. Values of nitrate simulated by GLEAMS showed the same trend as ammonium, with peaks at the beginning of simulation and after sludge application, and zero concentration in the remaining period. In contrast, nitrate values from TROPGLEAMS were positive until the end of the simulation, when there was a sharp decrease in nitrate concentration, caused by significant leaching of N from high rainfall amounts, and more importantly, due to the immobilization of nitrogen caused by the introduction of a large amount of crop residue with high C:N ratio on the day of harvest.

A decrease in measured values is observed in both depths after the second sludge application, but values from TROPGLEAMS did not show this trend. The high mobility of nitrate and the number of factors interacting in its calculation, along with the methodology used to collect measured data are sources of uncertainty that make comparisons between measured and simulated values difficult. The soil solution extractor disturbs the movement of water through the soil profile by increasing the velocity of downward movement above the extractor tip, promoting upward movement below the tip, and lateral movement in its proximity. To account for these disturbances, values measured at 30 cm were compared with the average soil solution concentration simulated for layers 4 and 5, which end at 30 and 40 cm depth, respectively. Values measured at 60 cm depth were compared only with values of layer 7, the last layer simulated, although it is known that soil water of layers below the extractor tip also integrated soil water samples. RMSE between measured and simulated values were 24.2 and 67.4 for the GLEAMS and TROPGLEAMS, respectively. For its calculation, data from depths 30 and 60 cm were used. The lower RMSE for GLEAMS has to be interpreted with care. Even with higher RMSE, TROPGLEAMS results can be considered better, because 13 out of 14 data from GLEAMS were zero.

Figures 4.26 and 4.27 show observed and measured values of TKN in layers 0-30 and 30-60 cm depth. The difference in initial values of TKN is due to different C:N ratios used by the models to calculate initial nitrogen concentrations: 10 for GLEAMS and 13 for TROPGLEAMS. While a small increase of TKN was measured in both soil layers between the end of the second and third years, for the 0-30 cm layer, GLEAMS simulated a step in the value of TKN on the day of sludge application, resulting in an increase larger than that observed, while TROPGLEAMS simulated two peaks of TKN after sludge application followed by a decay on its value until the initial value was reached. For the 30-60 cm layer, while GLEAMS kept the same value of TKN during the whole period, a decrease was observed in the results of TROPGLEAMS. The limited number of observed data makes it impossible to draw conclusions about general results of GLEAMS and

TROPGLEAMS, but the available values do indicate improved performance of TROPGLEAMS, especially in the simulation of the first layer.

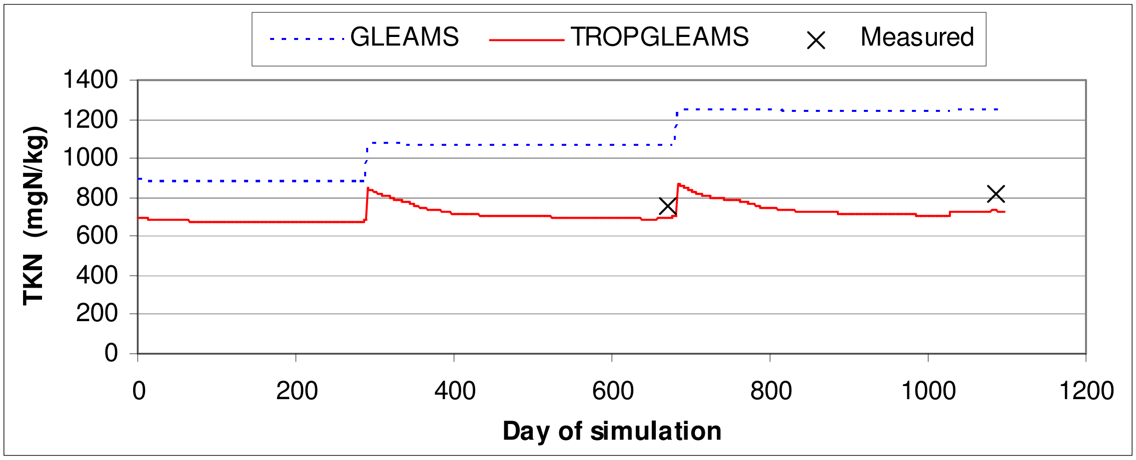


**Figure 4.26.** Measured and simulated values of TKN in layer 0-30 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

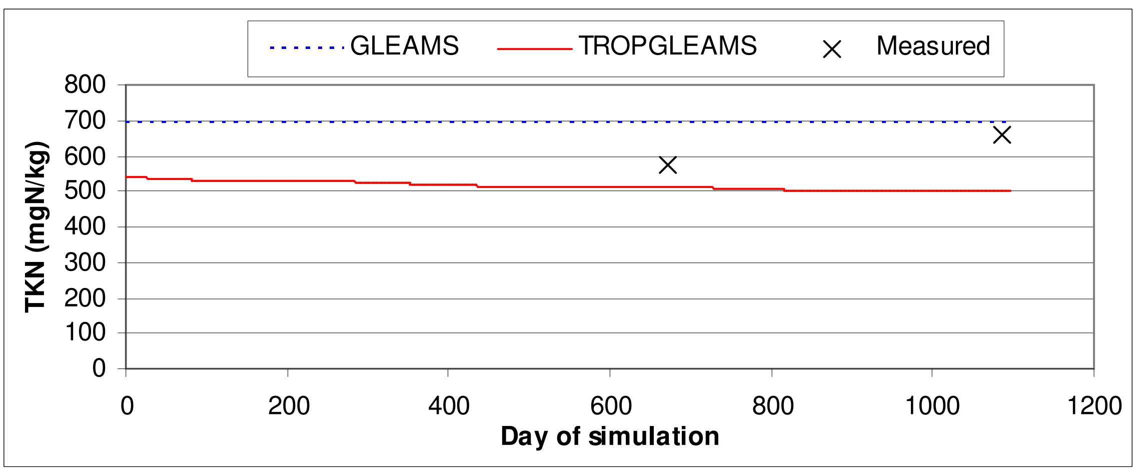


**Figure 4.27.** Measured and simulated values of TKN in layer 30-60 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

Silva et al. (2001) reported increases of $SO_4^{2-}$ in a tropical soil 484 days after application of different doses of sewage sludge. Because sulfur and nitrogen dynamics in soil are linked to the organic matter dynamics, high application of sludge is expected to increase TKN concentration, and this was observed in the treatment in discussion. A decrease in the rate of soil organic matter decomposition would certainly make

TROPGLEAMS results more closely match the trend observed in this treatment and the results of Silva et al. (2001). Future research on this subject is recommended.

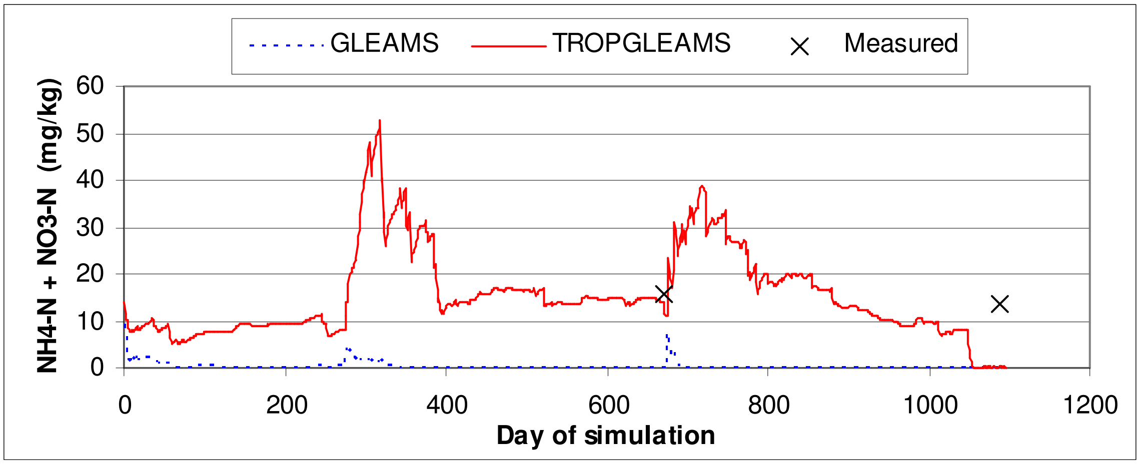


**Figure 4.28.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 0-30 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

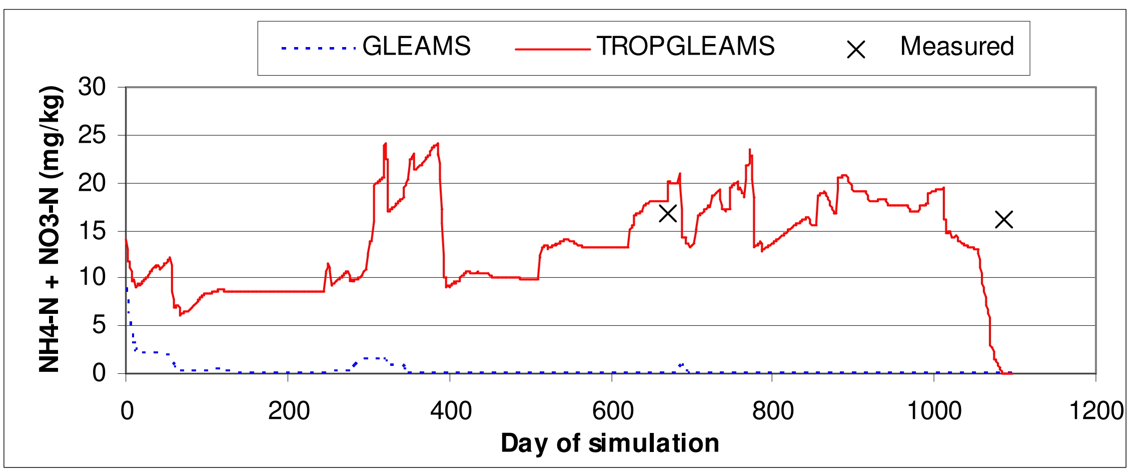


**Figure 4.29.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 30-60 cm depth from plots of treatment Sludge dose A of the Piracicaba plot study.

Figures 4.28 and 4.29 show observed and measured values of ammonium + nitrate in layers 0-30 and 30-60 cm depth. GLEAMS showed the same trend that was observed for concentrations in soil solution, with a value of zero for most of the period of simulation. TROPGLEAMS simulated positive values during the whole period, the its results were more representative of the measured values than the result of GLEAMS. The sharp decrease in mineral nitrogen concentration at the end of the simulation was explained previously. Both GLEAMS and TROPGLEAMS simulate the introduction of crop residue to the soil only on the day of harvest and both models consider the very high C:N ratio of sugarcane residue. With high humidity due to rainfall events in this period and high temperatures, high mineralization of crop residue was simulated and the immobilization of mineral N was a consequence, which resulted in the decrease of mineral N concentration simulated by TROPGLEAMS.

Figures 4.30, 4.31, and 4.32 show measured and simulated values of $NH_4^+$-N concentration in soil solution at 30 and 60 cm depths for treatments Mineral fertilization, Sludge dose B, and Sludge dose C.

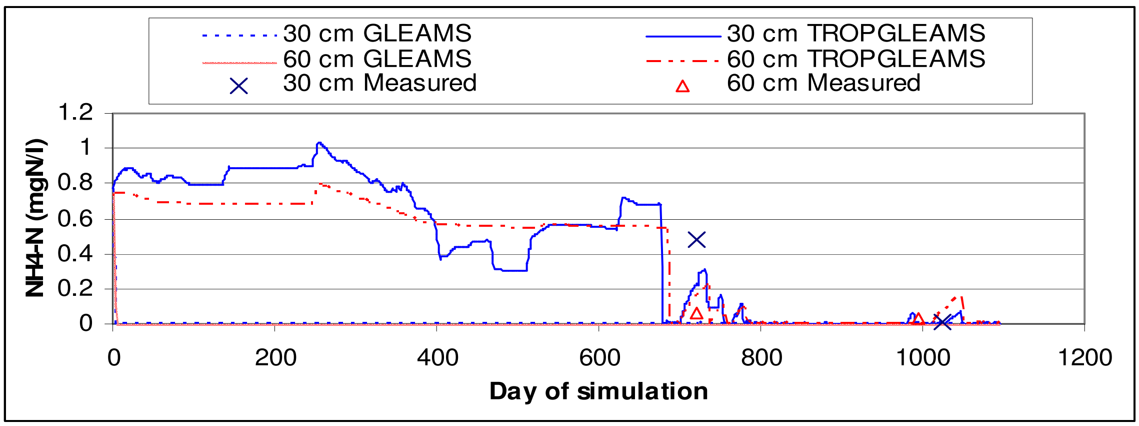


**Figure 4.30.** Measured and simulated values of $NH_4^+$-N in soil solution at 30 and 60 cm depths from plots of treatment Mineral fertilization of the Piracicaba plot study.

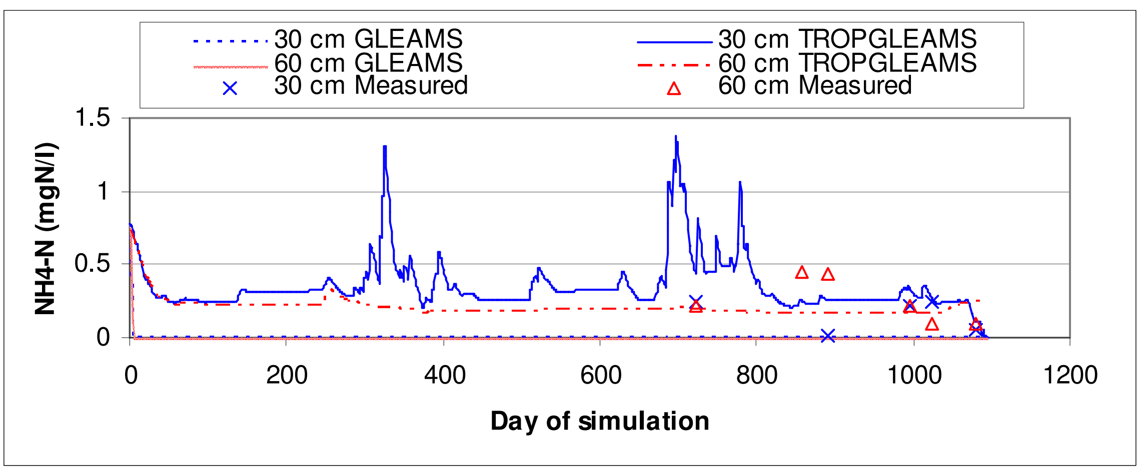


**Figure 4.31.** Measured and simulated values of $NH_4^+$-N in soil solution at 30 and 60 cm depths from plots of treatment Sludge dose B of the Piracicaba plot study.

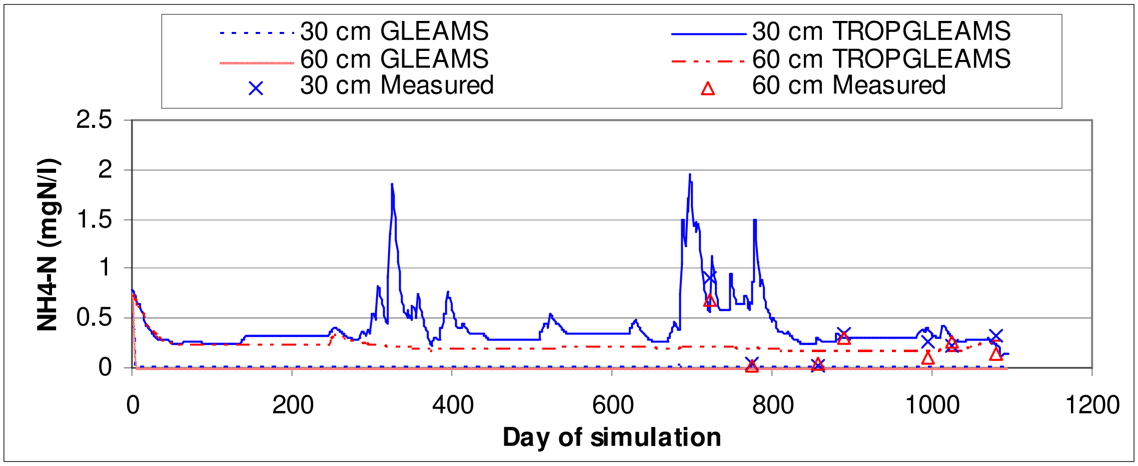


**Figure 4.32**. Measured and simulated values of $NH_4^+$-N in soil solution at 30 and 60 cm depths from plots of treatment Sludge dose C of the Piracicaba plot study.

For these three treatments, as for treatment Sludge dose A, TROPGLEAMS showed better results than GLEAMS in the simulation of $NH_4^+$-N concentration in soil solution, since results of GLEAMS were zero during most of the period of the three simulations, while TROPGLEAMS resulted in positive values most of the time. For the FertMin treatment, no significant concentration of ammonium was measured in soil solution after day 776, except a concentration of 0.01 mg/L measured on day 1024. TROPGLEAMS simulated $NH_4^+$-N concentration very well; it predicted a value very close to the measured one on day 722 and simulated a zero concentration over almost 200 days, when measured values were below the detection limit.

For treatments Sludge dose B and Sludge dose C, overall, TROPGLEAMS overpredicted values of $NH_4^+$-N concentration. The overprediction was more significant for 60 cm depth. For concentrations at 30-cm depth, the peaks of $NH_4^+$-N after the second sludge application simulated by TROPGLEAMS were proportional to the amount of applied sludge (1.5 and 2.0 mgN/L for dose B and dose C, respectively); however, this proportionality was not observed in the measured values. Concentrations measured on day 722, 39 days after sludge application, were 0.24 and 0.9 for dose B and dose C, respectively, but a higher value for treatment B was expected, since values measured on the other days were between 0.01 and 0.25.

Figures 4.33 to 4.38 show measured and simulated values of $NO_3^-$-N concentration in soil solution at 30 and 60 cm depths for treatments Mineral fertilization, Sludge dose B, and Sludge dose C.

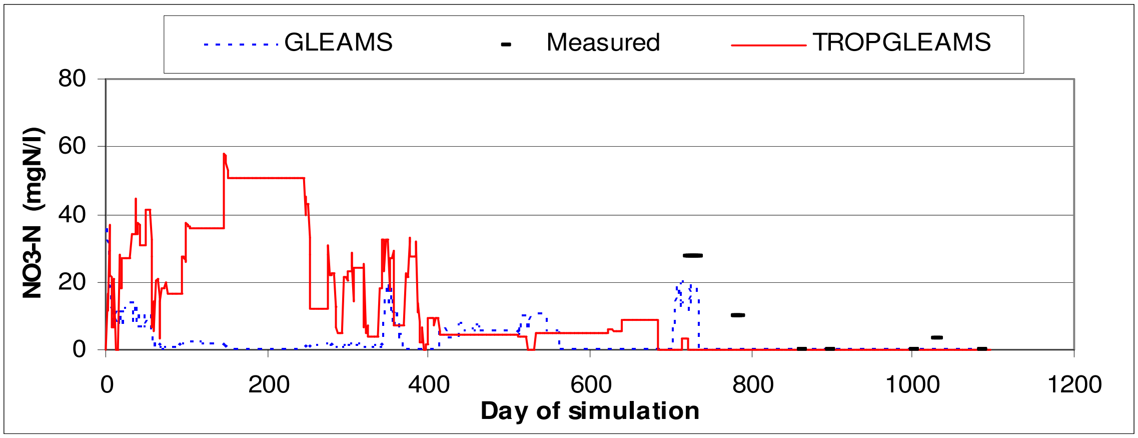


**Figure 4.33.** Measured and simulated values of $NO_3^-$-N in soil solution at 30 cm depth from plots of treatment Mineral fertilization of the Piracicaba plot study.

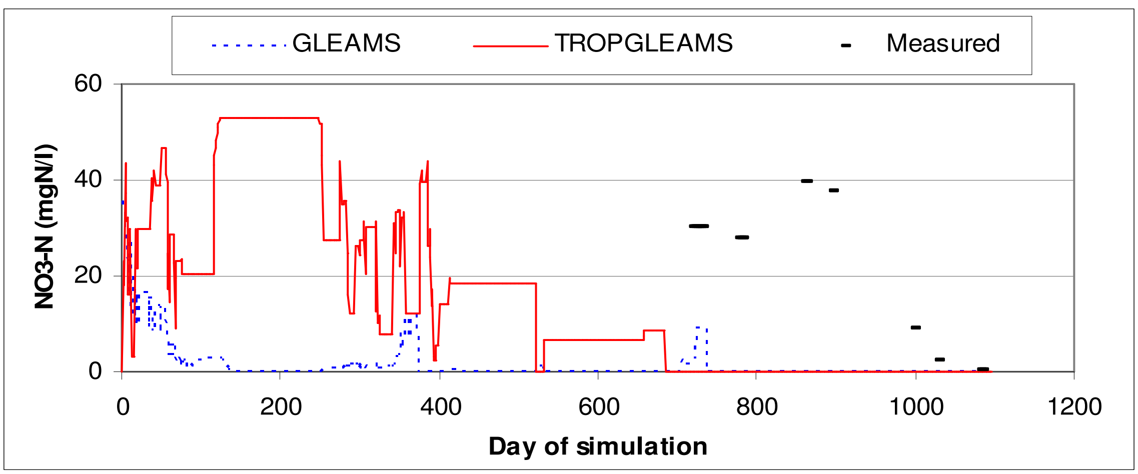


**Figure 4.34.** Measured and simulated values of $NO_3^-$-N in soil solution at 60 cm depth from plots of treatment Mineral fertilization of the Piracicaba plot study.

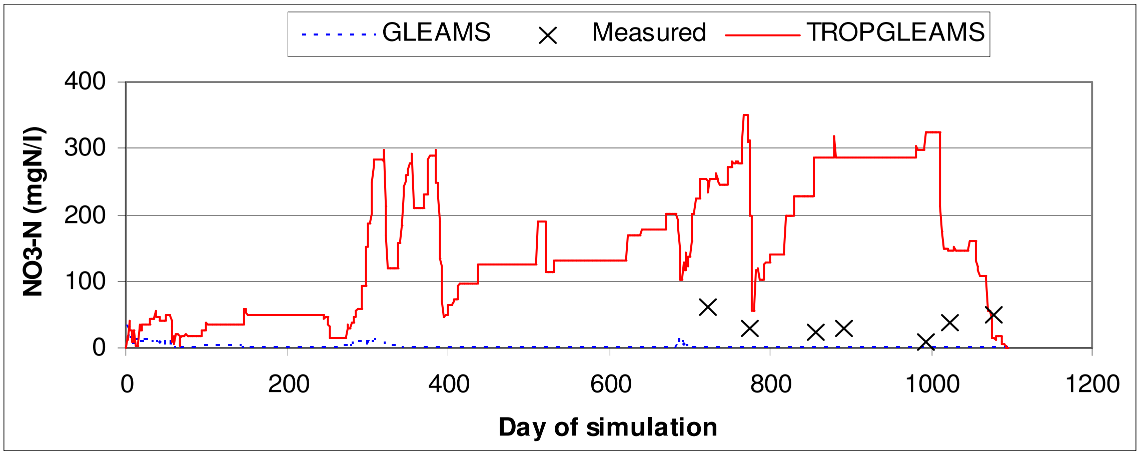


**Figure 4.35.** Measured and simulated values of $NO_3^-$-N in soil solution at 30 cm depth from plots of treatment Sludge dose B of the Piracicaba plot study.

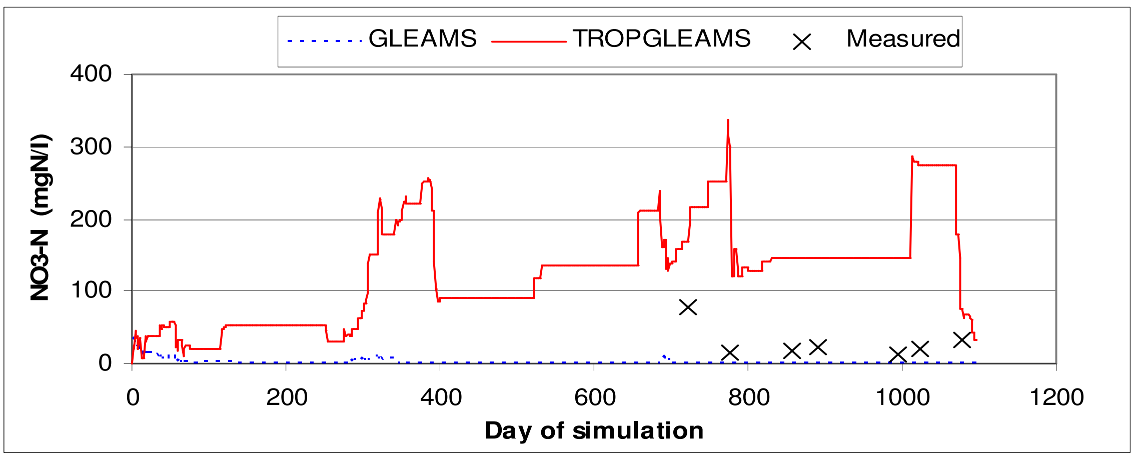


**Figure 4.36.** Measured and simulated values of $NO_3^-$-N in soil solution at 60 cm depth from plots of treatment Sludge dose B of the Piracicaba plot study.

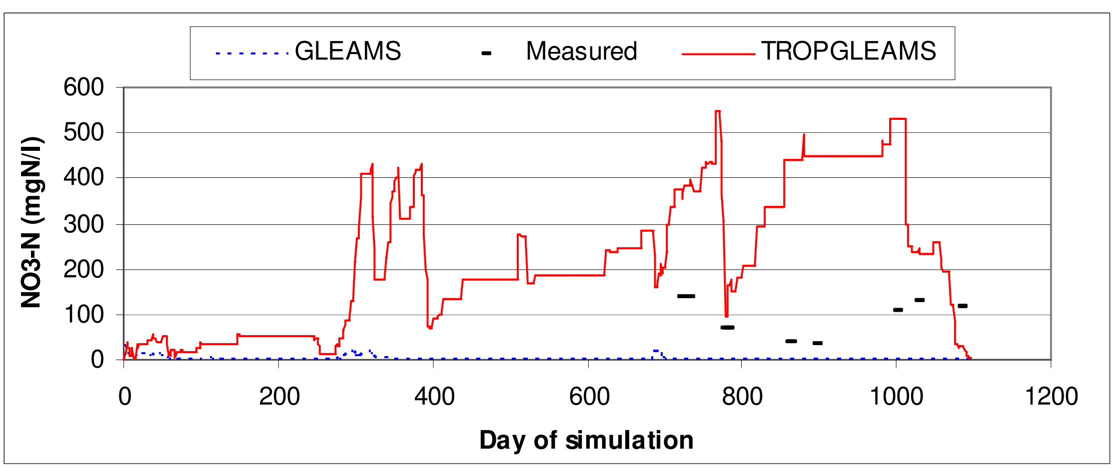


**Figure 4.37.** Measured and simulated values of $NO_3^-$-N in soil solution at 30 cm depth from plots of treatment Sludge dose C of the Piracicaba plot study.

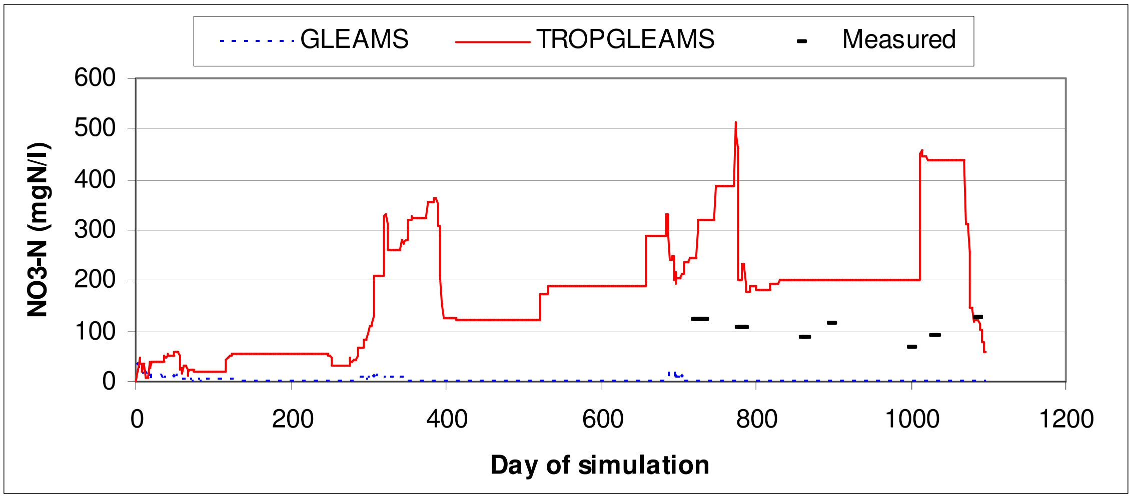


**Figure 4.38.** Measured and simulated values of $NO_3^-$-N in soil solution at 60 cm depth from plots of treatment Sludge dose C of the Piracicaba plot study.

For the treatment Mineral fertilization, the sharp decrease of $NO_3^-$-N in soil solution simulated by both models at 30 cm depth was caused mainly by the high amount of mineral nitrogen the models immobilized during the degradation of the crop residue that was incorporated into soil by the model on the day of harvesting. In 55 days, all nitrogen applied (120 kgN/ha) was consumed. Other factors were involved in this fast decay, including denitrification and plant uptake, but the most significant was N immobilization. The TROPGLEAMS simulation for layer 6, which ends at 50 cm depth, remained at zero concentration after day 696, indicating that the results of layer 7, which ends at 60-cm depth, were not correlated to the application of mineral nitrogen on day 699. Immobilization of mineral N was not high in this layer, because both the original and modified GLEAMS distribute crop residue to soil layers according to their depths and the quantity introduced to layer 7 was very low in comparison to the quantity of less deep layers.

The results of GLEAMS for treatments Sludge dose B and Sludge dose C, showed the same trend as for treatment Sludge dose A, in which a value equal to zero was observed for almost the whole simulation. The quantity of mineral nitrogen in the sewage sludge applied in the second year of simulation (192 and 286 kg N /ha for dose B and dose C, respectively) along with the quantity of organic nitrogen (1415 and 2102 kg/ha) were higher than N immobilized by TROPGLEAMS and the model overestimated values of $NO_3^-$-N in soil solution. A reduction of the rates of nitrification would reduce this overestimation, but an increase of $NH_4^+$-N concentration of would be expected, reducing the goodness-of-fit of the model for $NH_4^+$-N. The application of TROPGLEAMS to more areas with measured values of $NO_3^-$-N and $NH_4^+$-N is suggested in order to have a fine adjustment of the nitrification rates.

Figures 4.39, 4.40, and 4.41 show measured and simulated values of TKN in layers 0-30 and 30-60 cm depth for treatments Mineral fertilization, Sludge dose B, and Sludge dose C.

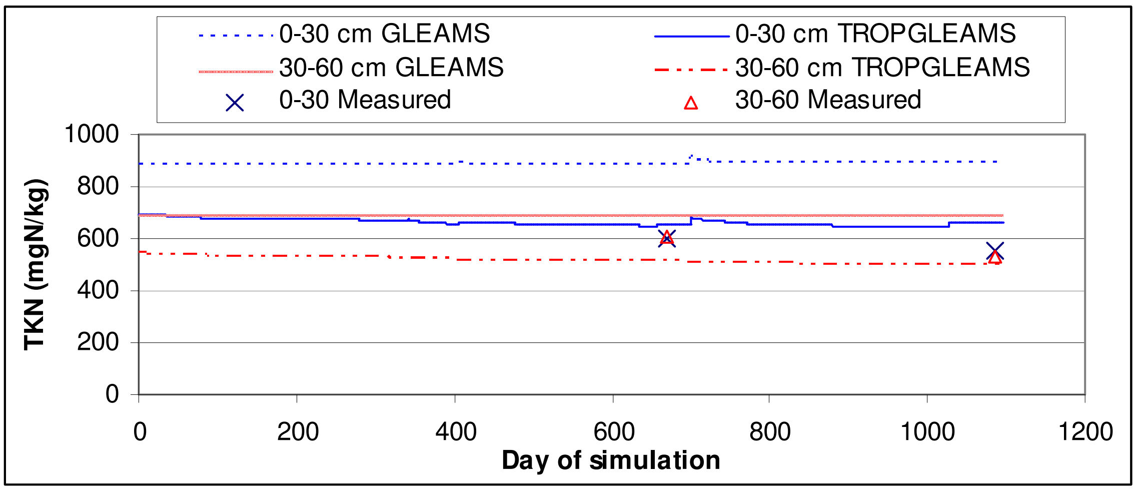


**Figure 4.39.** Measured and simulated values of TKN in layers 0-30 and 30-60 cm depth from plots of treatment Mineral fertilization of the Piracicaba plot study.

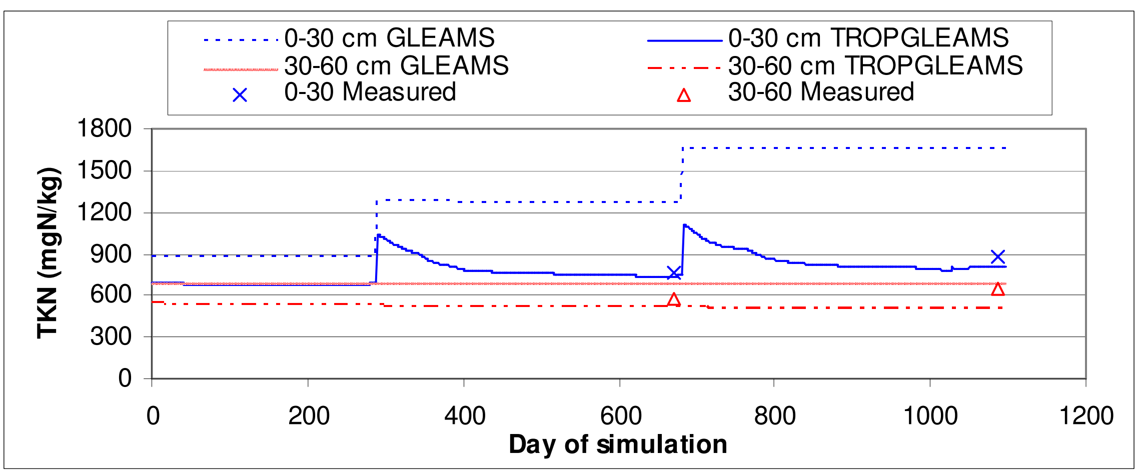


**Figure 4.40.** Measured and simulated values of TKN in layers 0-30 and 30-60 cm depth from plots of treatment Sludge dose B of the Piracicaba plot study.

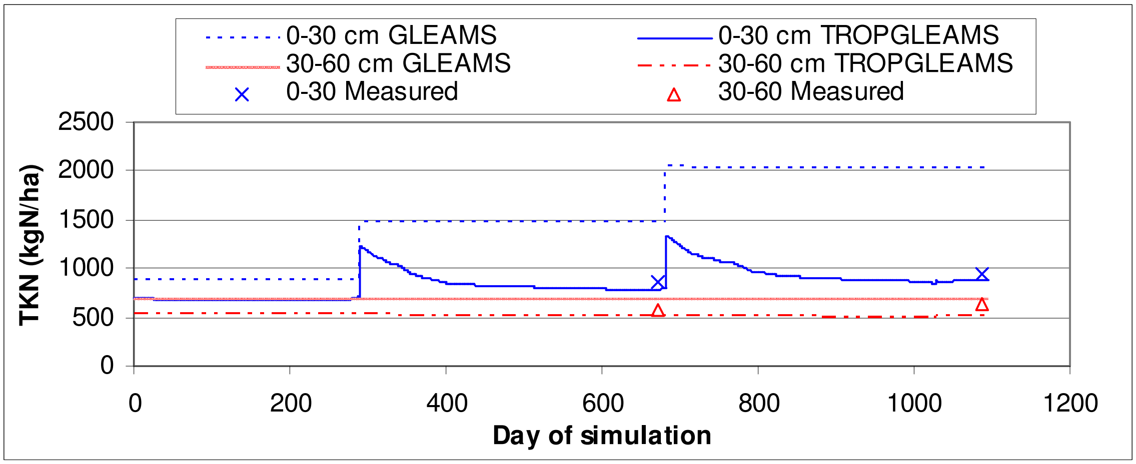


**Figure 4.41.** Measured and simulated values of TKN in layers 0-30 and 30-60 cm depth from plots of treatment Sludge dose C of the Piracicaba plot study.

For treatments Mineral fertilization, Sludge dose B, and Sludge dose C in the 30-60 cm depth layer, both models predicted the same results for TKN that were simulated for treatment Sludge dose A, but measured values varied. From day 671 to day 1087, a decrease was measured in the treatment Mineral fertilization, while increases were observed in treatments Sludge doses B and C; however, the increases were not directly proportional to the amount of applied N, since TKN was higher for treatment Sludge dose B than for dose C. Neither GLEAMS nor TROPGLEAMS simulate the movement of organic nitrogen to lower layers, which may have some significance in soils with a high quantity of macro pores, such as the soil used in the study that was the source of the measured data.

For the 0-30 cm depth layer, GLEAMS overpredicted values of TKN in all treatments. In contrast, TROPGLEAMS overpredicted slightly for the treatment Mineral fertilization and predicted values very close to the measured ones in the other two treatments. In treatment Mineral fertilization, the overprediction of GLEAMS was clearly caused by the values set during the calculation of initial N concentrations. For treatments Sludge dose B and Sludge dose C, GLEAMS simulated the same steps observed in the results for treatment Sludge dose A, increasing the values of TKN after each sludge application with no decay in its value. For TROPGLEAMS, peaks in TKN values on the day of sludge application were followed by decaying concentrations until equilibrium concentrations were reached.

With only two measured values of TKN, it is inappropriate to draw conclusions on the superiority of TROPGLEAMS over GLEAMS, but the better performance of TROPGLEAMS in the simulation of TKN in all treatments, especially the one that did not receive sludge, shows that the changes made to the code of the original model to calculate initial values was an improvement that is very appropriate for the soil of the plots planted with sugarcane used in this model validation.

Figures 4.42 to 4.47 show measured and simulated concentrations of mineral nitrogen ($NH_4^+$-N + $NO_3^-$-N) in layers 0-30 and 30-60 cm depth for treatments Mineral fertilization, Sludge dose B, and Sludge dose C.

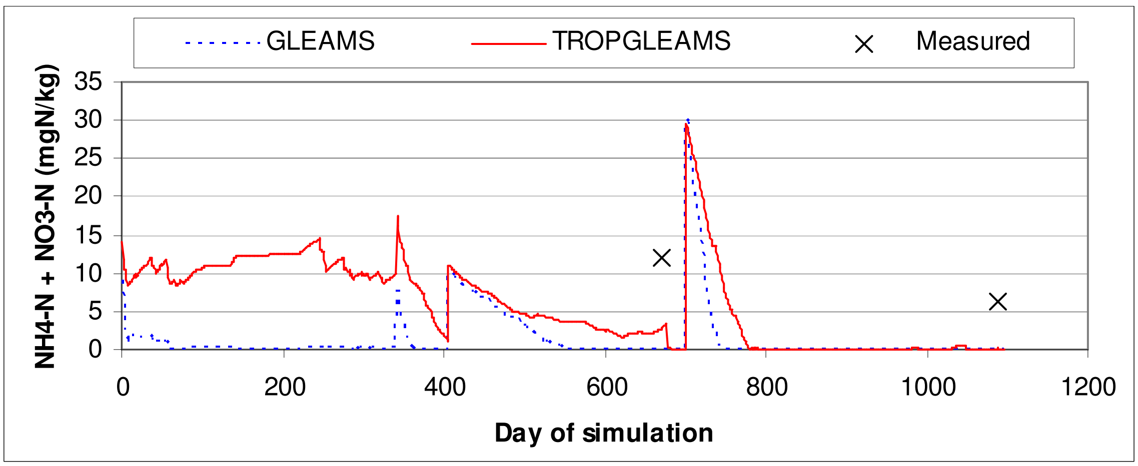


**Figure 4.42.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 0-30 cm depth from plots of Mineral fertilization treatment of the Piracicaba plot study.

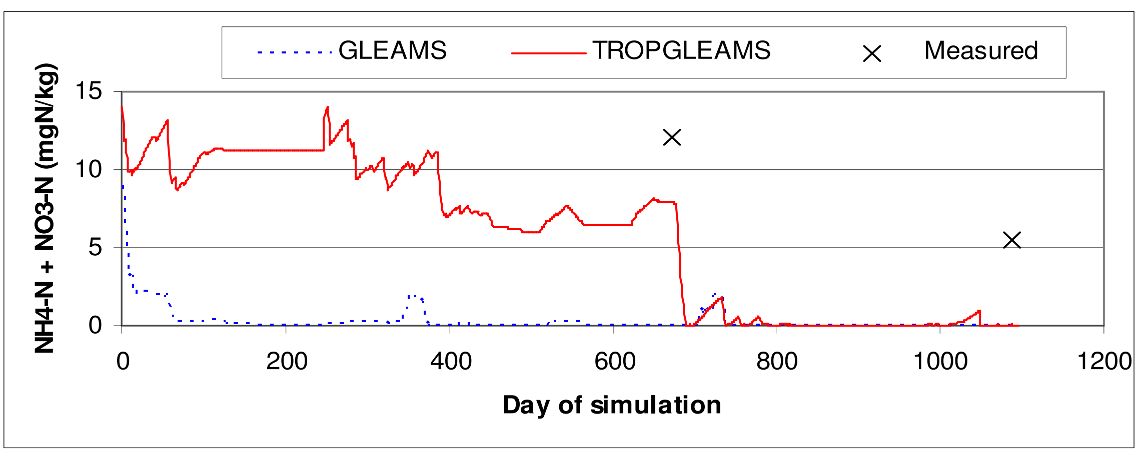


**Figure 4.43.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 30-60 cm depth from plots of Mineral fertilization treatment of the Piracicaba plot study.

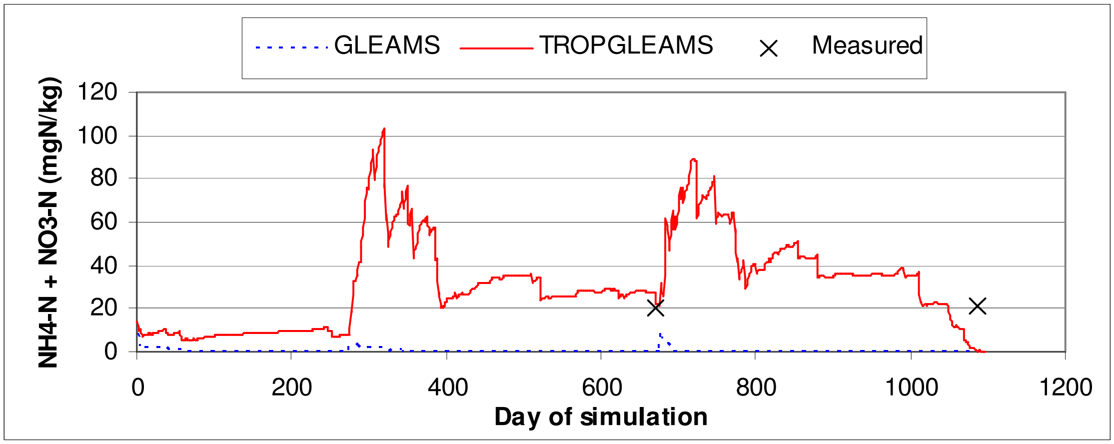


**Figure 4.44.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 0-30 cm depth from plots of treatment Sludge dose B of the Piracicaba plot study.

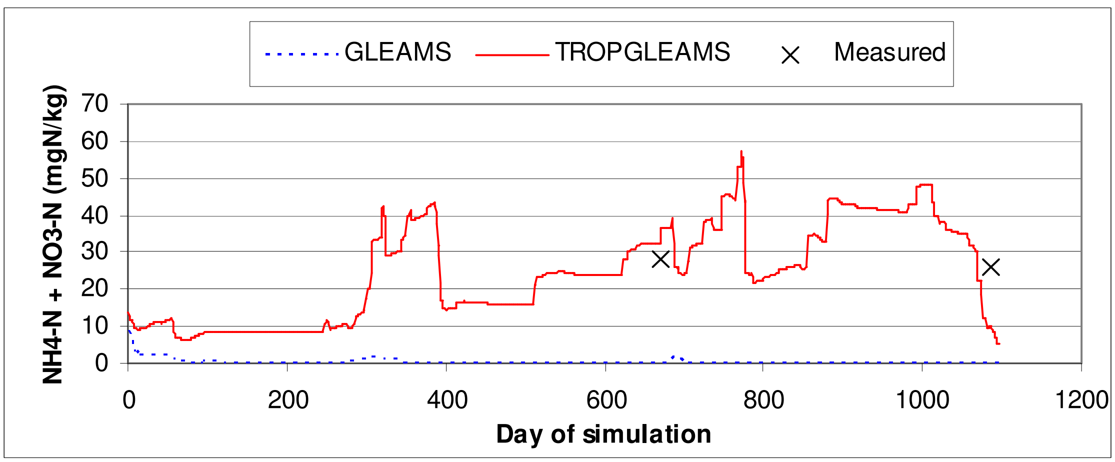


**Figure 4.45.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 30-60 cm depth from plots of treatment Sludge dose B of the Piracicaba plot study.

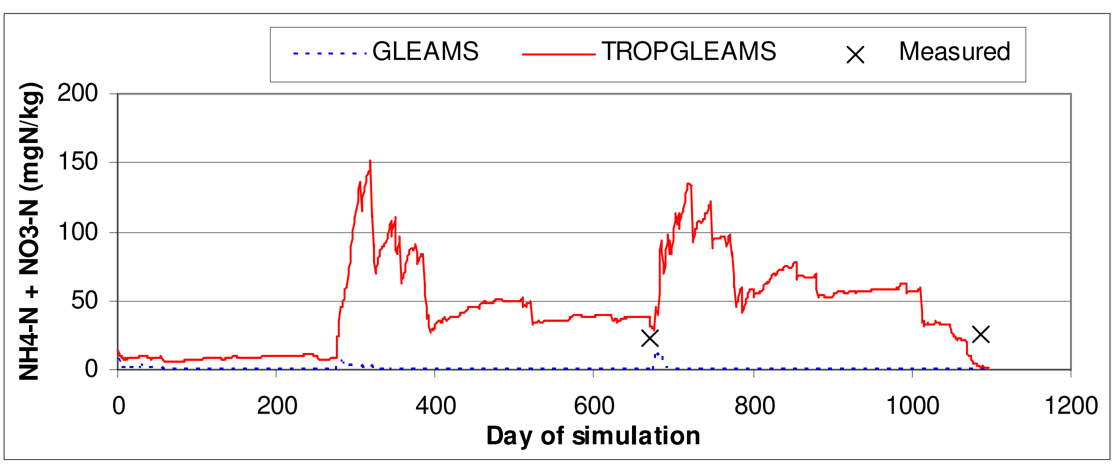


**Figure 4.46.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 0-30 cm depth from plots of treatment Sludge dose C of the Piracicaba plot study.

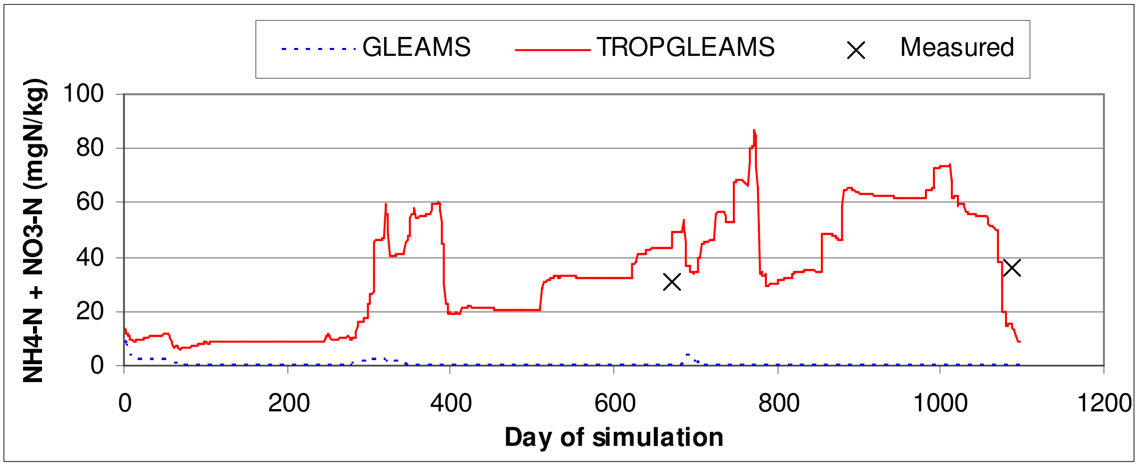


**Figure 4.47.** Measured and simulated values of $NH_4^+$-N + $NO_3^-$-N in layer 30-60 cm depth from plots of treatment Sludge dose C of the Piracicaba plot study.

Figures 4.42 to 4.47 basically repeat what was observed in the figures related to the concentration of $NH_4^+$-N and $NO_3^-$-N in soil solution. GLEAMS simulated values of zero in almost all simulations while TROPGLEAMS predicted positive values for the entire simulation, except for underpredictions of measured values in the end of the simulations of sludge treatments and after the day of harvest in treatment Mineral fertilization. For the treatments Sludge dose B and Sludge dose C, measured values were very close to the simulated ones, but the decrease in simulated values at the end of both simulations was not matched by decreases in measured values. This fact indicates that the C:N ratio of 80 may be too high, especially for the roots of sugarcane.

Table 4.11 shows RMSE between measured and simulated concentrations of $NH_4^+$-N and $NO_3^-$-N in soil solution using GLEAMS and TROPGLEAMS. For the calculation of the RMSE for $NH_4^+$-N, 4, 11, and 14 measured values were available for treatments Mineral Fertilization, Sludge dose B, and Sludge dose C, respectively. For $NO_3^-$-N, 14 measured values were available for all treatments. On the dates when measured values of ammonium were available, all values simulated by GLEAMS were zero, while only one simulated by TROPGLEAMS was zero. For nitrate, 10, 6, and 13 values simulated by GLEAMS for treatments Mineral fertilization, Sludge dose B, and Sludge dose C, respectively, were zero, while for TROPGLEAMS, only 8 values for treatment Mineral fertilization were zero.

**Table 4.12.** RMSE between measured and simulated values of $NH_4^+$-N in soil solution extracted at 30 and 60 cm depth from plots of treatments Mineral fertilization, Sludge dose B, and Sludge dose C of the Piracicaba plot study.

| Treatment | $NH_4^+$-N | | $NO_3^-$-N | |
|---|---|---|---|---|
| | GLEAMS | TROPGLEAMS | GLEAMS | TROPGLEAMS |
| Min. Fertilization | 0.13 | 0.07 | 18.90 | 19.87 |
| Sludge Dose B | 0.22 | 0.17 | 158.60 | 185.56 |
| Sludge Dose C | 0.36 | 0.32 | 101.01 | 250.26 |

Table 4.12 shows that TROPGLEAMS only has a smaller RMSE than GLEAMS for $NH_4^+$-N. For $NO_3^-$-N, TROPGLEAMS had higher RMSE than GLEAMS for all treatments. The smaller values of RMSE for GLEAMS have to be evaluated with care because of the number of days in which model results were zero.

# 4.2.3. LAGES PLOT STUDY

A study conducted in Lages, Santa Catarina (Latitude: S 27°49'00"), and described by Guadagnin (2003), consists of an experiment performed between November of 1999 and November of 2001 using 10 plots with dimensions 22.1 x 3.5 m under natural rainfall. The plots were delimited by 2.00 x 0.20 m plates positioned in the soil to 10 cm depth. At the lower end of each plot a collector system was installed. It consisted of a gutter connected to a sedimentation tank (750 liter capacity) through a PVC tube. The sedimentation tank was connected to second tank of equal capacity through a divisor that allowed the passage of 1/9 of the runoff water. After the occurrence of each erosive rainfall, the depth of runoff was measured and samples of water and sediment were collected for analysis.

The following treatments were considered by Guadagnin (2003): disk plowing + twice leveling harrow without plant covering, rotation of wheat and soybean with three different soil management systems, and rotation of bean, common vetch, corn, and oat, also with three different soil management systems. The results from the wheat/soybean rotation plots were used in this model validation. The three soil management systems (treatments) considered in the rotation were conventional tillage, chisel + disk harrow, and no-tillage. The timeline of the activities is shown in table 4.13.

**Table 4.13.** Activities performed in the plots planted with a wheat/soybean rotation in the Lages plot study (Guadagnin (2003).

| Date | Activity |
|---|---|
| 11/1999 | Tillage: Disk plow + 2 Disk harrow for conventional tillage or Chisel + 2 Disk harrow for chisel + disk harrow managements |
| 11/1999 | Plant soybean |
| 05/2000 | Harvest soybean |
| 05/2000 | Tillage: Disk plow + 2 Disk harrow for conventional tillage or Chisel + 2 Disk harrow for chisel + disk harrow managements |
| 05/2000 | Plant wheat |
| 10/2000 | Wheat was plowed down by a rolling blade cutter |
| 11/2000 | Tillage: Disk plow + 2 Disk harrow for conventional tillage or Chisel + 2 Disk harrow for chisel + disk harrow managements |
| 11/2000 | Plant soybean |
| 04/2001 | Soybean was plowed down by a rolling blade cutter |
| 06/2001 | Tillage: Disk plow + 2 Disk harrow for conventional tillage or Chisel + 2 Disk harrow for chisel + disk harrow managements |
| 06/2001 | Plant wheat |
| 10/2001 | Harvest wheat |

The data collected from the plots and used in this model validation consisted of 51 measurements of $NO_3^-$-N, $NH_4^+$-N, and $PO_4$ concentrations in runoff from each plot, as well as total runoff and sediment yield for each crop period (total runoff and sediment yield between planting and harvesting of each crop). Climate data were obtained from the climatologic station of Lages and are shown in table 4.14. Guadagnin (2003) reported the amount of rainfall that occurred in the plots on the days of the 51 runoff measurements and since his data differed significantly from that of the climatologic station, they were used in the daily precipitation input file. Table C.3 of Appendix C shows daily precipitation used as model input. C-factor values were taken from Bertol et al. (2001) and from tables of the GLEAMS manual. Manning's n factor values were also taken from the GLEAMS manual using surface characteristics described by Guadagnin (2003). Soil chemical and physical characteristics were taken from Guadagnin (2003) and Bertol et al. (2001) and are shown in table 4.15. Since it was known that the plots were planted with wheat between May and October of 1999, this crop was also simulated in all model runs.

**Figure 4.14.** Climatic data used as model input in the simulations of the Lages plot study.

| Year | Mean monthly maximum temperature °C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1999 | 24.5 | 24.2 | 24.2 | 19.0 | 15.5 | 14.3 | 14.4 | 16.8 | 18.6 | 17.4 | 20.3 | 23.4 |
| 2000 | 24.8 | 23.9 | 21.7 | 20.9 | 16.2 | 16.5 | 13.1 | 16.9 | 17.0 | 22.0 | 23.0 | 24.6 |
| 2001 | 26.6 | 25.2 | 24.5 | 21.7 | 15.7 | 15.8 | 16.2 | 19.1 | 16.8 | 19.8 | 23.1 | 23.3 |
| | Mean monthly minimum temperature °C | | | | | | | | | | | |
| 1999 | 17.9 | 17.8 | 18.4 | 13.3 | 9.4 | 8.0 | 8.8 | 8.3 | 10.9 | 11.9 | 13.2 | 16.7 |
| 2000 | 17.7 | 17.7 | 16.2 | 13.7 | 9.5 | 10.4 | 4.3 | 8.1 | 11.2 | 15.0 | 15.7 | 17.1 |
| 2001 | 18.3 | 19.6 | 18.4 | 16.2 | 10.1 | 8.8 | 8.5 | 11.7 | 12.2 | 14.0 | 16.4 | 16.2 |
| | Mean monthly solar radiation MJ/m$^2$.day | | | | | | | | | | | |
| 1999 | 18.4 | 15.4 | 15.5 | 9.5 | 7.2 | 6.4 | 5.8 | 10.6 | 13.1 | 14.6 | 17.4 | 19.9 |
| 2000 | 16.4 | 14.1 | 13.7 | 9.3 | 8.0 | 7.3 | 6.6 | 9.2 | 11.1 | 14.1 | 17.9 | 19.9 |
| 2001 | 16.4 | 14.1 | 13.7 | 9.3 | 8.0 | 7.3 | 6.6 | 9.2 | 11.1 | 14.1 | 17.9 | 19.9 |
| | Mean monthly wind movement km/day | | | | | | | | | | | |
| 1999 | 141 | 108 | 131 | 123 | 143 | 99 | 121 | 124 | 140 | 212 | 158 | 194 |
| 2000 | 136 | 140 | 122 | 102 | 85 | 87 | 118 | 100 | 143 | 129 | 143 | 105 |
| 2001 | 106 | 124 | 75 | 79 | 108 | 80 | 107 | 87 | 163 | 150 | 141 | 137 |
| | Mean monthly dew point °C | | | | | | | | | | | |
| 1999 | 16.2 | 16.8 | 16.5 | 12.5 | 8.6 | 8.1 | 8.7 | 7.5 | 9.4 | 10.5 | 19.5 | 14.2 |
| 2000 | 17.3 | 16.7 | 16.0 | 15.4 | 11.2 | 10.0 | 5.5 | 8.6 | 10.1 | 15.0 | 15.6 | 14.6 |
| 2001 | 17.1 | 18.1 | 17.1 | 15.6 | 9.9 | 8.9 | 8.7 | 11.2 | 11.2 | 12.5 | 14.2 | 14.3 |

**Table 4.15.** Soil chemical and physical characteristics used as model input in the simulations for the Lages plot study (Guadagnin, 2003).

| | Depth (cm) | | |
|---|---|---|---|
| | 0-20 | 20-34 | 34-53 |
| Clay (g/100 g) | 40 | 40 | 42 |
| Silt (g/100 g) | 42 | 40 | 41 |
| Sand (g/100 g ) | 18 | 20 | 17 |
| Soil density (g/cm$^3$) | 1.30 | 1.35 | 1.33 |
| Porosity (cm$^3$/ cm$^3$) | 0.47 | 0.48 | 0.46 |
| Field capacity (cm/cm) | 0.36 | 0.36 | 0.36 |
| Wilting point (cm/cm) | 0.2 | 0.2 | 0.2 |
| Effective saturated conductivity (cm/h) | 0.6 | 0.6 | 0.6 |
| Organic matter (%) | 10.0 | 5.0 | 3.5 |
| Mineral N (mg/kg) | 5.0 | 0.1 | 0.1 |
| Extractable P (mg/kg) | 2,6 | 3,1 | 0,6 |
| pH $H_2O$ (1:1) | 5.7 | 5.2 | 4.9 |

TROPGLEAMS was run simulating the plot with conventional tillage with different values of curve number, Ncrit, and maximum nitrification rate. RMSE was calculated for each run using measured and simulated values of total runoff for each crop period and using the 51 measured data of $NO_3^-$-N, $NH_4^+$-N, and $PO_4$ in runoff along with values of the same variables simulated for the same days. The chosen curve number, Ncrit, and maximum nitrification rate values to be used as model input were the ones that resulted in the lower RMSE. The values were 0.05, 0.7, and 80 for Ncrit, maximum nitrification rate, and curve number (CN), respectively. Table 4.16 shows measured and simulated values of total runoff for each crop period using 80 as the curve number. Large differences between measured and simulated values of total runoff were observed with every value of curve number that was evaluated. While in the first two crop periods the model overpredicted runoff in the 30 data available, in the last two crop periods, with 21 values, the model overpredicted measured values. Uncertainty in the amount of rainfall on the days when runoff was not measured collaborated to the differences between simulated and measured values observed. As commented above, significant differences were observed in the values of rainfall in the days of runoff measurements reported for the plots by Guadagnin (2003) and the ones measured at the climatic station of Lages and the model probably simulated antecedent soil moisture different from real values, causing the differences showed in table 4.16.

**Table 4.16.** Measured and simulated values of total runoff for each crop period in a plot with a wheat/soybean rotation for the Conventional tillage treatment of the Lages plot study.

| Period | Crop | Measured | Simulated |
|---|---|---|---|
| | | --------------$m^3$/ha-------------- | |
| 11/1999-2/2000 | Soybean | 97 | 146 |
| 6/2000-10/2000 | Wheat | 391 | 715 |
| 11/2000-04/2001 | Soybean | 511 | 286 |
| 06/2001/10/2001 | Wheat | 2444 | 504 |

After choosing the best values for input parameters, GLEAMS was also applied simulating the conventional tillage treatment. Following this, TROPGLEAMS and

GLEAMS were applied simulating no-till and chisel plow + disk treatments. Measured and simulated $NO_3^-$-N, $NH_4^+$-N, and $PO_4$ in runoff from both models were plotted together and RMSE was calculated using the 51 measured values of $NO_3^-$-N, $NH_4^+$-N, and $PO_4$ in runoff along with values of the same variables simulated for the same days.

Figures 4.48, 4.49, and 4.50 and Tables D.1, D.2, and D.3 of Appendix D show measured and simulated values of $NH_4^+$-N, $NO_3^-$-N, and $PO_4$-P for the plots with conventional tillage

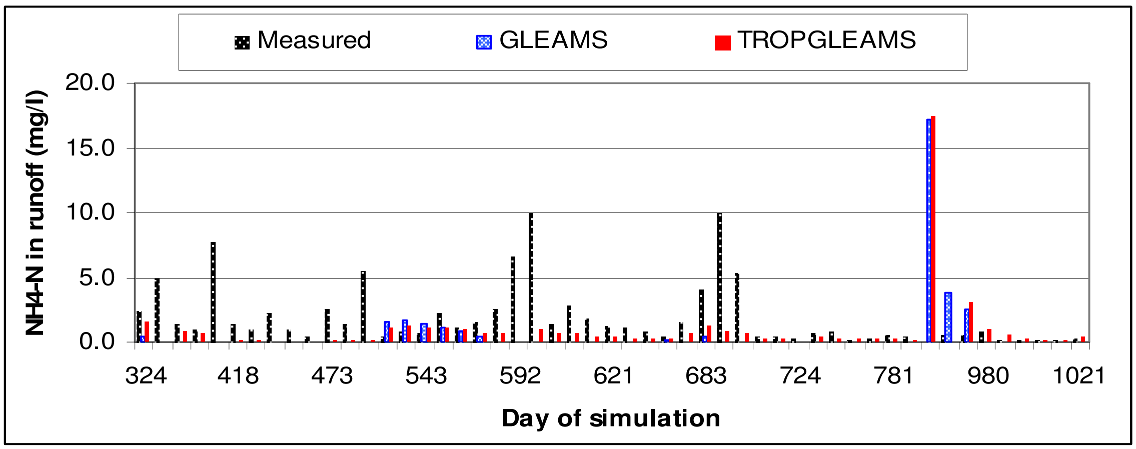


**Figure 4.48.** Measured and simulated values of $NH_4^+$-N in runoff from a plot with a wheat/soybean rotation for the Conventional tillage treatment of the Lages plot study.

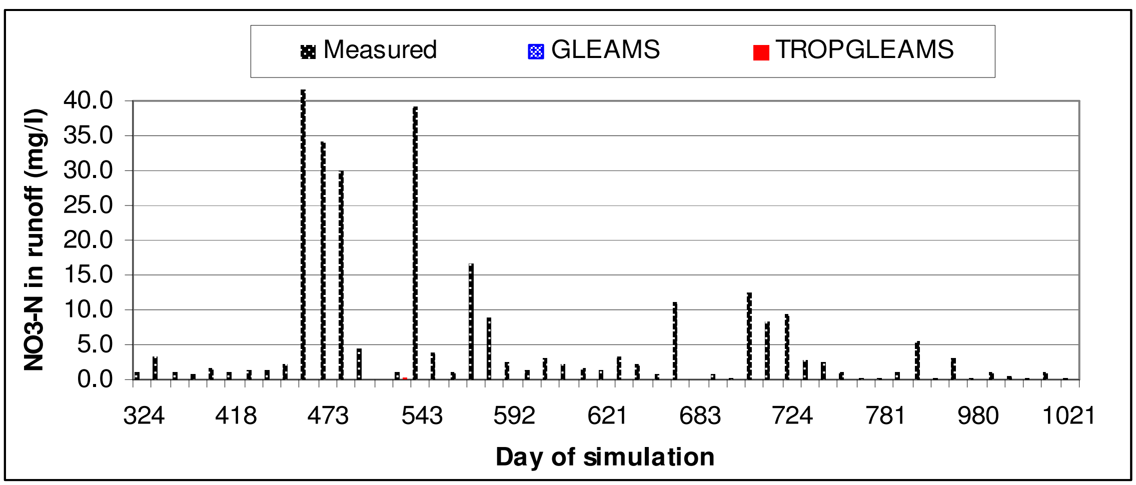


**Figure 4.49.** Measured and simulated values of $NO_3^-$-N in runoff from a plot planted with a wheat/soybean rotation for the conventional tillage treatment of the Lages plot study.

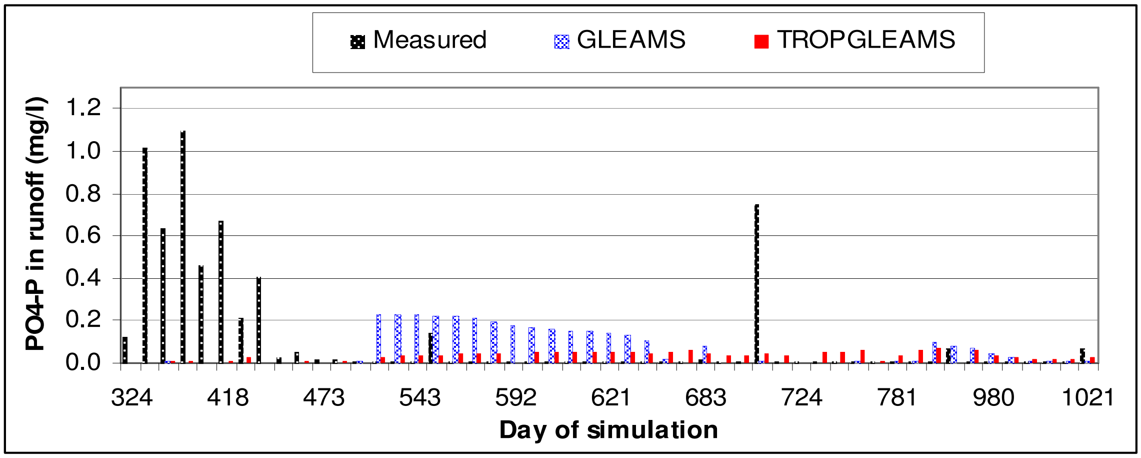


**Figure 4.50**. Measured and simulated values of $PO_4$-P in runoff from a plot with a wheat/soybean rotation for the conventional tillage treatment of the Lages plot study.

Overall, both models underestimated values of $NH_4^+$-N, $NO_3^-$-N, and $PO_4$-P in runoff. For $NH_4^+$-N, GLEAMS predicted 37 values of zero concentration in a dataset of 51 values, and positive values were predicted only on several days following N applications. Zero concentrations from TROPGLEAMS coincided with days when the model did not simulate runoff, characterizing not a model drawback but a probable inconsistency on the rainfall input file. Figure 4.51 shows maximum bar size equivalent to 2 mg $NH_4^+$-N/L in order to better show the variation of simulated and measured values throughout the simulation.

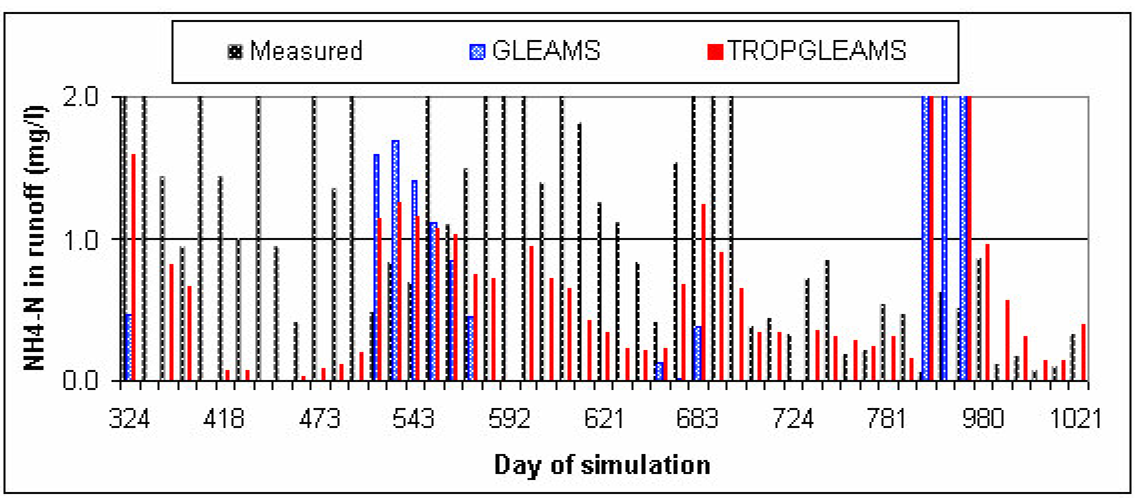


**Figure 4.51.** Measured and simulated values of $NH_4^+$-N in runoff from a plot with a wheat/soybean rotation for the conventional tillage treatment of the Lages plot study. Maximum graphed value equivalent to 2 mg/L.

While in the first crop period (days 324 to 490) TROPGLEAMS resulted in several very low and zero values of $NH_4^+$-N in runoff, in the second and third crop periods, measured and simulated values followed the same trend, with a good coincidence of results. During the second crop period (days 536 to 648), GLEAMS showed its best performance, but after the 5$^{th}$ day with measured data, the model predicted only zero concentration. At the beginning of the fourth crop period (after day 931), both models overpredicted results, but at the end, TROPGLEAMS predicted values very close to those measured. While the results of TROPGLEAMS followed the trend of measured values better than GLEAMS, RMSE for these simulations were similar, with values of 5.82 and 5.65 for GLEAMS and TROPGLEAMS, respectively.

All fertilizer nitrogen applied to the plots was in the form of urea. The quantity and method of fertilizer application was described by Guadagnin (2003); however, the dates of planting, tillage, and fertilization were not described, and this uncertainty is certainly one cause for the differences between measured and simulated values.

For $NO_3^-$-N in runoff, both models underpredicted values significantly. Using only positive values (not using zero simulated values), measured values were, on average, 334,277 and 10,784 times greater than the results of GLEAMS and TROPGLEAMS, respectively. Although several changes in the values of input parameters were tried in an effort to reduce this error, this was the best performance of TROPGLEAMS for this variable. Possible sources for the differences between measured and simulated values of $NO_3^-$-N in runoff for this plot are:

- Uncertainties in timing of fertilizer application, planting, and tillage operations because Guadagnin (2003) did not report the exact date for these operations;
- The value of the extraction coefficient for runoff may be higher than that used in temperate conditions due to higher rainfall energy;
- Both models simulate the passage of all nitrogen from the surface to the top soil layer on the day of each rainfall event. In cases of soil surfaces with a high quantity of crop residue, as was the case of the plot used in this simulation, this passage certainly does not occur completely and more nitrate remains available for extraction in runoff than that simulated by the models;

- GLEAMS and TROPGLEAMS consider the incorporation efficiency of disk plow and disk harrow as 80 and 75 %. This coefficient is used by the models to subtract material (nutrients, residue, and animal waste) from the surface during tillage operations. The difficulty of plowing small areas such as the study plot may have caused the incorporation efficiency to be lower than assumed, allowing more nitrogen to remain on the surface where it is more available for runoff than that simulated by both models; and
- Lages is located in one of the coldest areas of Brazil and its climate is characterized as subtropical. The optimal temperatures for ammonification and nitrification in TROPGLEAMS are 50$^{o}$C and 40$^{o}$C, respectively, while the mean maximum and mean minimum temperatures of Lages are 21.7 $^{o}$C and 11.5 $^{o}$C; this can be a significant source for the reduction of simulated values of the model.

More studies on the processes affecting nitrate in the soil surface and its extraction and transport in runoff are recommended.

For $PO_4$-P in runoff (figure 4.52), different trends are observed in the measured values and those simulated by GLEAMS and TROPGLEAMS. Measured results were very high in the beginning of the first crop period, but a sharp decrease was observed in its end, when all concentrations, except the ones measured on days 547, 683, 716, 963 and 1021, were reported as 0.01 mg $PO_4$-P/L. Figure 4.52 shows $PO_4$-P concentrations with maximum graphed value equivalent to 0.25 mg $PO_4$-P/L. For the first crop period, days 324 to 502, measured values were very high and both models underestimated the results. The contrary was observed in most of the rest of the simulation, when both models overestimated measured values. For the second crop period (days 502 to 648), the overestimation of GLEAMS was more significant than that of TROPGLEAMS, while for the third and forth crop periods, the overestimation of TROPGLEAMS was more significant.

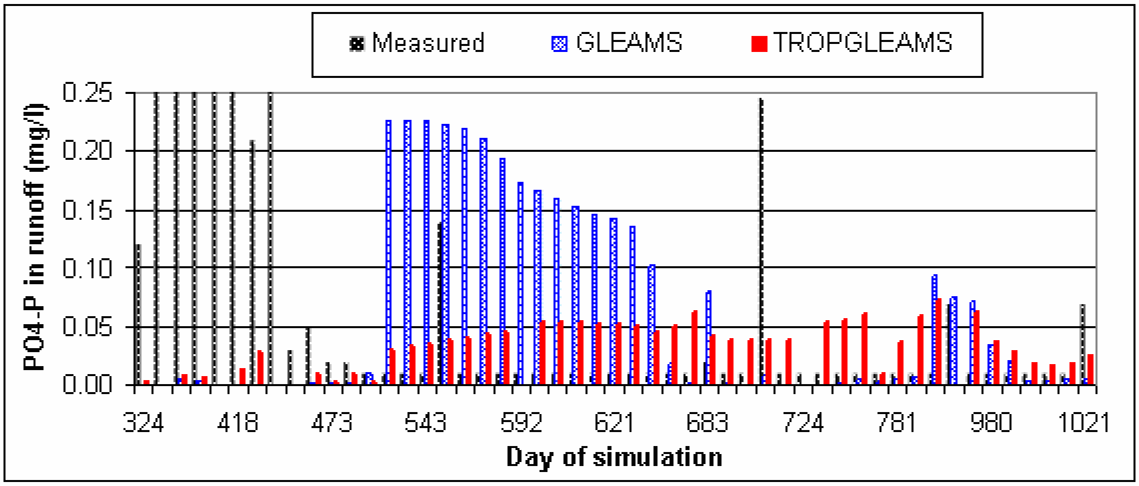


**Figure 4.52.** Measured and simulated values of $PO_4$-P in runoff from a plot planted with a wheat/soybean rotation for the conventional tillage treatment of the Lages plot study. Maximum graphed value equivalent to 0.25 mg $PO_4$-P/L.

TROPGLEAMS results showed a smaller range than that measured or simulated by GLEAMS. While measured values varied from 0.01 to 1.1 mg $PO_4$-P/L, the values of GLEAMS varied from 0.0 to 0.227 and the results of TROPGLEAMS varied from 0.0 to 0.074. For the first crop period, when soybeans were planted in soil covered with wheat residue, low values of P in runoff were predicted by both models because a conjunction of factors caused a simulation of a low quantity of labile P on soil surface. Contributing factors include a possible value of initial P lower than real values and a quantity of P mineralized by the model from wheat straws lower than real values. After the second crop period, with the addition of mineral P on the soil surface and crop residue, including soybean residue, which has low C/P, TROPGLEAMS results were consistently higher than measured values. For this period, most measured values were 0.01 mg $PO_4$-P/L, while results of TROPGLEAMS varied according to the quantity of mineral P added from fertilizers and organic P from crop residue. The general overestimation of TROPGLEAMS after the first crop period may be due to several factors, including:

- Uncertainties related to the methods used for sampling and analysis. The time between runoff collection and analysis, if too long, may allow the sorption of soluble P to the particles of sediments, reducing the concentration of P in runoff. Results of analysis of P in the runoff water accumulated in the collector tanks may result in concentrations lower than real if the water is not well homogenized before sampling.

Errors in laboratory procedures and calculations are also source of uncertainties in field studies.

- Possibility that the extraction coefficient of runoff used in TROPGLEAMS (the same used in GLEAMS) is too high for the high P adsorption of the soil of the plots.

While the rates of decomposition in TROPGLEAMS may be suspected as being too high, this may not be one of the causes of high values of P because a similar response would be expected for $NH_4^+$-N in runoff, which was not observed.

Although overestimating measured values, RMSE of TROPGLEAMS was lower than that of GLEAMS. For this treatment, RMSE between measured values and values simulated by GLEAMS and TROPGLEAMS was 0.30 and 0.28, respectively, showing that the results of the modified model were closer to the measured values than those of the original model.

Figures 4.53 and 4.54 and Tables D.4 and D.7 of Appendix D show measured and simulated values of $NH_4^+$-N in runoff for the treatments Chisel + disk and No-till, respectively. In order to ease graphic interpretation, maximum bar size of both figures was set as 5.0 mg $NH_4^+$-N/L.

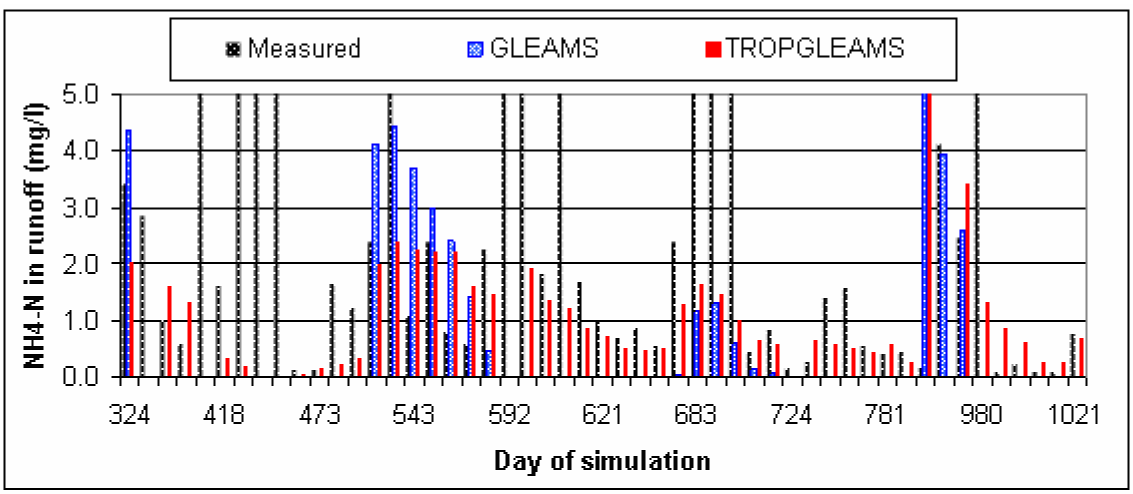


**Figure 4.53.** Measured and simulated values of $NH_4^+$-N in runoff from a plot with a wheat/soybean rotation for the chisel + harrow disk treatment of the Lages plot study. Values truncated at 5 mg/L.

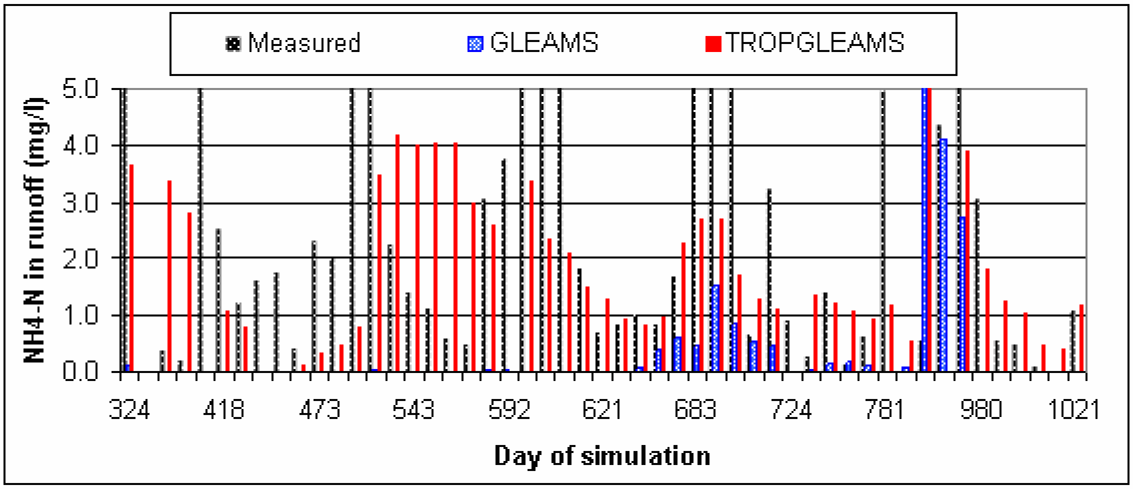


**Figure 4.54.** Measured and simulated values of $NH_4^+$-N in runoff from a plot with a wheat/soybean rotation for the treatment No-tillage of the Lages plot study. Values truncated at 5 mg/L.

Similar to what was observed for the Conventional Tillage treatment, for the Chisel+disk and No-tillage treatments GLEAMS and TROPGLEAMS were not able to follow the high values measured in the plots on certain days, resulting in an overall underprediction of results from both models, although TROPGLEAMS performed better than GLEAMS in these two simulations. In 51 days of measured values, GLEAMS predicted 33 zero values for Chisel+disk and and 28 for No Tillage treatments, while TROPGLEAMS only resulted in zero values on the days when no runoff was simulated.

Since the incorporation of surface material was more complete under the Conventional tillage treatment, while No-tillage treatment promoted no incorporation and Chisel+disk treatments promoted intermediate incorporation, greatest loss of nutrients in runoff is expected for No-tillage, followed by Chisel+disk and Conventional tillage. Table 4.13 shows median and average values of $NH_4^+$-N in runoff for the three management systems.

**Table 4.17.** Median and average of three datasets of measured values of $NH_4^+$-N in runoff and that simulated by GLEAMS and TROPGLEAMS from plots with a wheat/soybean rotation for the Conventional tillage, Chisel+disk, and No-tillage treatments of the Lages plot study.

| Treatment | Measured | | GLEAMS | | TROPGLEAMS | |
|---|---|---|---|---|---|---|
| | Median | Average | Median | Average | Median | Average |
| Conv. tillage | 0.95 | 2.21 | 0.00 | 0.62 | 0.35 | 0.85 |
| Chisel + disk | 1.40 | 5.06 | 0.00 | 1.00 | 0.66 | 1.25 |
| No-tillage | 1.65 | 2.90 | 0.00 | 0.59 | 1.24 | 1.95 |

For the calculation of these statistics for Conventional tillage, the higher measured value was discarded, since it was graphically considered an outlier. Median was not considered a good statistic for GLEAMS due to the high number of zero values in the dataset, but was considered appropriate for the measured data and values from TROPGLEAMS. Average was not a good statistic for the measured values due to some very high values in the dataset, but was considered appropriate for GLEAMS and TROPGLEAMS. Median and average values from TROPGLEAMS were higher in No-tillage, followed by Chisel+disk and Conventional tillage due to the quantity of material that is left available for runoff on the soil surface, as noted above.  The median of the measured values agrees with this expected order, but the GLEAMS dataset does not match the order for any of the statistics.

For the Chisel+disk treatment, GLEAMS and TROPGLEAMS predictions were similar to those predicted for Conventional tillage. While both models predicted very low and zero values during the first crop period, for the remainder of the simulation TROPGLEAMS results followed the trend of the observed values but GLEAMS had values different from zero only on the days following fertilizer application.

For the No-tillage treatment, TROPGLEAMS had the greatest difference from the measured values during the first period and the beginning of the second crop period. A very close fit with measured values was observed in the rest of the simulation. On the other hand, GLEAMS showed only five results closer to the measured values than the results of TROPGLEAMS.

**Table 4.18.** RMSE between measured and simulated values of $NH_4^+$-N in runoff in plots with a wheat/soybean rotation for the Chisel + disk and No-tillage treatments of the Lages plot study.

| Treatment | GLEAMS | TROPGLEAMS |
|---|---|---|
| Chisel + disk | 11.55 | 11.38 |
| No-tillage | 4.50 | 4.05 |

Table 4.18 shows RMSE between measured and simulated values for the Chisel + disk and No-tillage treatments. Similar to the results for the Conventional tillage treatment, RMSE values were smaller for TROPGLEAMS than for GLEAMS in Chisel + disk and No-tillage treatments, showing that the modified model performed better than the original one in the simulation of $NH_4^+$-N in runoff in the conditions of the plots in Lages, Brazil.

Figures 4.55 and 4.56 and tables C.5 and C.8 of Appendix C show measured and simulated values of $NO_3^-$-N in runoff for the treatments Chisel + disk and No-tillage, respectively.

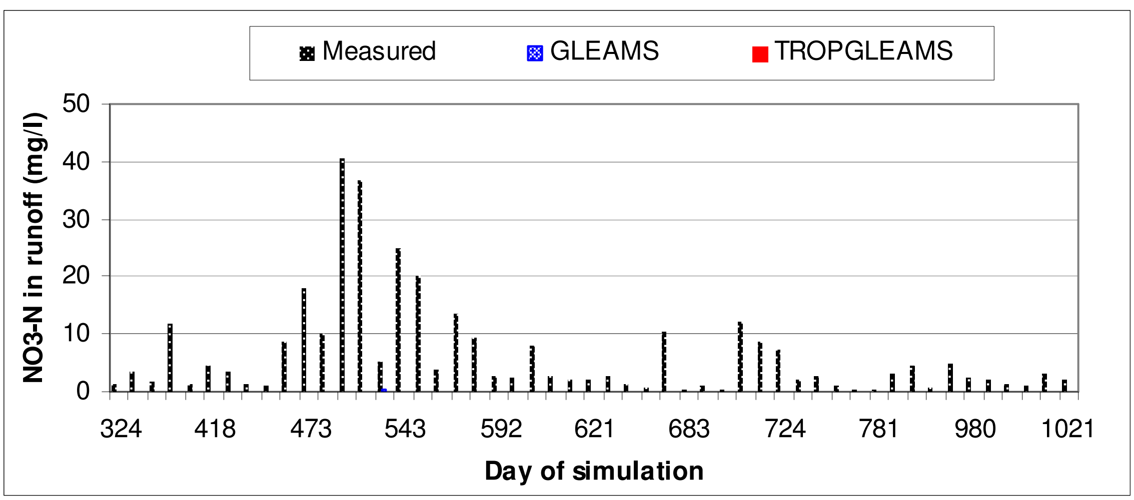


**Figure 4.55.** Measured and simulated values of $NO_3^-$-N in runoff from a plot with a wheat/soybean rotation for the Chisel + disk treatment of the Lages plot study.

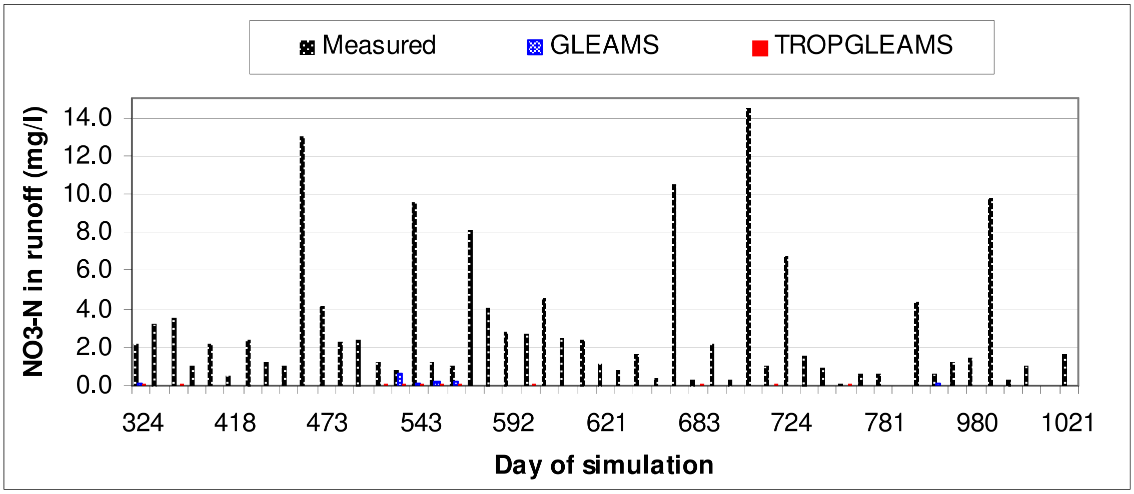


**Figure 4.56.** Measured and simulated values of $NO_3^-$-N in runoff from a plot with a wheat/soybean rotation for the No-tillage treatment of the Lages plot study.

High underprediction of $NO_3^-$-N concentration in runoff was also observed for Chisel + disk and No-tillage treatments, indicating that both models did not perform well in the calculation of this parameter for the plot conditions of Lages, Brazil, assuming that the measured values are correct. Repeating the calculation used for the data from the plot with conventional tillage, measured values for the treatment Chisel + disk were, on average, 196,781 and 10,933 times greater than the results of GLEAMS and TROPGLEAMS, respectively. For the treatment No-tillage, these numbers were 396,115 and 300,558.

Figures 4.57 and 4.58 show measured and simulated values of $PO_4$-P in runoff for the Chisel + disk and No-tillage treatments, respectively. Maximum graphed values of 1.0 and 2.5 mg $PO_4$-P/L were used in order to ease interpretation. $PO_4$-P concentration in runoff from the Chisel + disk treatment shows the same trend as was seen for Conventional tillage, but with higher values. Measured values varied from 0.01 to 10.24 mg PO4-P/L, while values simulated by GLEAMS and TROPGLEAMS ranged from 0.0 to 0.724 and from 0.0 to 0.196 mg $PO_4$-P/L, respectively. Values of $PO_4$-P in runoff greater than those of Conventional tillage were expected for this treatment because the tillage operations used here do not incorporate material from the soil surface as effectively as Conventional tillage.  As observed for Conventional tillage, values of TROPGLEAMS showed the lower variation during this simulation.

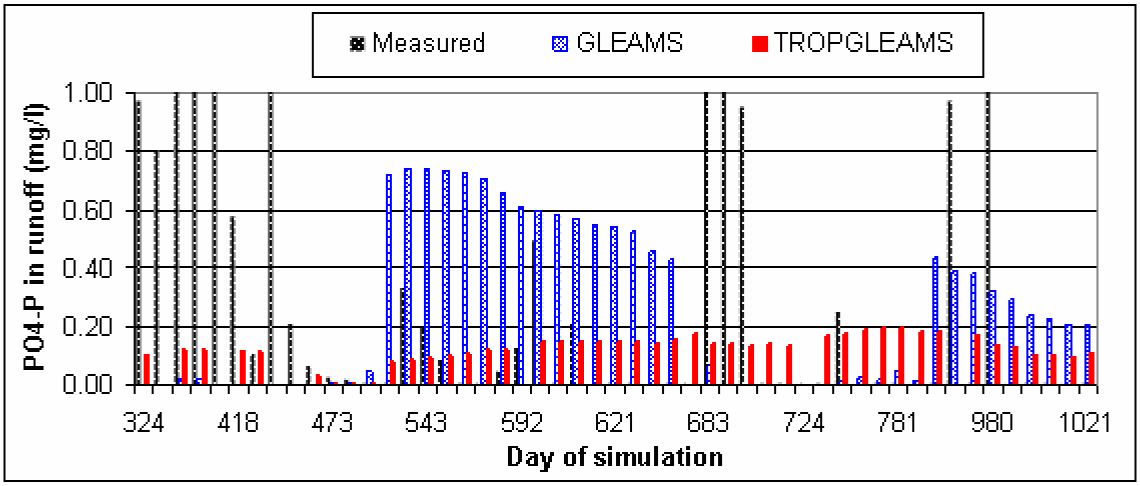


**Figure 4.57.** Measured and simulated values of $PO_4$-P in runoff from a plot with a wheat/soybean rotation for Chisel + disk treatment of the Lages plot study.

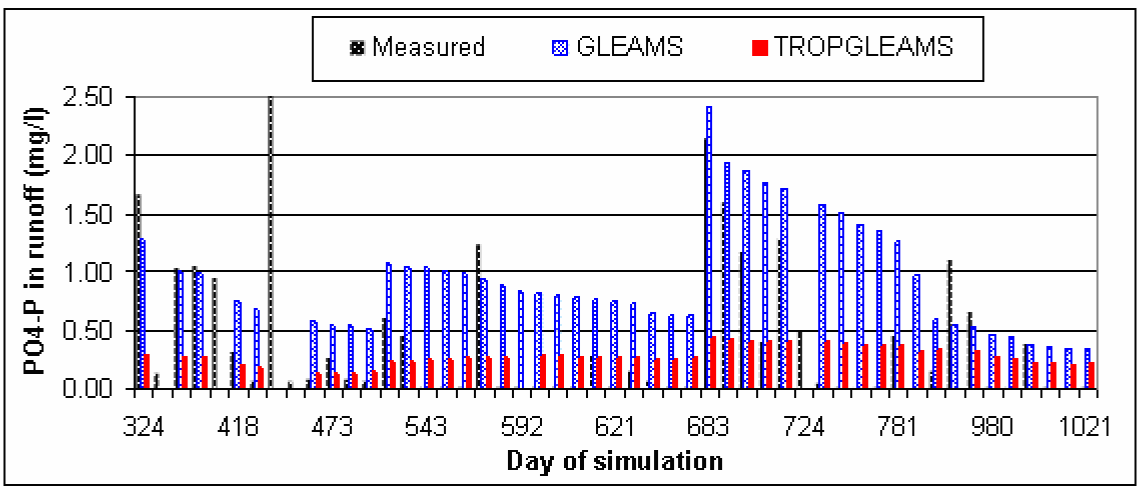


**Figure 4.58.** Measured and simulated values of $PO_4$-P in runoff from a plot with a wheat/soybean rotation for the No-tillage treatment of the Lages plot study.

For the No-tillage treatment, GLEAMS was more effective in the simulation of peaks of high measured values than TROPGLEAMS. This could be observed in the beginning of the first, second, and third crop periods, when high measured values were followed by high values simulated by GLEAMS, while values of TROPGLEAMS did not vary significantly.

Because most applied P was kept on the soil surface, greater P concentration in runoff was expected for this treatment and this was observed. Maximum values were

3.18, 2.42, and 0.049 for measured values and values simulated by GLEAMS and TROPGLEAMS, respectively.

Without the influence of tillage operations, the results of the No-tillage treatment show the differences between the model used in GLEAMS and TROPGLEAMS to simulate P transformations. The model used in TROPGLEAMS was derived in highly weathered Oxisols and 57% of applied P is transformed to active mineral P (PMINP) on the day of application. The inability of TROPGLEAMS to follow the peaks of measured values in the beginning of each crop period may rest on this fact. After a period of high concentrations, measured values dropped sharply, while results of GLEAMS remained high. This fact made values from TROPGLEAMS closer to measured values in most of the simulation. Table 4.15 shows values of RMSE between measured and simulated values. As observed for the Conventional tillage treatment, for Chisel + disk and No-tillage, RMSE values of TROPGLEAMS were lower than those of GLEAMS, indicating that TROPGLEAMS performed better than GLEAMS in the simulation of P in runoff for the conditions of the plots in Lages, Brazil.

**Table 4.19.** RMSE between measured and simulated values of $PO_4$-P in runoff from plots with a wheat/soybean rotation for the Chisel + disk and No-tillage treatments of the Lages plot study.

| Treatment | GLEAMS | TROPGLEAMS |
|---|---|---|
| Chisel + disk | 1.59 | 1.56 |
| No-tillage | 0.84 | 0.69 |

# 4.3. SENSITIVITY ANALYSIS

The sensitivity analysis of TROPGLEAMS was performed to evaluate changes in model output due to changes in temperature, pH, and the retardation factor for nitrate leaching (Ncrit). Ncrit and pH were the only new input parameters for TROPGLEAMS while temperature was assessed because significant changes in model response for temperature were included in TROPGLEAMS code. For temperature, GLEAMS was also included in the analysis in order to compare the sensitivity of both models. For pH and Ncrit, only the sensitivity of TROPGLEAMS was assessed, since Ncrit is an input variable only for TROPGLEAMS and pH is not an input parameter in GLEAMS when simulating highly weathered soils. Output variables related to temperature were $NH_4^+$-N and $NO_3^-$-N in leachate, $PO_4$-P in runoff, $NH_4^+$-N and $PO_4$-P in sediment, and $NO_3^-$-N and $NH_4^+$-N in runoff. $NO_3^-$-N in leachate and in runoff were the output variables evaluated in relation to both Ncrit and pH. For this sensitivity analysis, the model was run simulating a plot with a wheat-soybean rotation and conventional tillage during three years using the same input files used in the model application to the Lages plot study. Relative sensitivity was calculated as:

$$Sr = \left( \frac{O - O_b}{P - P_b} \right) \frac{P_b}{O_b} \qquad (4.1)$$

where O is model output variable of interest, P is parameter value, and b is a subscript representing the parameter and output values of the base scenario. The values of the base scenario were not a unique pair of values. Considering the sensitivity analysis for Ncrit, with values 0.0, 0.01, 0.02, 0.04, 0.06, and 0.08 calculated through $NO_3^-$-N in leachate, the base values for Ncrit of 0.01 are Ncrit 0.0 and its corresponding value of $NO_3^-$-N in leachate. In the same way, the base values for Ncrit of 0.08 are Ncrit 0.06 and its corresponding value of $NO_3^-$-N in leachate.

## 4.3.1. MODEL SENSITIVITY TO TEMPERATURE

The first value of temperature for this analysis was a set of monthly mean minimum and maximum temperatures resulting in an average annual temperature of 16.13$^o$C. This set of values was repeated in the three years of simulation and TROPGLEAMS was run having 0.03 and 4.5 as the values of Ncrit and pH, respectively. For the other model runs, mean monthly values of minimum and maximum temperatures received four increases of 15% each so that mean annual temperatures were 18.54, 21.31, 24.52, and 28.20$^o$C for the second, third, fourth, and fifth runs, respectively. Total values of $NH_4^+$-N and $NO_3^-$-N in leachate, $PO_4$-P in runoff, $NH_4^+$-N and $PO_4$-P in sediment, and $NO_3^-$-N and $NH_4^+$-N in runoff for the whole simulation were used to create graphics having mean annual temperature on the X-axis as well as to calculate the model relative sensitivity.

Figures 4.59 and 4.60 show total $NO_3^-$-N in leachate and in runoff, respectively, with mean annual temperatures varying from 16.12 to 28.20°C and table 4.20 shows relative sensitivity of both models to variations in mean annual temperature considering total $NO_3^-$-N in leachate and runoff as output variables. Figures 4.61, 4.62, and 4.63 show total $NH_4^+$-N in leachate, in runoff, and in sediment, respectively, with the same variation in mean annual temperatures, while table 4.21 shows the relative sensitivity of both models considering total $NH_4^+$-N in leachate and in runoff as the output variables and table 4.22 shows relative sensitivity of GLEAMS and TROPGLEAMS to variations in temperature having total $NH_4^+$-N in sediment as the output variable. Total $NO_3^-$-N and $NH_4^+$-N in leachate and in runoff and total $NH_4^+$-N in sediment are the sum of each output variables in a three year simulation.

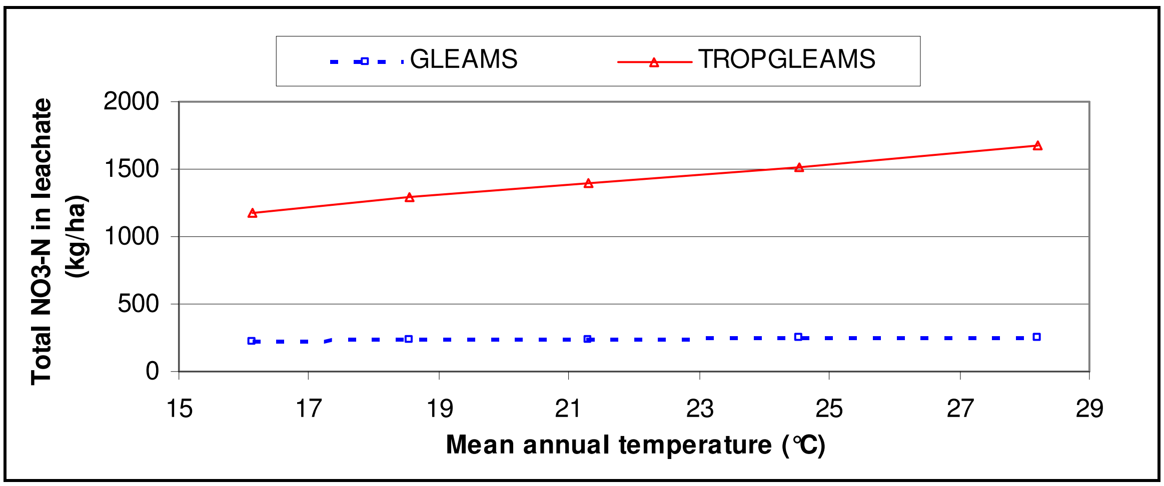


**Figure 4.59.** Total $NO_3^-$-N in leachate from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

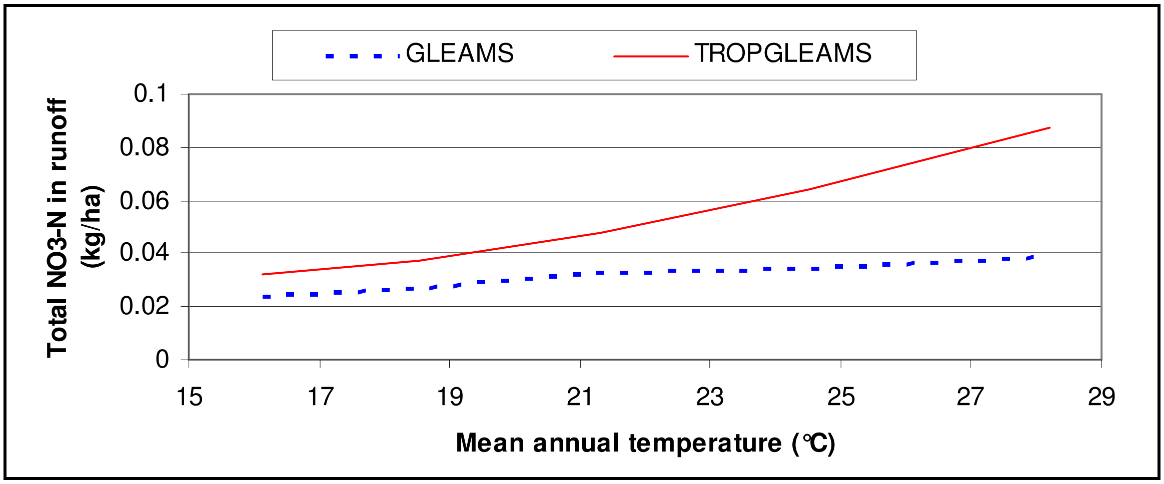


**Figure 4.60.** Total $NO_3^-$-N in runoff from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C.

**Table 4.20.** Relative sensitivity of GLEAMS and TROPGLEAMS to variations in temperature having $NO_3^-$-N in leachate and in runoff as output variables for a three year simulation. The baseline for each value is the condition set with the next smaller value of temperature.

| Temperature | Relative sensitivity for $NO_3^-$-N in leachate | | Relative sensitivity for $NO_3^-$-N in runoff | |
|---|---|---|---|---|
| | GLEAMS | TROPGLEAMS | GLEAMS | TROPGLEAMS |
| 18.54 | 0.17 | 0.67 | 0.88 | 1.14 |
| 21.31 | 0.24 | 0.59 | 1.39 | 1.86 |
| 24.52 | 0.10 | 0.56 | 0.27 | 2.24 |
| 28.20 | 0.19 | 0.70 | 0.92 | 2.48 |

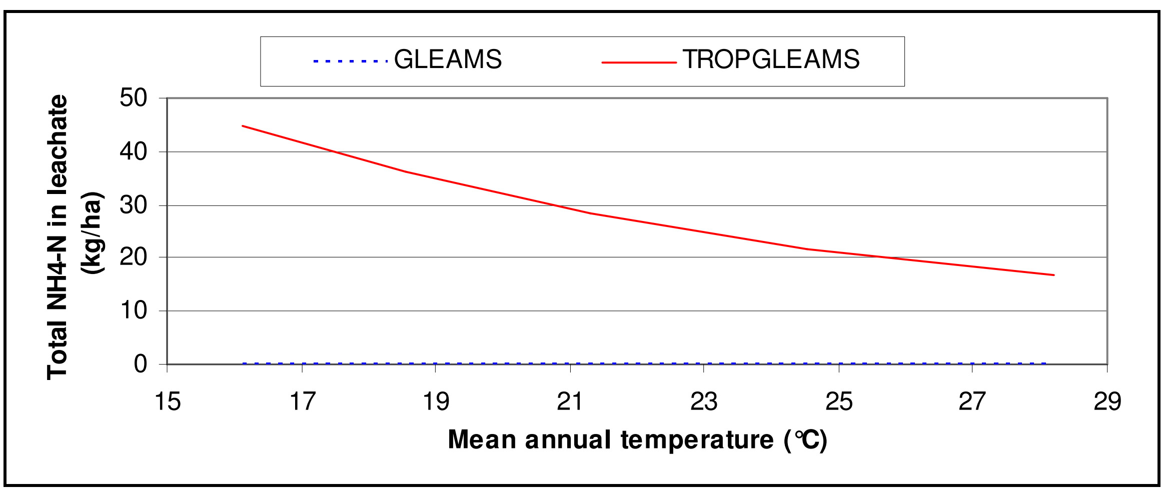


**Figure 4.61.** Total $NH_4^+$-N in leachate from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

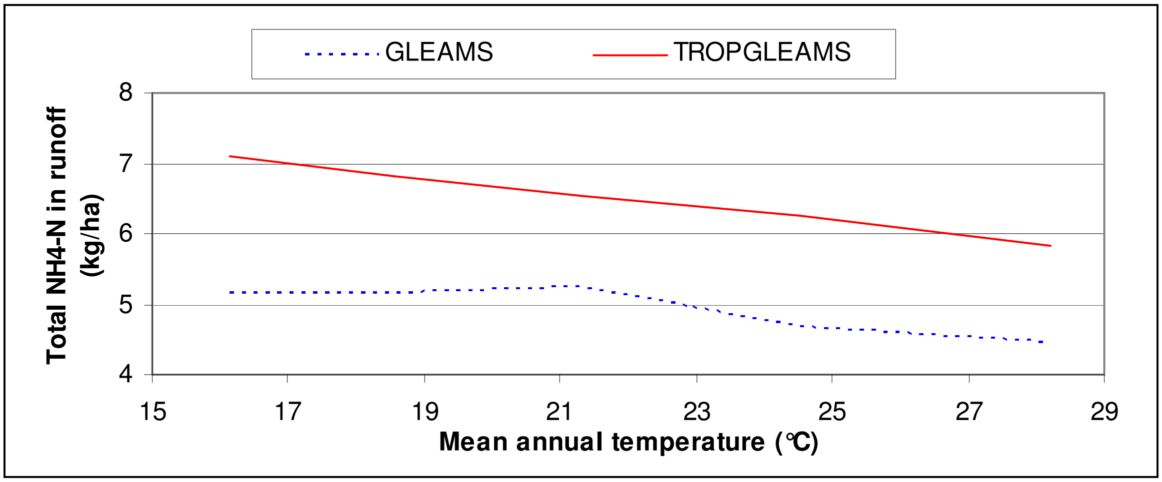


**Figure 4.62.** Total $NH_4^+$-N in runoff from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

**Table 4.21.** Relative sensitivity of GLEAMS and TROPGLEAMS to variations in temperature having $NH_4^+$-N in leachate and in runoff as output variables for a three year simulation. The baseline for each value is the condition set with the next smaller value of temperature.

| Temperature | Relative sensitivity for $NH_4^+$-N in leachate | | Relative sensitivity for $NH_4^+$-N in runoff | |
|---|---|---|---|---|
| | GLEAMS | TROPGLEAMS | GLEAMS | TROPGLEAMS |
| 18.54 | 0 | -1.31 | 0.00 | -0.28 |
| 21.31 | 0 | -1.47 | 0.09 | -0.26 |
| 24.52 | 0 | -1.52 | -0.70 | -0.30 |
| 28.20 | 0 | -1.48 | -0.35 | -0.46 |

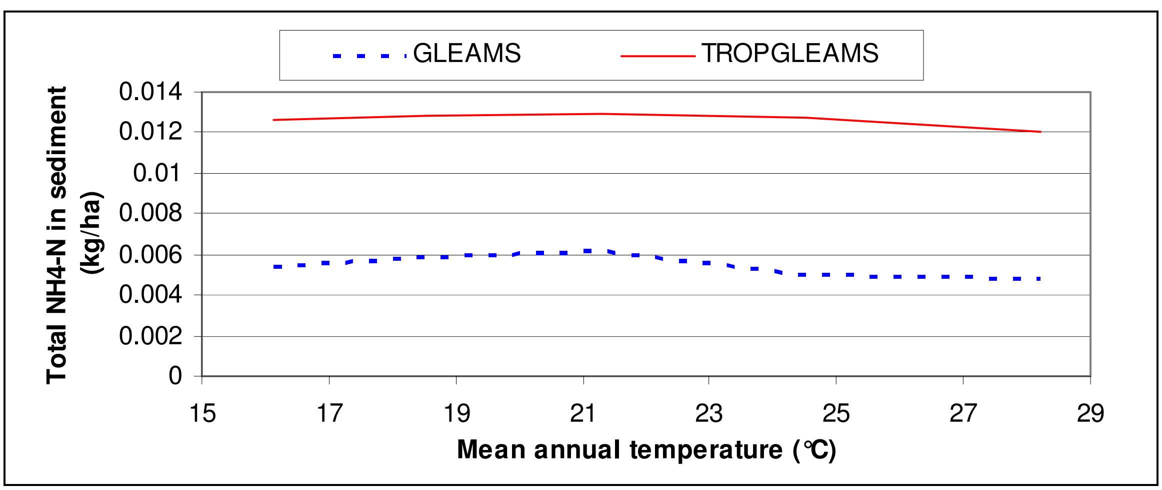


**Figure 4.63.** Total $NH_4^+$-N in sediment from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

**Table 4.22.** Relative sensitivity of GLEAMS and TROPGLEAMS to variations in temperature having $NH_4^+$-N in sediment as output variable for a three year simulation. The baseline for each value is the condition set with the next smaller value of temperature.

| Temperature | Relative sensitivity for $NH_4^+$-N in sediment | |
|---|---|---|
| | GLEAMS | TROPGLEAMS |
| 18.54 | 0.59 | 0.14 |
| 21.31 | 0.42 | 0.04 |
| 24.52 | -1.27 | -0.08 |
| 28.20 | -0.21 | -0.38 |

Both models showed positive relative sensitivity for $NO_3^-$-N in leachate and runoff. TROPGLEAMS showed negative relative sensitivity for $NH_4^+$-N in runoff and leachate. GLEAMS showed no sensitivity for $NH_4^+$-N in leachate, while, for $NH_4^+$-N in runoff, GLEAMS showed no sensitivity for temperatures between 16.12 and 21.31°C, and negative sensitivity for temperatures above 21.31°C. For $NH_4^+$-N in sediment, both models showed positive sensitivity for temperatures between 16.12 and 21.31°C, and negative sensitivity for temperatures above 21.31°C.

For GLEAMS, the trend of total $NH_4^+$-N in runoff was very similar to that of $NH_4^+$-N in sediment, but the same was not observed in TROPGLEAMS. The same trend was expected in both models because both simulate mineralization then divide formed ammonium into sediment-bound and soluble forms. The equations used by GLEAMS and TROPGLEAMS for ammonium formation are different, but they use the same equations for its division into sediment-bound and soluble ammonium. In this way, the quantity of total sediment-bound and runoff $NH_4^+$-N calculated by each model should be different, but the trend of changes should be similar.

It can be observed that the models related to nitrification in both GLEAMS and TROPGLEAMS are more sensitive to variations in temperature than those related to ammonification. This fact causes a build-up of nitrate in soil solution at higher temperatures, making more of this ion available for losses. On the other hand, with higher increases in the rates of nitrification than of ammonification, less ammonium is available for losses, resulting in negative sensitivity. For $NH_4^+$-N in sediment, although an increase of losses was observed at temperatures ranging from 16.12 to 21.31°C, a reduction of values in both models was observed at temperatures ranging from 16.12 to 28.2°C.

TROPGLEAMS is more sensitive to variations in temperature than GLEAMS for these five output variables except for $NH_4^+$-N in sediment. Linear responses were observed in both models for $NO_3^-$-N and $NH_4^+$-N in leachate, as well as for $NO_3^-$-N in runoff in GLEAMS. Non-linear responses were observed in TROPGLEAMS for both $NH_4^+$-N and $NO_3^-$-N in runoff and in GLEAMS, for $NH_4^+$-N in runoff. Both models also showed non-linear sensitivity for $NH_4^+$-N in sediment.

Figures 4.64 and 4.65 show total $PO_4$-P in runoff and in sediment, respectively, for mean annual temperatures varying from 16.12 to 28.20°C while Table 4.23 shows values of relative sensitivity of both models for the same temperature variation and output variables.

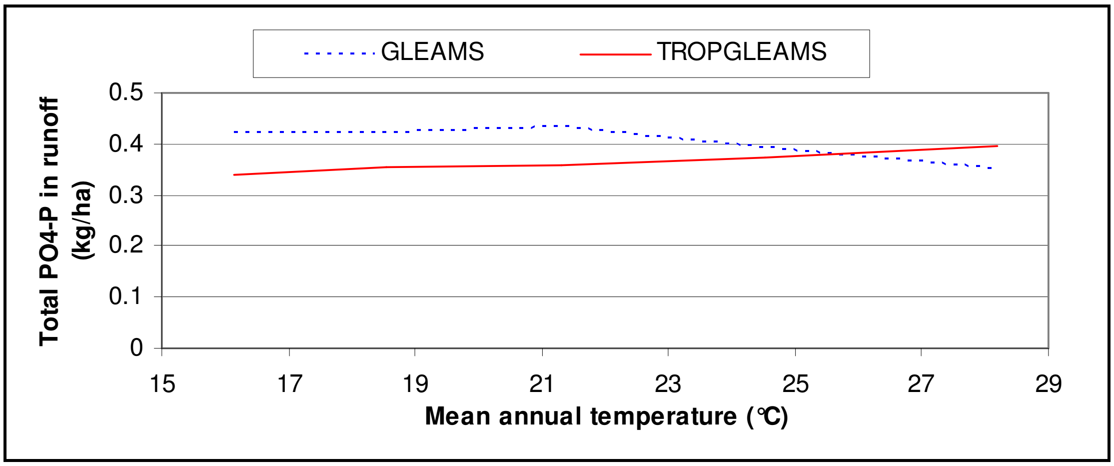


**Figure 4.64.** Total $PO_4$-P in runoff from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

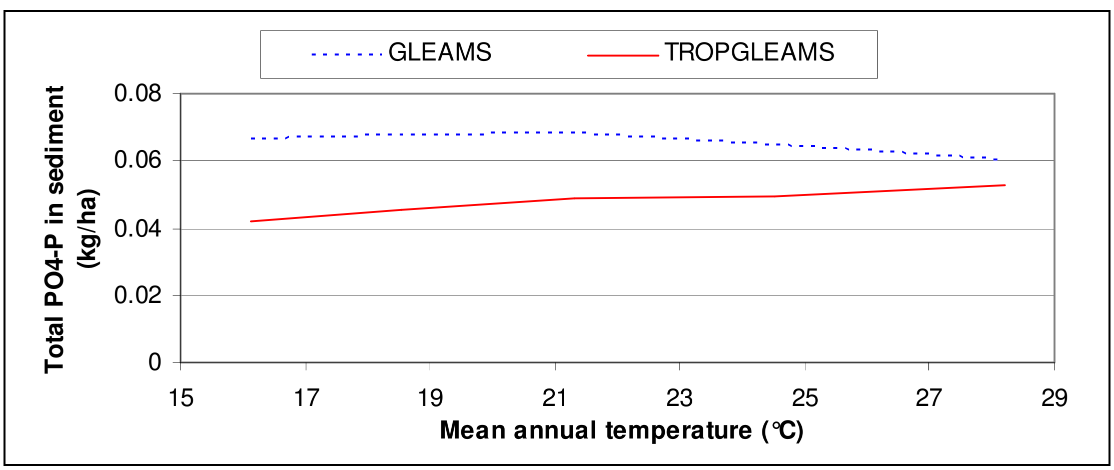


**Figure 4.65.** Total $PO_4$-P in sediment from plots planted with a wheat/soybean rotation with mean annual temperature varying from 18.54 to 28.20°C for a three year simulation.

**Table 4.23.** Relative sensitivity of GLEAMS and TROPGLEAMS to variations in temperature having $PO_4$-P in sediment and in runoff as output variables. The baseline for each value is the condition set with the next smaller value of temperature.

| Temperature | Relative sensitivity for $PO_4$-P in runoff | | Relative sensitivity for $PO_4$-P in sediment | |
|---|---|---|---|---|
| | GLEAMS | TROPGLEAMS | GLEAMS | TROPGLEAMS |
| 18.54 | 0.03 | 0.28 | 0.14 | 0.48 |
| 21.31 | 0.13 | 0.11 | 0.02 | 0.58 |
| 24.52 | -0.58 | 0.27 | -0.29 | 0.02 |
| 28.20 | -0.72 | 0.36 | -0.52 | 0.47 |

While values of total $PO_4$-P in runoff and total $PO_4$-P in sediment in GLEAMS decreased with increasing temperatures, values from TROPGLEAMS for both output variables increased with increasing temperatures. The same trend for both variables was expected, because both GLEAMS and TROPGLEAMS first calculate the quantity of labile P, then partition it into sediment-bound and soluble P pools.

For both output variables, GLEAMS showed positive low values of relative sensitivity with temperature varying from 16.12 to 21.31°C and negative values for temperatures above 21.31°C, while TROPGLEAMS showed a positive value of relative sensitivity at all temperatures.

For the effect of temperature variation from 16.12 to 28.20°C on $PO_4$-P in runoff, the models showed the same absolute value of relative sensitivity, but with different relationships. While GLEAMS shows inverse relationships between temperature variation and $PO_4$-P in runoff, TROPGLEAMS shows a direct relationship. Different relationships were also observed for $PO_4$-P in sediment, with the sensitivity of TROPGLEAMS almost three times that of GLEAMS. For both output variables, relative sensitivity was linear for TROPGLEAMS and non-linear for GLEAMS.

## 4.3.2. MODEL SENSITIVITY TO THE NITROGEN RETARDATION FACTOR NCRIT

For assessing the sensitivity of TROPGLEAMS to Ncrit, the model was run using values of Ncrit equal to 0.0, 0.01, 0.02, 0.04, 0.06, and 0.08. These values were chosen because soils with no nitrate sorption capacity have Ncrit equal to zero and the value for a highly weathered Oxisol of Guadeloupe was measured as 0.05. A maximum value of 0.08

was set in order to explore model performance in the extreme range. The temperature dataset used had a mean annual temperature of 24.52°C, and the chosen pH was 6.5. Total $NO_3^-$-N in leachate and in runoff for a three year simulation were the output variables used to assess model sensitivity to Ncrit. Relative sensitivity was calculated for each value of Ncrit using the same methodology used to assess model sensitivity to temperature.

Figure 4.66 shows total $NO_3^-$-N in leachate and total $NO_3^-$-N in runoff simulated by TROPGLEAMS with nitrate leaching retardation factor (Ncrit) varying from 0.0 to 0.08, while Table 4.24 shows values of relative sensitivity of both models for the same output variables and variation of Ncrit. With an increasing value of the retardation factor, a build-up of nitrate is observed in soil layers, less nitrate is available for leaching, while more is available on the soil surface for runoff. This tendency could be observed in the values simulated by TROPGLEAMS and resulted in negative relative sensitivity to increasing values of Ncrit for $NO_3^-$-N in leachate and positive relative sensitivity to $NO_3^-$-N in runoff.

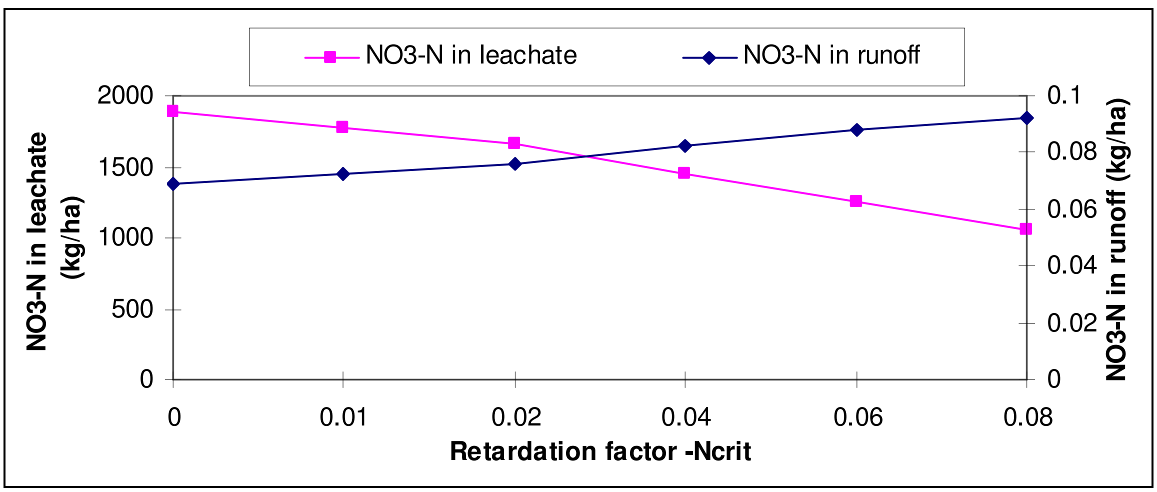


**Figure 4.66.** Total $NO_3^-$-N in leachate and in runoff from plots planted with a wheat/soybean rotation with nitrogen leaching retardation factor varying from 0.0 to 0.08 for a three year simulation using TROPGLEAMS.

**Table 4.24.** Relative sensitivity of TROPGLEAMS to variations in Ncrit, having $NO_3^-$-N in leachate and in runoff as output variables. The baseline for each value is the condition set with the next smaller value of Ncrit.

| Ncrit | Relative sensitivity for $NO_3^-$-N in leachate | Relative sensitivity for $NO_3^-$-N in runoff |
|---|---|---|
| 0.01 | 0.00 | 0.00 |
| 0.02 | -0.06 | 0.05 |
| 0.04 | -0.12 | 0.08 |
| 0.06 | -0.28 | 0.13 |
| 0.08 | -0.46 | 0.14 |

Relative sensitivity at Ncrit equal to 0.01 was zero because the base value of the input parameter was zero. Increasing absolute values of relative sensitivity are observed in both output variables, characterizing TROPGLEAMS as non-linearly sensitive to changes in Ncrit for $NO_3^-$-N in leachate and in runoff as output variables.

## 4.3.3. MODEL SENSITIVITY TO PH

The same methodology discussed for assessing model sensitivity to Ncrit was used in assessing the sensitivity of TROPGLEAMS to pH. The output variables used were $NO_3^-$-N in leachate and in runoff, since pH affects only the calculation of nitrification. Values of pH evaluated were 3.0, 3.5, 4.5, 5.5, 6.5, and 7.5. These values were chosen because no nitrification is calculated by TROPGLEAMS at pH under 3.0 and a maximum rate is reached at pH 6.5. Values were also calculated at pH 7.5 to assess model performance at this extreme value. Ncrit was set as 0.03 and the temperature dataset used had a mean annual temperature of 24.52°C.

Total $NO_3^-$-N in leachate and in runoff for a three year simulation were the output variables used to assess model sensitivity to pH. Relative sensitivity was calculated for each value of pH using the same methodology used to assess model sensitivity to temperature.

Figure 4.67 shows total $NO_3^-$-N in leachate and in runoff simulated by TROPGLEAMS with pH varying from 3.0 to 7.5, while Table 4.21 shows the relative sensitivity of both models for the same output variables and variation of pH.

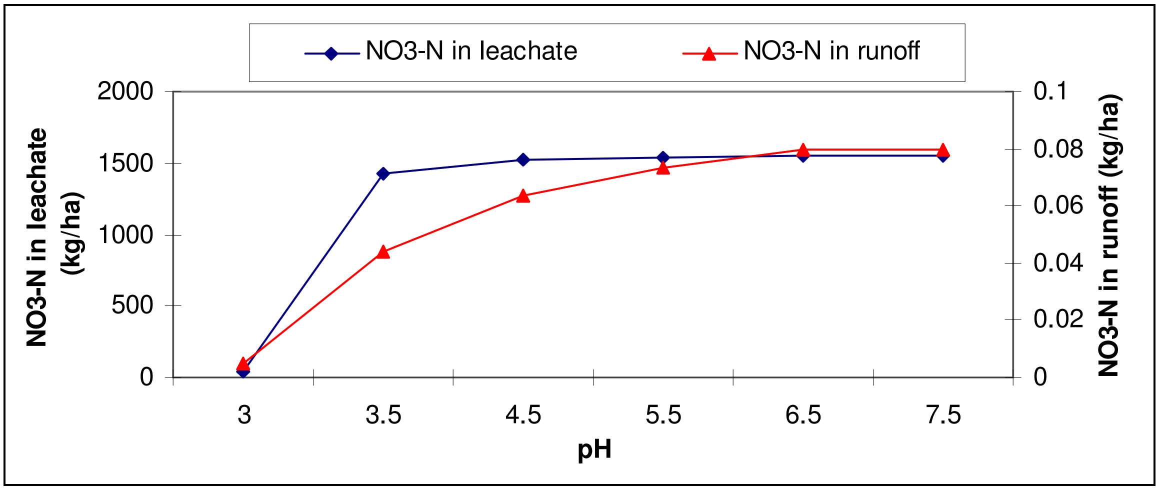


**Figure 4.67.** Total $NO_3^-$-N in leachate and in runoff from plots planted with a wheat/soybean rotation with pH varying from 3.0 to 7.5 for a three year simulation using TROPGLEAMS.

**Table 4.25.** Relative sensitivity of TROPGLEAMS to variations in pH, having $NO_3^-$-N in leachate and in runoff as output variables. The baseline for each value is the condition set with the next smaller value of pH.

| pH | Relative sensitivity for $NO_3^-$-N in leachate | Relative sensitivity for $NO_3^-$-N in runoff |
|---|---|---|
| 3.5 | 183.88 | 46.95 |
| 4.5 | 0.25 | 1.58 |
| 5.5 | 0.07 | 0.66 |
| 6.5 | 0.04 | 0.47 |
| 7.5 | 0.00 | 0.00 |

With pH equal to zero, no nitrification was simulated by TROPGLEAMS and nitrate available for leaching and runoff was only the concentrations set for initial conditions because all nitrogen input to the plot was in the form of organic nitrogen or urea. Increasing pH increases the rate of nitrification up to pH=6.5, when the rate reaches maximum value. With greater rates of nitrification, more nitrate is formed and becomes available for leaching and runoff. This tendency was observed in the simulations that resulted in Figure 4.72. Higher values of $NO_3^-$-N in leachate and runoff were simulated when soil pH increased from 3.0 to 6.5. Increasing pH above 6.5 did not result in higher values of the output variables in analysis. Relative sensitivity of TROPGLEAMS is positive for $NO_3^-$-N in both leachate and runoff. The model is more sensitive for lower pH and not sensitive for pH higher than 6.5.

# CHAPTER V
# CONCLUSIONS AND RECOMMENDATIONS

## 5.1. CONCLUSIONS

The widely-used NPS model GLEAMS (Knisel and Davis, 1999) was adapted to better represent the transformations and losses of nitrogen and phosphorus in leachate and in runoff from crop fields under humid tropical conditions. Model subroutines related to the simulation of potential evapotranspiration, nutrient initial values, transformations and transport of nitrogen and phosphorus, and transport of nitrogen were changed and the modified model was named TROPGLEAMS.

TROPGLEAMS was evaluated using specific components of model verification, model validation, and sensitivity analysis. Verification was carried out through a general analysis of the model, calculation of a mass balance of nutrients, and the observation of the variation of selected output variables in time. Model validation included the application of GLEAMS and TROPGLEAMS to three data sets, with comparison of measured values of selected output variables with values simulated by the models. Measured data were obtained from three studies. The first study was carried out in Piracicaba, SP, Brazil and used replicate lysimeters planted with sugarcane. Data of cumulative percolated water and mineral nitrogen in leachate were used. The second study was also located in Piracicaba and included plots planted with sugarcane fertilized with mineral nitrogen and different doses of sewage sludge. Soil water suction extractors were installed at 30 and 60 cm soil depth and composite soil water samples were collected and analyzed for total Kjeldahl nitrogen (TKN), nitrate, and ammonium. Soil samples were also collected and also compared with model results. The third study included plots located in Lages, SC, Brazil with a wheat-soybean rotation. The data collected from the plots and used in the model validation consisted of 51 measurements of $NO_3^-$-N, $NH_4^+$-N, and $PO_4$ concentrations in runoff from each plot, as well as total runoff and sediment yield for each crop period (total runoff and sediment yield between planting and harvesting of each crop). Graphical comparison between the results of both models and between measured and simulated values, along with the calculation of the root means square error (RMSE) between measured values and that simulated by both models were used to assess the performance of both models under tropical conditions.

The limited availability of field data, in particular the lack of long term data on losses of nutrients undertypical tropical conditions, constrains the conclusions that can be drawn from this study. Yet, the following can be stated:

- The changes made in GLEAMS resulted in a model that is more accurate than the original in simulating fate and transport of nutrients under humid tropical conditions.
- The FAO Penman Monteith algorithm implemented in TROPGLEAMS to calculate potential evapotranspiration (PET) resulted in a better prediction of actual ET than that predicted by GLEAMS.
- TROPGLEAMS improves the representation of nitrogen and phosphorus kinetics and the influence of environmental factors (temperature, pH, and soil water content) in the transformations between their several pools. In terms of mass balance of nutrients, TROPGLEAMS is as accurate as GLEAMS is.
- TROPGLEAMS was more accurate than GLEAMS in the simulation of nitrogen in leachate in the Piracicaba lysimeter study.
- For the environmental conditions of the Piracicaba plot study, TROPGLEAMS was superior to GLEAMS in simulating ammonium and nitrate concentration in soil solution and mineral nitrogen and TKN concentration in soil.
- GLEAMS and TROPGLEAMS did not predict $NO_3^-$-N in runoff well in the environmental conditions of the Lages plot study. Both models highly overpredicted this variable, indicating that improvements in TROPGLEAMS related to superficial movement of nitrate are needed. Losses of $NH_4^+$-N and $PO_4$-P in runoff in plots of the same study were better predicted with TROPGLEAMS than with GLEAMS.
- TROPGLEAMS simulated the effect of tillage on losses of $NH_4^+$-N in runoff in the Lages plot study better than GLEAMS.

- The inclusion of a retardation factor for the simulation of nitrate leaching (Ncrit) as well as the new model to simulate nitrification using a pH factor resulted in better simulation of transformations and losses of nitrogen under tropical conditions.

# 5.2. RECOMMENDATIONS

TROPGLEAMS is the first field-scale NPS model adapted for simulating fate and transport of nitrogen and phosphorus under tropical conditions. Several algorithms were implemented during its adaptation, while most subroutines and internal databases continued the same as in GLEAMS. In addition, during the model validation carried out for this study, it was observed that the model was more accurate in simulating losses in leachate than losses in runoff.

Future work need to be done in order to improve model representation and accuracy, and the following research is suggested:

- The database of GLEAMS/TROPGLEAMS contains default values of parameters PY (potential yield), DMY (ratio total dry matter/yield), CNR (C:N ratio on harvest), RNP (N/P ratio on harvest), C1, and C2 (coefficients to simulate the percent N content of the dry matter). It was observed that the high C:N ratio for sugarcane caused a decrease in the values of $NH_4^+$-N and $NO_3^-$-N in soil solution after harvesting (when the model incorporates all crop residue in the soil and on the soil surface) and that this decrease did not reflect measured values in most cases. The validity of the model default values should be checked having in mind the different crop varieties usually planted in the tropics.
- GLEAMS has a model to calculate interception for forested fields, but this phenomenon is not simulated for crop fields. The inclusion of a model to simulate rainfall interception in crop fields will certainly give more accuracy to the GLEAMS hydrology component.
- The model that simulates soil temperature was not evaluated under tropical conditions. Since soil temperature affects nutrient kinetics, the evaluation of this model is recommended.

- GLEAMS and TROPGLEAMS calculate coefficients that constrain the quantity of ammonium and labile phosphorus available for plant uptake and leaching. These coefficients are calculated using the clay content of each layer. During this study, it was observed that soil P sorption, a variable also calculated using soil clay content, was overpredicted in highly clayey tropical soils. The appropriateness of using the equation that constrains ammonium and labile phosphorus available for plant uptake and leaching also has to be verified.
- In GLEAMS and TROPGLEAMS, the transformation between labile P (PLAB) and active mineral P (PMINP) is the result of the difference in their concentration multiplied by soil water, temperature, and sorption factors. The temperature factor has values less than 1 for temperatures below 25$^{o}$C, but shows a sharp increase in temperatures above 25$^{o}$C (1.75 and 5.5 at temperatures of 30 and 40$^{o}$C, respectively). Since soil temperatures in the first soil layers of tropical soils reach 40$^{o}$C very frequently, this model may overestimate the rate of transformations between PLAB and PMINP and its validity for being used under tropical conditions has to be evaluated.
- It was observed during the application of TROPGLEAMS to the Piracicaba plot study that, although the results of soil TKN concentration for TROPGLEAMS were more accurate than for GLEAMS, a measured increase in TKN after sludge application was not accompanied by increases in the values of TROPGLEAMS. A decrease in the rate of soil organic matter decomposition would certainly make TROPGLEAMS results closer to the values observed. More studies are suggested in order to check the validity of the rate of soil organic matter decomposition used in TROPGLEAMS.
- GLEAMS and TROPGLEAMS underpredicted $NO_3^-$-N concentration in runoff significantly. More studies on the processes involving nitrate in soil surface in the tropics is suggested, mainly those related to the coefficient of extraction of $NO_3^-$-N for runoff and the temperature on the soil surface.
- TROPGLEAMS overpredicted $PO_4$-P in runoff and one of the causes for this may be the value of the P extraction coefficient for runoff used in the model. This

coefficient may be too high for tropical soils, which have more P adsorption capacity than temperate soils. The evaluation of the P extraction coefficient for runoff is suggested.

- The application of TROPGLEAMS to different areas of the humid tropics is recommended in order to further evaluate it under a broader range of soils and crop systems.

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# APPENDIX

## APPENDIX A – ORGANIC FERTILIZATION

The nutrient input file editor, shows five options for fertilizer application: surface, incorporated, injected, fertigation, and liquid animal waste. Since the same menu is open when either chemical or organic fertilizers are to be used, it is supposed that the model is capable of simulating subsurface organic fertilizer application. In the day of fertilization either the subroutines FERTIL or ANWAST are called if the fertilizer is inorganic or organic, respectively. While FERTIL has algorithms to simulate all options contained in the input editor, subroutine ANWAST has complete algorithm only for simulating surface application. If the user opts for incorporating animal waste, the model keeps the fertilizer in soil surface. Figure A1 shows model result of organic P in kg/ha in the first three soil layers when in the input parameter file was set the application of manure on day 50 incorporated to 20 cm and a passage of a tillage using disk harrow on day 100.

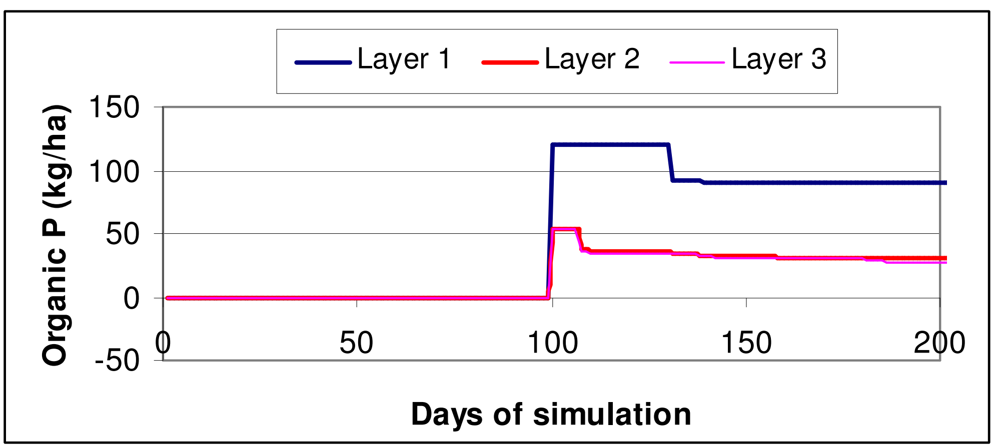


**Figure A.1.** Result of the simulation of an application of manure on day 50 incorporated to 20 cm and the use of a disk harrow on day 100 using the original GLEAMS

It can be observed that organic P applied through manure is kept in soil surface from the day of application to the day of tillage, when the superficial material is incorporated according to the algorithm of the subroutine PLOW.

Since the incorporation of manure is an agricultural practice frequently used in the tropics, the subroutine ANWAST was modified to simulate the incorporation of animal waste. The change was the simulation of the use of a disk harrow just after surface application of organic material. In this case, all components modeled by GLEAMS are mixed in the layers reached by the tillage implement according to the same algorithm of the subroutine PLOW. Figure A.2 shows simulated organic P (kg/ha) in the first three soil layers after the application of manure on day 50 incorporated to the depth of 20 cm and the use of a disk harrow on day 100 using TROPGLEAMS.

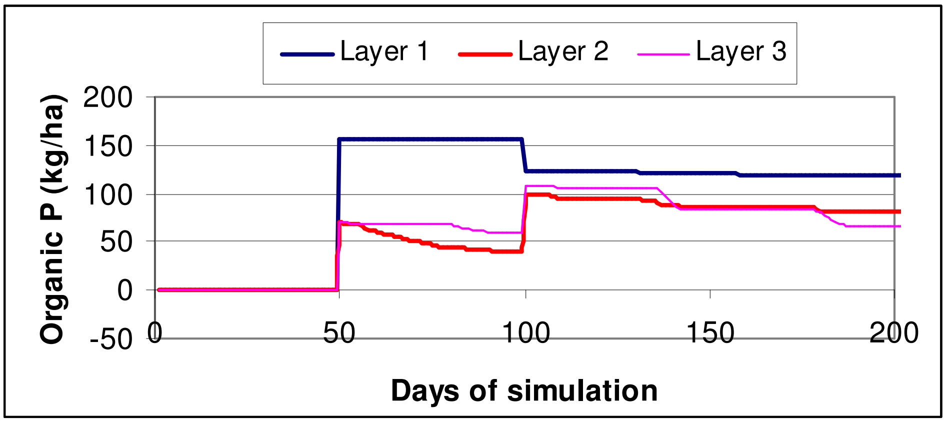


**Figure A2 .** TROPGLEAMS Simulation of the application of manure on day 50 incorporated to depth 20 cm and the use of disk harrow on day 100.

After the changes, the model passed to be capable of simulating the incorporation of animal waste in the same time in which it is applied, as can be seen in figure A.2.

# APPENDIX B – BALANCE OF NUTRIENTS

**Table B.1.** Annual nutrient balances for the first year of a 3-year simulation of a field planted with sugarcane using the modified GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| NITROGEN | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 84.27 | 215,35 | 131,08 |
| $NH_4^+$ | 160.11 | 161,66 | 1,54 |
| Potentially mineralizable N | 1476.35 | 108,15 | -1368,2 |
| Stable soil N | 7007.97 | 7007,96 | -0,01 |
| Crop residue organic N | 40 | 0 | -40 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 23.2 | 1,38 | -21,82 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 0 | 32,57 | 32,57 |
| Runoff N | | | 0 |
| Sediment N | | | -0.01 |
| $NO_3^-$ Leached | | | -1112.01 |
| $NH_4^+$ Leached | | | -69.64 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -113.18 |
| Yield N | | | 0 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 30 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 8791.91 | | |
| Sum end pools | | -7527.07 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.1. Continuation

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 19.08 | 60.29 | 41.21 |
| Active Org P | 340.65 | 292.8 | -47.85 |
| Crop Org P | 10 | 0 | -10 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 117.18 | 278.37 | 161.19 |
| Stable Min P | 468.73 | 499.55 | 30.82 |
| SURFACE | | | |
| Residue P | 2.9 | 2.01 | -0.89 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 0 | 5.41 | 5.41 |
| Runoff P | | | 0 |
| Sediment P | | | 0 |
| P Leached | | | -0.11 |
| Yield P | | | 0 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 180 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 958.54 | | |
| Sum End Pools | | -1138.43 | |
| **Phosphorus Balance** | | | **0.00** |

**Table B.2.** Annual nutrient balances for the second year of a 3-year simulation of a field planted with sugarcane using the modified GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| **NITROGEN** | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 215.35 | 57.96 | -157.39 |
| $NH_4^+$ | 161.66 | 76.97 | -84.69 |
| Potentially mineralizable N | 108.15 | 22.7 | -85.45 |
| Stable soil N | 7007.96 | 7007.96 | 0 |
| Crop residue organic N | 0 | 76.25 | 76.25 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 1.38 | 6.24 | 4.86 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 32.57 | 132.83 | 100.26 |
| Runoff N | | | 0 |
| Sediment N | | | 0 |
| $NO_3^-$ Leached | | | -190.34 |
| $NH_4^+$ Leached | | | -11.35 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -26.52 |
| Yield N | | | -77.94 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 160 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 7527.07 | | |
| Sum end pools | | -7380.91 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.2. Continuation

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 60.29 | 20.82 | -39.47 |
| Active Org P | 292.8 | 296.22 | 3.42 |
| Crop Org P | 0 | 10.4 | 10.4 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 278.37 | 180.41 | -97.96 |
| Stable Min P | 499.55 | 591.39 | 91.84 |
| SURFACE | | | |
| Residue P | 2.01 | 1.24 | -0.77 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 5.41 | 23.16 | 17.76 |
| Runoff P | | | 0 |
| Sediment P | | | 0 |
| P Leached | | | -0.05 |
| Yield P | | | -14.74 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 0 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 1138.43 | | |
| Sum End Pools | | -1123.65 | |
| **Phosphorus Balance** | | | **0.00** |

**Table B.3**. Annual nutrient balances for the third year of a 3-year simulation of a field planted with sugarcane using the modified GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| NITROGEN | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 57.96 | 0.04 | -57.92 |
| $NH_4^+$ | 76.97 | 0.05 | -76.91 |
| Potentially mineralizable N | 22.7 | 6.73 | -15.97 |
| Stable soil N | 7007.96 | 7007.73 | -0.23 |
| Crop residue organic N | 76.25 | 140.93 | 64.68 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 6.24 | 50.52 | 44.29 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 132.83 | 4.68 | -128.15 |
| Runoff N | | | 0 |
| Sediment N | | | -0.23 |
| $NO_3^-$ Leached | | | -1.8 |
| $NH_4^+$ Leached | | | -1.89 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -2.62 |
| Yield N | | | -163.68 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 0 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 7380.91 | | |
| Sum end pools | | -7210.69 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.3. Continuation

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 20.82 | 19.23 | -1.59 |
| Active Org P | 296.22 | 299.63 | 3.41 |
| Crop Org P | 10.4 | 26.68 | 16.28 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 180.41 | 129.3 | -51.11 |
| Stable Min P | 591.39 | 590.73 | -0.66 |
| SURFACE | | | |
| Residue P | 1.24 | 12.18 | 10.94 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 23.16 | 5.75 | -17.41 |
| Runoff P | | | 0 |
| Sediment P | | | -0.04 |
| P Leached | | | -0.03 |
| Yield P | | | -40.09 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 0 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 1123.65 | | |
| Sum End Pools | | -1083.49 | |
| **Phosphorus Balance** | | | **0.00** |

**Table B.4.** Annual nutrient balances for the first year of a 3-year simulation of a field planted with sugarcane using the original GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| NITROGEN | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 42.13 | 5.84 | -36.3 |
| $NH_4^+$ | 16.85 | 0 | -16.85 |
| Potentially mineralizable N | 1135.66 | 1143.87 | 8.21 |
| Stable soil N | 5487.83 | 5487.82 | -0.01 |
| Crop residue organic N | 40 | 3.64 | -36.36 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 23.2 | 16.86 | -6.34 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 0 | 19.37 | 19.37 |
| Runoff N | | | 0 |
| Sediment N | | | -0.01 |
| $NO_3^-$ Leached | | | -89.13 |
| $NH_4^+$ Leached | | | 0 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -9.15 |
| Yield N | | | 0 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 30 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 6745.67 | | |
| Sum end pools | | -6677.39 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.4. Continuation.

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 56.88 | 139.59 | 82.72 |
| Active Org P | 1015.65 | 1024.16 | 8.51 |
| Crop Org P | 10 | 0 | -10 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 418.09 | 506.68 | 88.59 |
| Stable Min P | 1672.36 | 1676.79 | 4.43 |
| SURFACE | | | |
| Residue P | 2.9 | 3.83 | 0.93 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 0 | 4.54 | 4.54 |
| Runoff P | | | 0 |
| Sediment P | | | 0 |
| P Leached | | | -0.28 |
| Yield P | | | 0 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 180 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 3175.87 | | |
| Sum End Pools | | -3355.59 | |
| **Phosphorus Balance** | | | **0.00** |

**Table B.5.** Annual nutrient balances for the second year of a 3-year simulation of a field planted with sugarcane using the original GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| **NITROGEN** | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 5.84 | 32.71 | 26.88 |
| $NH_4^+$ | 0 | 3.15 | 3.15 |
| Potentially mineralizable N | 1143.87 | 1143.82 | -0.05 |
| Stable soil N | 5487.82 | 5487.81 | 0 |
| Crop residue organic N | 3.64 | 44.36 | 40.72 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 16.86 | 5.88 | -10.98 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 19.37 | 70.29 | 50.92 |
| Runoff N | | | 0 |
| Sediment N | | | 0 |
| $NO_3^-$ Leached | | | -5.26 |
| $NH_4^+$ Leached | | | 0 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -5.42 |
| Yield N | | | -38.68 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 160 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 6677.39 | | |
| Sum end pools | | -6788.03 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.5. Continuation

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 139.59 | 83.23 | -56.36 |
| Active Org P | 1024.16 | 1027.64 | 3.48 |
| Crop Org P | 0 | 8.83 | 8.83 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 506.68 | 482.31 | -24.36 |
| Stable Min P | 1676.79 | 1752.35 | 75.56 |
| SURFACE | | | |
| Residue P | 3.83 | 1.61 | -2.22 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 4.54 | 17.43 | 12.89 |
| Runoff P | | | 0 |
| Sediment P | | | 0 |
| P Leached | | | -0.13 |
| Yield P | | | -12.05 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 30 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 3355.59 | | |
| Sum End Pools | | -3373.4 | |
| **Phosphorus Balance** | | | **0.00** |

**Table B.6.** Annual nutrient balances for the third year of a 3-year simulation of a field planted with sugarcane using the original GLEAMS. Use of the first scheme of fertilization, in which only mineral fertilizers were applied.

| **NITROGEN** | | | |
|---|---|---|---|
| | Begin kg/ha | End kg/ha | Net change kg/ha |
| SOIL | | | |
| $NO_3^-$ | 32.71 | 0.06 | -32.65 |
| $NH_4^+$ | 3.15 | 0 | -3.15 |
| Potentially mineralizable N | 1143.82 | 1143.36 | -0.46 |
| Stable soil N | 5487.81 | 5487.64 | -0.18 |
| Crop residue organic N | 44.36 | 69.63 | 25.27 |
| Animal waste organic N | 0 | 0 | 0 |
| SURFACE | | | |
| Residue N | 5.88 | 21.87 | 16 |
| Soluble $NH_3$ | 0 | 0 | 0 |
| Soluble $NO_3^-$ | 0 | 0 | 0 |
| Animal waste organic N | 0 | 0 | 0 |
| Animal waste $NH_4^+$ | 0 | 0 | 0 |
| Plant N | 70.29 | 1.45 | -68.84 |
| Runoff N | | | 0 |
| Sediment N | | | -0.22 |
| $NO_3^-$ Leached | | | -0.05 |
| $NH_4^+$ Leached | | | 0 |
| Volatized $NH_3^-$ | | | 0 |
| Denitrified N | | | -0.14 |
| Yield N | | | -63.61 |
| Bale N | | | 0 |
| Burned N | | | 0 |
| Fixed N | | | 0 |
| Rainfall N | | | 0 |
| Irrigation N | | | 0 |
| Fertilizer $NO_3^-$ | | | 0 |
| Fertilizer $NH_4^+$ | | | 0 |
| Animal waste organic N | | | 0 |
| Animal waste $NO_3^-$ | | | 0 |
| Animal waste $NH_4$ | | | 0 |
| Sum begin pools | 6788.03 | | |
| Sum end pools | | -6724.01 | |
| **Nitrogen Balance** | | | **0.00** |

Table B.6. Continuation

| PHOSPHORUS | | | |
|---|---|---|---|
| | BEGIN (KG/HA) | END (KG/HA) | NET CHANGE (KG/HA) |
| SOIL | | | |
| Labile P | 83.23 | 54.13 | -29.1 |
| Active Org P | 1027.64 | 1030.01 | 2.37 |
| Crop Org P | 8.83 | 24.21 | 15.38 |
| Animal waste organic P | 0 | 0 | 0 |
| Active Min P | 482.31 | 440.36 | -41.95 |
| Stable Min P | 1752.35 | 1769.84 | 17.49 |
| SURFACE | | | |
| Residue P | 1.61 | 16.95 | 15.34 |
| Sol P | 0 | 0 | 0 |
| Animal waste organic P | 0 | 0 | 0 |
| Plant P | 17.43 | 4.55 | -12.88 |
| Runoff P | | | -0.03 |
| Sediment P | | | -0.13 |
| P Leached | | | -0.09 |
| Yield P | | | -33.1 |
| Bale P | | | 0 |
| Burned P | | | 0 |
| Irrigation P | | | 0 |
| Fertilizer P | | | 0 |
| Animal waste organic P | | | 0 |
| Animal waste P | | | 0 |
| Sum Beg Pools | 3373.4 | | |
| Sum End Pools | | -3340.06 | |
| **Phosphorus Balance** | | | **0.00** |

# APPENDIX C – RAINFALL DATA

**Table C.1**.Daily precipitation + irrigation data used as input in the Piracicaba lysimeter study.

| Year | Precipitation + irrigation (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 0.08 | 3.15 | 2.56 | 0.14 | 0.64 | 0.93 | 0.65 | 1.59 | 0.09 | 0.28 |
| 1996 | 0 | 2.57 | 0 | 0 | 0 | 0.34 | 0.2 | 0.91 | 0 | 0.31 |
| 1996 | 0.03 | 0 | 0 | 0.32 | 0 | 0 | 0.03 | 0 | 0 | 0.32 |
| 1996 | 0 | 0.34 | 0.28 | 0.52 | 0.05 | 0.46 | 0.42 | 1.66 | 0.11 | 0.97 |
| 1996 | 0.42 | 0.78 | 0 | 0 | 1.3 | 0 | 0 | 0.73 | 0.09 | 0.66 |
| 1996 | 0 | 1.3 | 0 | 0 | 0.43 | 1.76 | 1.25 | 1.04 | 1.46 | 2.1 |
| 1996 | 0.18 | 0.01 | 0.19 | 0.45 | 0 | 1.12 | 2.24 | 0.74 | 0.27 | 1.3 |
| 1996 | 0 | 0.47 | 0 | 0.71 | 0.49 | 0.83 | 0.03 | 1.3 | 0.18 | 0.12 |
| 1996 | 0 | 1.3 | 0.69 | 0 | 0 | 2.08 | 0.28 | 0 | 0.51 | 0 |
| 1996 | 1.75 | 0 | 0 | 1.75 | 0 | 0 | 1.75 | 0 | 0 | 1.75 |
| 1996 | 0 | 2.05 | 0.01 | 0.01 | 0.09 | 0.02 | 0.8 | 0 | 2.02 | 0 |
| 1996 | 0 | 2.05 | 0 | 0 | 2.05 | 0 | 0 | 2.18 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0.52 | 0 | 0 | 0 | 0.31 |
| 1996 | 0.02 | 0 | 0 | 0.52 | 0 | 1.76 | 0.24 | 0.03 | 0.19 | 0 |
| 1996 | 0 | 0.32 | 0.09 | 0.08 | 0 | 0 | 0.52 | 0 | 0 | 0 |
| 1996 | 2 | 0 | 0 | 0 | 0 | 2 | 0.17 | 0.33 | 0 | 0 |
| 1996 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 2.03 | 0 | 0 | 0 | 0 | 0 | 1.01 | 0.82 |
| 1996 | 0 | 0 | 0 | 0 | 0.16 | 0 | 0 | 1 | 0 | 0 |
| 1996 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 1996 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0.07 | 0 |
| 1996 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 1996 | 0 | 1.02 | 0.12 | 0.05 | 0 | 0 | 1.18 | 0 | 0 | 1 |
| 1996 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 1996 | 0 | 0 | 0 | 0 | 0.52 | 0.66 | 2.68 | 0.39 | 0.64 | 0 |
| 1996 | 0 | 2.17 | 1.63 | 3.16 | 0 | 0 | 0 | 0 | 1 | 1.14 |
| 1996 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0.48 | 0.05 | 0 |
| 1996 | 0.97 | 0 | 0 | 0 | 0 | 2.05 | 1.46 | 0 | 0.39 | 1.05 |
| 1996 | 0 | 0 | 0 | 2.24 | 0 | 2.34 | 2.04 | 0 | 0 | 0 |
| 1996 | 0 | 1.3 | 0.44 | 0.86 | 0 | 0 | 0.65 | 0 | 1.44 | 2.12 |
| 1996 | 0.57 | 0 | 0 | 1.23 | 2.64 | 1.63 | 1.48 | 0.31 | 0 | 0 |
| 1996 | 0 | 0.65 | 0 | 0 | 0 | 0 | 0.19 | 0.37 | 0.54 | 3.32 |
| 1996 | 0.46 | 2.62 | 0 | 2.2 | 2.2 | 0.03 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 1.5 | 0 | 0 | 0.04 | 0.04 | 0.01 | 0.18 | 0.03 |
| 1996 | 0 | 0.43 | 0 | 0 | 0.6 | 0.07 | 0.11 | 0.11 | 0 | 0.25 |
| 1996 | 0.84 | 0.2 | 0 | 0.15 | 0.07 | 0.23 | 1.11 | 0 | 0.37 | 0.03 |
| 1996 | 0 | 0.2 | 0.11 | 0.13 | 0 | 0.02 | | | | |

**Table C.2**. Daily precipitation data used as input in the Piracicaba plot study.

| Year | Daily precipitation (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 0.17 | 6.85 | 5.57 | 0.31 | 1.4 | 2.02 | 1.42 | 3.45 | 0.19 | 0.61 |
| 1996 | 0 | 5.45 | 0 | 0 | 0 | 0.82 | 0.43 | 1.99 | 0 | 0.68 |
| 1996 | 0.06 | 0 | 0 | 0 | 0 | 0 | 0.06 | 0 | 0 | 0 |
| 1996 | 0 | 0.82 | 0.61 | 1.14 | 0.1 | 0 | 0.92 | 1.66 | 0.11 | 0.97 |
| 1996 | 0.65 | 1.21 | 0 | 0 | 0 | 0 | 0 | 1.12 | 0.13 | 1.01 |
| 1996 | 0 | 0 | 0 | 0 | 0.66 | 2.71 | 1.92 | 4.63 | 2.24 | 3.22 |
| 1996 | 0.28 | 0.01 | 0.29 | 0.69 | 0 | 1.73 | 3.45 | 1.14 | 0.42 | 0 |
| 1996 | 0 | 0.73 | 0 | 1.09 | 0.76 | 1.27 | 0.04 | 0 | 0.28 | 0.19 |
| 1996 | 0 | 0 | 1.06 | 0 | 0 | 0 | 0.43 | 0 | 0.79 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0.02 | 0.01 | 0.09 | 0.02 | 1.06 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.31 |
| 1996 | 0.02 | 0 | 0 | 0 | 0 | 2.35 | 0.24 | 0.03 | 0.19 | 0 |
| 1996 | 0 | 0.32 | 0.09 | 0.08 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0.17 | 0.33 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.01 | 0.82 |
| 1996 | 0 | 0 | 0 | 0 | 0.16 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.07 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 1.02 | 0.12 | 0.05 | 0 | 0 | 1.18 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0.52 | 0.66 | 2.68 | 0.39 | 0.64 | 0 |
| 1996 | 0 | 2.17 | 1.63 | 3.16 | 0 | 0 | 0 | 0 | 0 | 1.14 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.48 | 0.05 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 3.15 | 2.24 | 0 | 0.39 | 1.61 |
| 1996 | 0 | 0 | 0 | 3.45 | 0 | 3.6 | 3.14 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0.68 | 1.32 | 0 | 0 | 0 | 0 | 2.22 | 0.19 |
| 1996 | 0.88 | 0 | 0 | 0 | 0.98 | 0.97 | 2.28 | 0.31 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.37 | 0.54 | 5.11 |
| 1996 | 0.46 | 4.04 | 0 | 3.38 | 3.41 | 0.03 | 0 | 0 | 0 | 0 |
| 1996 | 0 | 0 | 0 | 0 | 0 | 0.15 | 0.17 | 0.04 | 0.72 | 0.14 |
| 1996 | 0 | 1.72 | 0 | 0 | 2.4 | 0.28 | 0.44 | 0.46 | 0 | 0 |
| 1996 | 3.37 | 0.81 | 0 | 0.46 | 0.3 | 0.92 | 4.46 | 0.01 | 0 | 0.14 |
| 1996 | 0 | 0.81 | 0.43 | 0.52 | 0 | 0.08 | | | | |
| 1997 | 0 | 0.04 | 0 | 0 | 0 | 0.03 | 0.29 | 1.26 | 0.11 | 2.58 |
| 1997 | 0.65 | 1.09 | 0.2 | 0.11 | 0.04 | 0.01 | 0.58 | 0 | 1.92 | 3.03 |
| 1997 | 0.1 | 1.94 | 1.95 | 2.73 | 0.27 | 1.65 | 3.61 | 3.36 | 0 | 0.12 |
| 1997 | 3.18 | 0 | 0.68 | 1.06 | 0 | 0 | 0 | 0 | 0 | 0.07 |
| 1997 | 0.01 | 0 | 1.33 | 0.33 | 0.32 | 0.42 | 2.85 | 0.96 | 0.02 | 0 |
| 1997 | 0.38 | 0.06 | 0 | 0.22 | 0 | 0 | 0 | 0 | 0 | 0 |

Table C.2 continuation.

| Year | Daily precipitation (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1997 | 0 | 0.32 | 0.2 | 1.86 | 0.02 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 2.61 | 0 | 0.29 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.01 | 2 |
| 1997 | 0 | 0.45 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 1.41 | 0 | 0 | 0.13 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0.01 | 0.18 | 0 | 0 | 0.01 | 0 |
| 1997 | 0 | 0.59 | 0.01 | 2.01 | 1.48 | 0 | 0.01 | 1.19 | 0.01 | 0 |
| 1997 | 0 | 0 | 0 | 0.29 | 1.2 | 5.08 | 0.06 | 0 | 0 | 0 |
| 1997 | 0.01 | 0.52 | 0.54 | 0.01 | 1.46 | 0.87 | 0 | 0 | 0 | 0 |
| 1997 | 0.79 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.01 |
| 1997 | 0 | 1.82 | 0.01 | 0.02 | 0 | 0.01 | 0 | 0.01 | 0.01 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0 | 0.01 | 0.02 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0.01 | 0 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0.01 | 0 | 0 | 1.55 | 0.01 | 0 | 0 | 0 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.17 | 0 |
| 1997 | 0 | 0 | 0.01 | 0 | 0 | 0 | 3.5 | 0.17 | 0 | 0 |
| 1997 | 0 | 0 | 2.4 | 0.08 | 0 | 0 | 0 | 1.28 | 0.15 | 0 |
| 1997 | 0 | 1.32 | 0.01 | 1.29 | 0 | 0 | 0 | 0 | 0.4 | 0.24 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.11 | 0.53 | 0.01 |
| 1997 | 0 | 0.11 | 1.78 | 0.04 | 0 | 0 | 0 | 0.46 | 0.63 | 0 |
| 1997 | 0 | 0 | 0.29 | 0.07 | 2.83 | 0 | 0 | 0 | 0 | 0.25 |
| 1997 | 0.16 | 0 | 0 | 0 | 0 | 0.85 | 0.87 | 0.01 | 2.4 | 1.66 |
| 1997 | 2.83 | 3.75 | 0.07 | 0 | 0.42 | 0.81 | 0.09 | 4.57 | 0.01 | 0.87 |
| 1997 | 3.29 | 0.46 | 0 | 0 | 0.48 | 0.89 | 0.01 | 2.2 | 0.01 | 0 |
| 1997 | 2.64 | 0.01 | 0 | 0 | 0 | 0 | 0.32 | 1.89 | 0.09 | 0 |
| 1997 | 0 | 0.07 | 0.01 | 0 | 0.35 | 0 | 0 | 7.68 | 0.72 | 0.03 |
| 1997 | 0 | 0 | 0 | 0.98 | 0 | | | | | |
| 1998 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0.07 | 1.27 | 0.04 | 0 |
| 1998 | 0 | 1.42 | 0 | 0 | 0.05 | 1.64 | 5 | 0 | 0 | 0.1 |
| 1998 | 0 | 0 | 0 | 0 | 0.45 | 0 | 0 | 0.77 | 0.01 | 0 |
| 1998 | 0.02 | 0.58 | 0.01 | 0 | 3.32 | 0.81 | 0.01 | 0.2 | 0.02 | 0 |
| 1998 | 2.13 | 1.7 | 0.45 | 2.74 | 1.89 | 0.14 | 0 | 0 | 0 | 5 |
| 1998 | 2.05 | 0.01 | 0 | 0 | 4.71 | 3.2 | 0.03 | 0.42 | 0.48 | 0 |
| 1998 | 0.47 | 0.92 | 0.41 | 0.01 | 0 | 0 | 0.01 | 0.2 | 0 | 3.62 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.94 | 0 | 0 |
| 1998 | 2.22 | 0 | 0 | 0.09 | 0 | 0 | 2.18 | 1 | 0.16 | 0 |
| 1998 | 0.72 | 0 | 0 | 0 | 0 | 0.05 | 0.16 | 0 | 2.46 | 0 |
| 1998 | 0 | 0.01 | 0 | 0 | 0 | 0 | 1.21 | 0.43 | 0 | 0 |
| 1998 | 0 | 0 | 0 | 0.02 | 0.01 | 0 | 0.01 | 1.53 | 0.4 | 0 |

Table C.2 continuation.

| Year | Daily precipitation (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1998 | 0 | 0 | 1.06 | 2.63 | 0.04 | 0 | 0 | 0 | 0.01 | 0.01 |
| 1998 | 0 | 0 | 0 | 0 | 0.02 | 0.31 | 0 | 0 | 0 | 0 |
| 1998 | 0.01 | 0.01 | 0 | 0 | 0 | 0.37 | 1.73 | 0 | 2.17 | 0.92 |
| 1998 | 0.03 | 0.01 | 0 | 0.01 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0.01 | 0 | 0 | 0 | 1.62 |
| 1998 | 0.01 | 0 | 0 | 0 | 0.76 | 0.01 | 0 | 0 | 0 | 0.02 |
| 1998 | 0.02 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0.02 | 0.01 | 0 | 0.62 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0.77 |
| 1998 | 0.01 | 0.02 | 0 | 0 | 0.01 | 0 | 0 | 0 | 0 | 0 |
| 1998 | 0 | 0 | 0 | 0.66 | 0.01 | 0.09 | 0.61 | 0.01 | 0 | 0 |
| 1998 | 0.39 | 0.03 | 0 | 0 | 0 | 0.41 | 0 | 0 | 0 | 0 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.68 | 0.15 | 0 |
| 1998 | 2.32 | 0.47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1998 | 0 | 3.3 | 0.16 | 0.19 | 0 | 0 | 0 | 0 | 0 | 0.06 |
| 1998 | 0.95 | 0.14 | 0.37 | 0 | 0 | 1.03 | 0.01 | 1.79 | 0 | 0.14 |
| 1998 | 4.14 | 1.44 | 0 | 1.59 | 0 | 0 | 0 | 0.01 | 1.38 | 1.19 |
| 1998 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.82 | 0.35 |
| 1998 | 0.11 | 0 | 0.37 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.01 |
| 1998 | 0 | 0.23 | 0 | 0.16 | 0.15 | 0 | 1.2 | 0 | 0 | 0 |
| 1998 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.74 |
| 1998 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 2.03 | 4.7 | 0.03 |
| 1998 | 0 | 0 | 1.11 | 1.84 | 3.84 | 0.1 | 0 | 0.8 | 2.17 | 0.51 |
| 1998 | 0.03 | 0 | 0 | 0 | 0 | 1.1 | 1.73 | 0.64 | 0.59 | 0.01 |
| 1998 | 1.88 | 0 | 1.99 | 0.03 | 0 | | | | | |

**Table C.3**. Daily precipitation data used as input in the Lages plot study.

| Year | Daily precipitation (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1999 | 0 | 0 | 0 | 1.81 | 0.12 | 0 | 0 | 0 | 0 | 0 |
| 1999 | 0 | 0.03 | 0 | 0.7 | 0.02 | 0 | 0.03 | 0.62 | 0.5 | 0.21 |
| 1999 | 2.54 | 2.86 | 0.68 | 0 | 0 | 0 | 0 | 3.53 | 0.07 | 0 |
| 1999 | 0 | 0 | 0.53 | 0 | 0 | 0.3 | 0 | 0.09 | 3.68 | 1.15 |
| 1999 | 0.05 | 0 | 0 | 1.07 | 0.22 | 0 | 0.98 | 0.02 | 0 | 0 |
| 1999 | 0.12 | 1.28 | 0 | 0 | 1.26 | 0.26 | 1.61 | 0 | 0 | 0 |
| 1999 | 1.51 | 0 | 0 | 0 | 0 | 0 | 0 | 0.41 | 2.19 | 0 |
| 1999 | 0 | 0 | 0.02 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0.97 |
| 1999 | 0.05 | 0 | 0 | 0 | 0.47 | 0 | 0 | 0.47 | 0 | 0.5 |
| 1999 | 0.54 | 2.7 | 0.03 | 0 | 1.27 | 0 | 2.26 | 0 | 0 | 0 |
| 1999 | 4.61 | 2.94 | 0.1 | 0.21 | 3.17 | 0.24 | 0.03 | 0 | 0 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0.59 | 1.28 | 0.33 | 0 | 0 | 0 |
| 1999 | 0.14 | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 | 0.57 | 0.15 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 2.4 | 0.74 | 0.33 | 5.26 | 0.02 |
| 1999 | 0 | 0 | 0 | 0.03 | 0 | 0.26 | 0 | 0 | 0.03 | 0.17 |
| 1999 | 4.82 | 0 | 0.39 | 0 | 0 | 0 | 0 | 0.2 | 0.39 | 0.02 |
| 1999 | 0.41 | 0 | 0 | 0 | 0.02 | 0.02 | 0 | 0 | 0 | 0.67 |
| 1999 | 0.05 | 0 | 7.63 | 5.96 | 0.2 | 0 | 0.6 | 0.65 | 0.02 | 0 |
| 1999 | 0.07 | 0.04 | 0 | 0 | 0 | 0 | 0 | 0.02 | 1.52 | 0.86 |
| 1999 | 1.71 | 0 | 0 | 0 | 0 | 0 | 0.89 | 1.91 | 0.02 | 0 |
| 1999 | 0.67 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 1.11 | 0.3 | 0 | 0 | 0.02 | 0.06 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.14 | 2.04 |
| 1999 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 | 1.43 | 0 |
| 1999 | 0.98 | 0.7 | 0.01 | 0 | 0 | 0.02 | 2.33 | 0.23 | 0 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1999 | 0 | 2.14 | 0 | 2.95 | 6.45 | 0 | 0 | 0 | 0.44 | 4.29 |
| 1999 | 0.94 | 0 | 0 | 0 | 0 | 0.03 | 0 | 0.59 | 3.29 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0.13 | 0 | 0 | 0.18 | 0.05 | 0 |
| 1999 | 0.05 | 0 | 0 | 0 | 0 | 0.49 | 0 | 1.5 | 2.77 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.57 | 0.04 | 0 |
| 1999 | 0 | 0 | 0 | 2.96 | 0 | 0.21 | 1.09 | 0.03 | 0 | 0.69 |
| 1999 | 0.09 | 0 | 0 | 0 | 0 | 0 | 2.94 | 0.22 | 0 | 0.42 |
| 1999 | 0 | 1.6 | 0 | 0.02 | 0 | 0 | 2.22 | 0.31 | 0.16 | 0 |
| 1999 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1999 | 0 | 0 | 0 | 0.12 | 1.36 | | | | | |
| 2000 | 0 | 0 | 0 | 0.25 | 0.4 | 0 | 0.45 | 1.43 | 0 | 1.79 |
| 2000 | 0.01 | 0 | 0.16 | 0.38 | 1.94 | 2.24 | 0.74 | 0.34 | 0 | 0 |
| 2000 | 0 | 0 | 4.51 | 0.2 | 0.45 | 0 | 0 | 0 | 1.44 | 0 |
| 2000 | 2.49 | 0.28 | 0.07 | 0.05 | 1.63 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0.15 | 0 | 0 | 0 | 0.41 | 2.1 | 0 | 0 | 0 | 0 |

Table C.3 continuation

| Year | Daily precipitation (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | 0 | 0.44 | 3.68 | 3.56 | 0 | 0 | 0 | 0 | 0.67 | 2.03 |
| 2000 | 2.4 | 0 | 0 | 0.15 | 0.38 | 1.17 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0.16 | 0 | 0 | 0 | 0.12 | 0.7 | 0.04 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 1.74 | 0.03 | 0 | 1.15 | 0.02 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 9.81 | 2.05 | 0 | 0 | 0 | 2.88 | 1.16 | 0.61 |
| 2000 | 0.05 | 0.13 | 0 | 0.02 | 0 | 0 | 0 | 0 | 0.15 | 0.62 |
| 2000 | 0 | 0 | 0.12 | 0.89 | 3.4 | 2.06 | 0.5 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0.39 | 0.12 | 0.29 | 0 |
| 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 1.16 | 0.01 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 2.36 | 0.05 | 0.02 | 0.01 |
| 2000 | 0 | 0 | 0 | 0 | 0.15 | 0 | 0 | 0 | 1.23 | 2.08 |
| 2000 | 1.64 | 0.15 | 0 | 0 | 0 | 0 | 1.4 | 1.3 | 0.79 | 0 |
| 2000 | 0.02 | 1.76 | 0 | 1.25 | 0 | 1.28 | 0.01 | 0 | 0.02 | 0 |
| 2000 | 0.39 | 0.62 | 6.98 | 0.04 | 0 | 0 | 0.26 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 0.03 | 3.06 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0.74 | 0.02 | 0.24 | 0.43 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0.31 | 0 | 0 | 0 | 0 | 1.82 | 1.32 | 0 | 1.26 |
| 2000 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 4.32 |
| 2000 | 0.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 3.17 | 0.05 | 7 | 1.7 | 1.83 | 9.39 | 0.01 | 0.15 |
| 2000 | 0 | 0.05 | 2.88 | 0 | 0.53 | 1.95 | 0.07 | 3.23 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 0 | 2.57 | 0.02 | 0 | 4.01 | 0.05 | 0 |
| 2000 | 0 | 0 | 4.4 | 4.72 | 0 | 3.74 | 8.17 | 0.58 | 0.15 | 0.61 |
| 2000 | 0.71 | 0.07 | 0.04 | 2.45 | 0 | 0 | 1.58 | 0.06 | 0.01 | 4.39 |
| 2000 | 7.28 | 0 | 0 | 0 | 0 | 0 | 0.89 | 0 | 0 | 0 |
| 2000 | 0 | 0.02 | 0.3 | 0.23 | 1.25 | 0 | 1.82 | 1.34 | 0 | 0 |
| 2000 | 0 | 0 | 0.77 | 0 | 0 | 0.54 | 0 | 0 | 0.21 | 0.05 |
| 2000 | 0 | 0 | 0.15 | 1.7 | 2.33 | 0 | 0 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 0 | 0 | 0 | 6.3 | 1.72 | 0 | 1.75 | 0 |
| 2000 | 6.85 | 0 | 0 | 0 | 0 | 3.06 | 1.3 | 0.82 | 0.98 | 0.34 |
| 2000 | 0 | 0.18 | 1.85 | 0.64 | 3.61 | 0 | | | | |
| 2001 | 0 | 0 | 0 | 0 | 0.02 | 2.79 | 1.56 | 2.64 | 0.42 | 0.01 |
| 2001 | 0.65 | 0.01 | 0 | 0.02 | 0.28 | 1.92 | 0.04 | 0.19 | 3.6 | 3.32 |
| 2001 | 0 | 0 | 2.52 | 0.56 | 0 | 0 | 0.17 | 0.31 | 3.67 | 1.16 |
| 2001 | 1.3 | 0 | 0.08 | 0 | 0.66 | 4.2 | 0.07 | 0 | 0 | 0 |
| 2001 | 0.01 | 0 | 0.02 | 1.85 | 0.32 | 0.22 | 0 | 0 | 1.12 | 1.66 |
| 2001 | 0.25 | 0 | 0.36 | 0.13 | 0 | 2.03 | 0 | 0 | 0.05 | 0.03 |
| 2001 | 0 | 0.16 | 1.41 | 0 | 0 | 0.02 | 0.28 | 0.98 | 0 | 0 |
| 2001 | 0 | 0 | 0 | 1.75 | 0.83 | 1.93 | 0.48 | 0.14 | 0 | 0 |
| 2001 | 0.19 | 1.35 | 0.15 | 0 | 1.99 | 1.1 | 0 | 0 | 0 | 0.4 |
| 2001 | 4.18 | 0.03 | 0 | 0 | 0 | 0 | 0.08 | 1 | 4.7 | 0.13 |

Table C.3 continuation.

| Year | Daily precipitation (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.46 |
| 2001 | 0.39 | 0.51 | 0 | 3.72 | 0 | 0.44 | 0 | 0 | 0 | 0 |
| 2001 | 0 | 0.24 | 3.3 | 3.6 | 0.02 | 0 | 0 | 0 | 0.25 | 0.12 |
| 2001 | 0 | 0 | 0 | 0 | 0 | 1.35 | 1.25 | 0.02 | 0 | 0.48 |
| 2001 | 0.46 | 3.52 | 0 | 0 | 0 | 0 | 1.08 | 0.2 | 0.01 | 0 |
| 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 0.64 | 0.02 | 0 | 0 |
| 2001 | 0 | 0 | 0 | 0.03 | 0.02 | 0.01 | 4.15 | 0.15 | 0 | 0.47 |
| 2001 | 0.62 | 0 | 0 | 0.02 | 0.12 | 4.94 | 1.11 | 0.02 | 0 | 0 |
| 2001 | 0 | 0.02 | 0.03 | 0.02 | 0.02 | 0.32 | 0.01 | 0.07 | 0 | 0 |
| 2001 | 0 | 1.23 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0.26 | 3.9 |
| 2001 | 4.81 | 0 | 0 | 0 | 0.02 | 0.53 | 1.76 | 0.19 | 0 | 0 |
| 2001 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001 | 0 | 2.42 | 2.82 | 0 | 0 | 0 | 0.47 | 0 | 2.08 | 0 |
| 2001 | 1.06 | 0 | 0 | 0 | 0 | 0 | 0.44 | 1.34 | 2.02 | 0 |
| 2001 | 0.3 | 0 | 0.01 | 3.9 | 0 | 0.92 | 0.66 | 0 | 0 | 0 |
| 2001 | 0 | 0 | 0 | 0 | 1.21 | 0.1 | 0 | 0.52 | 0.68 | 0 |
| 2001 | 0.03 | 3 | 0 | 0 | 16.8 | 0.08 | 0 | 0 | 0 | 0.3 |
| 2001 | 0 | 3.78 | 0 | 0 | 0 | 0.03 | 0.22 | 0.07 | 0.15 | 2.06 |
| 2001 | 1.09 | 0.17 | 0 | 0.6 | 0.03 | 0 | 0 | 0 | 0 | 0 |
| 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001 | 1.1 | 0.05 | 0 | 1.26 | 4.07 | 0 | 0 | 0.34 | 0.13 | 0 |
| 2001 | 0 | 0 | 0 | 0 | 0 | 0.68 | 0 | 0.31 | 0 | 0.03 |
| 2001 | 1.12 | 1.66 | 0.4 | 1.18 | 0.05 | 0.01 | 0 | 1.36 | 3.28 | 0.1 |
| 2001 | 0 | 0 | 0.11 | 0.02 | 1.56 | 0 | 5.2 | 0 | 0.06 | 0.42 |
| 2001 | 0 | 0 | 0 | 0 | 0.01 | 0.63 | 0 | 0 | 0.03 | 0 |
| 2001 | 0 | 0.01 | 0 | 0 | 0 | | | | | |

# APPENDIX D - VALUES OF NUTRIENTS IN RUNOFF FOR THE LAGES PLOT STUDY

**Table D.1.** Measured and simulated values of $NH_4$-N (mg/L) in runoff from a plot planted with a rotation of wheat/soybean with conventional tillage for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 2.440 | 0.464 | 1.600 |
| 375 | 4.870 | 0.000 | 0.000 |
| 380 | 1.440 | 0.000 | 0.819 |
| 381 | 0.950 | 0.000 | 0.675 |
| 411 | 7.730 | 0.000 | 0.000 |
| 418 | 1.440 | 0.000 | 0.083 |
| 426 | 1.010 | 0.000 | 0.090 |
| 449 | 2.320 | 0.000 | 0.000 |
| 452 | 0.950 | 0.000 | 0.000 |
| 468 | 0.420 | 0.000 | 0.036 |
| 473 | 2.520 | 0.000 | 0.097 |
| 474 | 1.350 | 0.000 | 0.123 |
| 490 | 5.430 | 0.000 | 0.204 |
| 536 | 0.490 | 1.589 | 1.141 |
| 542 | 0.840 | 1.699 | 1.256 |
| 543 | 0.700 | 1.416 | 1.161 |
| 547 | 2.200 | 1.116 | 1.076 |
| 551 | 1.100 | 0.844 | 1.032 |
| 558 | 1.500 | 0.444 | 0.751 |
| 570 | 2.520 | 0.000 | 0.727 |
| 592 | 6.580 | 0.000 | 0.000 |
| 595 | 34.16 | 0.000 | 0.954 |
| 605 | 1.400 | 0.000 | 0.725 |
| 618 | 2.800 | 0.000 | 0.653 |
| 620 | 1.820 | 0.000 | 0.437 |
| 621 | 1.260 | 0.000 | 0.354 |
| 623 | 1.120 | 0.000 | 0.244 |
| 648 | 0.840 | 0.000 | 0.228 |
| 652 | 0.420 | 0.132 | 0.244 |
| 665 | 1.540 | 0.008 | 0.682 |
| 683 | 4.140 | 0.374 | 1.241 |
| 700 | 202.000 | 0.007 | 0.915 |
| 711 | 5.380 | 0.000 | 0.659 |
| 716 | 0.390 | 0.000 | 0.344 |
| 721 | 0.450 | 0.000 | 0.350 |
| 724 | 0.340 | 0.000 | 0.000 |
| 739 | 0.730 | 0.000 | 0.359 |

Table D.1. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 750 | 0.850 | 0.000 | 0.319 |
| 761 | 0.200 | 0.000 | 0.298 |
| 767 | 0.220 | 0.000 | 0.257 |
| 781 | 0.550 | 0.000 | 0.326 |
| 830 | 0.480 | 0.000 | 0.167 |
| 931 | 0.070 | 17.133 | 17.408 |
| 963 | 0.630 | 3.858 | 0.000 |
| 964 | 0.520 | 2.523 | 3.048 |
| 980 | 0.870 | 0.000 | 0.966 |
| 985 | 0.120 | 0.000 | 0.575 |
| 1003 | 0.180 | 0.000 | 0.324 |
| 1006 | 0.080 | 0.000 | 0.149 |
| 1013 | 0.110 | 0.000 | 0.157 |
| 1021 | 0.330 | 0.000 | 0.399 |

**Table D.2.** Measured and simulated values of $NO_3$-N (mg/L) in runoff from a plot planted with a rotation of wheat/soybean with conventional tillage for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 1.130 | 0.002 | 0.124 |
| 375 | 3.220 | 0.000 | 0.000 |
| 380 | 1.200 | 0.009 | 0.016 |
| 381 | 0.700 | 0.000 | 0.010 |
| 411 | 1.530 | 0.000 | 0.000 |
| 418 | 1.160 | 0.000 | 0.000 |
| 426 | 1.370 | 0.000 | 0.001 |
| 449 | 1.320 | 0.000 | 0.000 |
| 452 | 2.110 | 0.000 | 0.000 |
| 468 | 41.530 | 0.000 | 0.000 |
| 473 | 34.300 | 0.001 | 0.000 |
| 474 | 29.960 | 0.000 | 0.003 |
| 490 | 4.550 | 0.000 | 0.000 |
| 536 | 0.000 | 0.000 | 0.009 |
| 542 | 1.230 | 0.120 | 0.157 |
| 543 | 39.200 | 0.015 | 0.017 |
| 547 | 3.800 | 0.041 | 0.028 |
| 551 | 1.000 | 0.044 | 0.083 |
| 558 | 16.800 | 0.000 | 0.001 |
| 570 | 8.820 | 0.000 | 0.030 |
| 592 | 2.380 | 0.000 | 0.000 |
| 595 | 1.400 | 0.000 | 0.024 |
| 605 | 3.080 | 0.000 | 0.005 |
| 618 | 2.240 | 0.000 | 0.008 |
| 620 | 1.540 | 0.000 | 0.000 |
| 621 | 1.260 | 0.000 | 0.007 |
| 623 | 3.220 | 0.000 | 0.000 |
| 648 | 2.240 | 0.000 | 0.000 |
| 652 | 0.700 | 0.000 | 0.000 |
| 665 | 11.060 | 0.003 | 0.003 |
| 683 | 0.110 | 0.002 | 0.046 |
| 700 | 0.850 | 0.005 | 0.007 |
| 711 | 0.220 | 0.002 | 0.005 |
| 716 | 12.430 | 0.000 | 0.001 |
| 721 | 8.460 | 0.005 | 0.054 |
| 724 | 9.410 | 0.000 | 0.000 |
| 739 | 2.800 | 0.000 | 0.005 |
| 750 | 2.600 | 0.000 | 0.001 |
| 761 | 1.000 | 0.000 | 0.021 |
| 767 | 0.340 | 0.000 | 0.000 |
| 781 | 0.410 | 0.000 | 0.007 |
| 830 | 1.120 | 0.000 | 0.000 |

Table D.2. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 5.500 | 0.005 | 0.042 |
| 963 | 0.230 | 0.088 | 0.000 |
| 964 | 2.960 | 0.000 | 0.006 |
| 980 | 0.330 | 0.000 | 0.011 |
| 985 | 1.130 | 0.000 | 0.000 |
| 1003 | 0.480 | 0.000 | 0.001 |
| 1006 | 0.302 | 0.000 | 0.000 |
| 1013 | 1.033 | 0.000 | 0.000 |
| 1021 | 0.410 | 0.001 | 0.006 |

**Table D.3.** Measured and simulated values of $PO_4$-P(mg/L) in runoff from a plot planted with a rotation of wheat/soybean with conventional tillage for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 0.120 | 0.001 | 0.004 |
| 375 | 1.020 | 0.000 | 0.000 |
| 380 | 0.640 | 0.004 | 0.008 |
| 381 | 1.100 | 0.003 | 0.008 |
| 411 | 0.460 | 0.000 | 0.000 |
| 418 | 0.670 | 0.000 | 0.013 |
| 426 | 0.210 | 0.000 | 0.029 |
| 449 | 0.410 | 0.000 | 0.000 |
| 452 | 0.030 | 0.000 | 0.000 |
| 468 | 0.050 | 0.002 | 0.010 |
| 473 | 0.020 | 0.002 | 0.004 |
| 474 | 0.020 | 0.002 | 0.010 |
| 490 | 0.010 | 0.011 | 0.003 |
| 536 | 0.010 | 0.227 | 0.031 |
| 542 | 0.010 | 0.227 | 0.034 |
| 543 | 0.010 | 0.226 | 0.035 |
| 547 | 0.140 | 0.223 | 0.038 |
| 551 | 0.010 | 0.219 | 0.042 |
| 558 | 0.010 | 0.211 | 0.045 |
| 570 | 0.010 | 0.194 | 0.046 |
| 592 | 0.010 | 0.173 | 0.000 |
| 595 | 0.010 | 0.167 | 0.054 |
| 605 | 0.010 | 0.160 | 0.054 |
| 618 | 0.010 | 0.153 | 0.054 |
| 620 | 0.010 | 0.146 | 0.053 |
| 621 | 0.010 | 0.142 | 0.052 |
| 623 | 0.010 | 0.136 | 0.052 |
| 648 | 0.010 | 0.102 | 0.045 |
| 652 | 0.010 | 0.018 | 0.050 |
| 665 | 0.010 | 0.002 | 0.063 |
| 683 | 0.020 | 0.080 | 0.043 |
| 700 | 0.010 | 0.002 | 0.040 |
| 711 | 0.010 | 0.000 | 0.039 |
| 716 | 0.750 | 0.008 | 0.040 |
| 721 | 0.010 | 0.000 | 0.039 |
| 724 | 0.010 | 0.000 | 0.000 |
| 739 | 0.010 | 0.000 | 0.055 |
| 750 | 0.010 | 0.002 | 0.056 |
| 761 | 0.010 | 0.004 | 0.062 |
| 767 | 0.010 | 0.003 | 0.011 |
| 781 | 0.010 | 0.005 | 0.037 |
| 830 | 0.010 | 0.007 | 0.059 |

Table D.3. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 0.010 | 0.094 | 0.074 |
| 963 | 0.070 | 0.075 | 0.000 |
| 964 | 0.010 | 0.071 | 0.063 |
| 980 | 0.010 | 0.034 | 0.038 |
| 985 | 0.010 | 0.021 | 0.029 |
| 1003 | 0.010 | 0.004 | 0.018 |
| 1006 | 0.010 | 0.003 | 0.017 |
| 1013 | 0.010 | 0.005 | 0.018 |
| 1021 | 0.070 | 0.005 | 0.025 |

**Table D.4.** Measured and simulated values of $NH_4$-N (mg/L) in runoff from a plot planted with a rotation of wheat/soybean with treatment Chisel + disk for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 3.430 | 4.364 | 2.053 |
| 375 | 2.860 | 0.000 | 0.000 |
| 380 | 1.020 | 0.000 | 1.611 |
| 381 | 0.600 | 0.000 | 1.343 |
| 411 | 18.340 | 0.000 | 0.000 |
| 418 | 1.620 | 0.000 | 0.335 |
| 426 | 7.430 | 0.000 | 0.217 |
| 449 | 43.810 | 0.000 | 0.000 |
| 452 | 38.440 | 0.000 | 0.000 |
| 468 | 0.140 | 0.000 | 0.068 |
| 473 | 0.130 | 0.000 | 0.180 |
| 474 | 1.640 | 0.000 | 0.234 |
| 490 | 1.230 | 0.000 | 0.366 |
| 536 | 2.400 | 4.122 | 2.016 |
| 542 | 8.400 | 4.447 | 2.380 |
| 543 | 1.100 | 3.708 | 2.264 |
| 547 | 2.380 | 3.008 | 2.224 |
| 551 | 0.800 | 2.378 | 2.217 |
| 558 | 0.600 | 1.402 | 1.631 |
| 570 | 2.240 | 0.455 | 1.474 |
| 592 | 5.600 | 0.000 | 0.000 |
| 595 | 47.320 | 0.000 | 1.923 |
| 605 | 1.820 | 0.000 | 1.385 |
| 618 | 8.400 | 0.000 | 1.249 |
| 620 | 1.680 | 0.000 | 0.870 |
| 621 | 0.980 | 0.000 | 0.729 |
| 623 | 0.700 | 0.000 | 0.521 |
| 648 | 0.880 | 0.000 | 0.490 |
| 652 | 0.560 | 0.000 | 0.531 |
| 665 | 2.380 | 0.024 | 1.306 |
| 683 | 15.340 | 1.161 | 1.661 |
| 700 | 6.700 | 1.289 | 1.496 |
| 711 | 7.950 | 0.585 | 1.017 |
| 716 | 0.450 | 0.141 | 0.663 |
| 721 | 0.840 | 0.065 | 0.613 |
| 724 | 0.170 | 0.000 | 0.000 |
| 739 | 0.280 | 0.007 | 0.681 |
| 750 | 1.400 | 0.000 | 0.601 |
| 761 | 1.600 | 0.000 | 0.543 |
| 767 | 0.560 | 0.000 | 0.469 |
| 781 | 0.440 | 0.000 | 0.594 |
| 830 | 0.450 | 0.000 | 0.299 |

Table D.4. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 0.160 | 17.369 | 17.998 |
| 963 | 4.110 | 3.939 | 0.000 |
| 964 | 2.480 | 2.595 | 3.405 |
| 980 | 5.130 | 0.000 | 1.332 |
| 985 | 0.120 | 0.000 | 0.863 |
| 1003 | 0.230 | 0.000 | 0.621 |
| 1006 | 0.120 | 0.000 | 0.292 |
| 1013 | 0.090 | 0.000 | 0.278 |
| 1021 | 0.770 | 0.000 | 0.713 |

**Table D.5.** Measured and simulated values of $NO_3$-N (mg/L) in runoff from a plot planted with a rotation of wheat/soybean with treatment Chisel + disk for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 1.550 | 0.016 | 0.110 |
| 375 | 3.320 | 0.000 | 0.000 |
| 380 | 1.640 | 0.026 | 0.032 |
| 381 | 11.860 | 0.001 | 0.016 |
| 411 | 1.510 | 0.000 | 0.000 |
| 418 | 4.580 | 0.000 | 0.000 |
| 426 | 3.560 | 0.000 | 0.002 |
| 449 | 1.250 | 0.000 | 0.000 |
| 452 | 1.010 | 0.000 | 0.000 |
| 468 | 8.750 | 0.000 | 0.000 |
| 473 | 18.200 | 0.002 | 0.000 |
| 474 | 10.150 | 0.000 | 0.005 |
| 490 | 40.600 | 0.001 | 0.001 |
| 536 | 36.900 | 0.000 | 0.030 |
| 542 | 5.080 | 0.194 | 0.125 |
| 543 | 24.900 | 0.023 | 0.030 |
| 547 | 20.200 | 0.065 | 0.048 |
| 551 | 3.800 | 0.068 | 0.107 |
| 558 | 13.400 | 0.000 | 0.001 |
| 570 | 9.520 | 0.013 | 0.023 |
| 592 | 2.800 | 0.000 | 0.000 |
| 595 | 2.380 | 0.000 | 0.049 |
| 605 | 7.980 | 0.000 | 0.005 |
| 618 | 2.660 | 0.000 | 0.009 |
| 620 | 2.100 | 0.000 | 0.000 |
| 621 | 2.100 | 0.000 | 0.015 |
| 623 | 2.940 | 0.000 | 0.000 |
| 648 | 1.540 | 0.000 | 0.001 |
| 652 | 0.700 | 0.000 | 0.001 |
| 665 | 10.500 | 0.003 | 0.006 |
| 683 | 0.430 | 0.001 | 0.063 |
| 700 | 1.100 | 0.001 | 0.012 |
| 711 | 0.340 | 0.003 | 0.005 |
| 716 | 12.320 | 0.000 | 0.000 |
| 721 | 8.510 | 0.011 | 0.054 |
| 724 | 7.220 | 0.000 | 0.000 |
| 739 | 2.020 | 0.000 | 0.011 |
| 750 | 2.900 | 0.000 | 0.003 |
| 761 | 1.000 | 0.000 | 0.047 |
| 767 | 0.280 | 0.000 | 0.001 |
| 781 | 0.230 | 0.003 | 0.016 |
| 830 | 3.160 | 0.000 | 0.000 |

Table D.5. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 4.500 | 0.007 | 0.043 |
| 963 | 0.800 | 0.099 | 0.000 |
| 964 | 4.900 | 0.000 | 0.006 |
| 980 | 2.430 | 0.000 | 0.016 |
| 985 | 2.060 | 0.000 | 0.001 |
| 1003 | 1.530 | 0.000 | 0.001 |
| 1006 | 0.880 | 0.000 | 0.000 |
| 1013 | 3.080 | 0.000 | 0.000 |
| 1021 | 1.950 | 0.001 | 0.015 |

**Table D.6.** Measured and simulated values of $PO_4$-P (mg/L) in runoff from a plot planted with a rotation of wheat/soybean with treatment Chisel + disk for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 0.97 | 0.001 | 0.102 |
| 375 | 0.8 | 0.000 | 0.000 |
| 380 | 1.1 | 0.022 | 0.122 |
| 381 | 1.09 | 0.020 | 0.125 |
| 411 | 1.76 | 0.000 | 0.000 |
| 418 | 0.58 | 0.002 | 0.114 |
| 426 | 0.11 | 0.001 | 0.113 |
| 449 | 10.24 | 0.000 | 0.000 |
| 452 | 0.21 | 0.000 | 0.000 |
| 468 | 0.07 | 0.001 | 0.035 |
| 473 | 0.03 | 0.007 | 0.010 |
| 474 | 0.02 | 0.007 | 0.008 |
| 490 | 0.01 | 0.048 | 0.006 |
| 536 | 0.01 | 0.724 | 0.082 |
| 542 | 0.33 | 0.742 | 0.091 |
| 543 | 0.2 | 0.738 | 0.094 |
| 547 | 0.09 | 0.734 | 0.103 |
| 551 | 0.01 | 0.726 | 0.111 |
| 558 | 0.01 | 0.708 | 0.120 |
| 570 | 0.05 | 0.662 | 0.125 |
| 592 | 0.13 | 0.613 | 0.000 |
| 595 | 0.5 | 0.600 | 0.147 |
| 605 | 0.01 | 0.584 | 0.148 |
| 618 | 0.22 | 0.568 | 0.151 |
| 620 | 0.01 | 0.552 | 0.151 |
| 621 | 0.01 | 0.541 | 0.150 |
| 623 | 0.01 | 0.525 | 0.150 |
| 648 | 0.01 | 0.453 | 0.146 |
| 652 | 0.01 | 0.431 | 0.154 |
| 665 | 0.01 | 0.001 | 0.177 |
| 683 | 2.8 | 0.067 | 0.146 |
| 700 | 1.4 | 0.003 | 0.141 |
| 711 | 0.95 | 0.001 | 0.139 |
| 716 | 0.01 | 0.003 | 0.140 |
| 721 | 0.01 | 0.000 | 0.138 |
| 724 | 0.01 | 0.000 | 0.000 |
| 739 | 0.01 | 0.000 | 0.170 |
| 750 | 0.25 | 0.011 | 0.179 |
| 761 | 0.01 | 0.028 | 0.192 |
| 767 | 0.01 | 0.023 | 0.194 |
| 781 | 0.01 | 0.045 | 0.196 |
| 830 | 0.01 | 0.012 | 0.181 |

Table D.6. Continuation.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 0.01 | 0.435 | 0.184 |
| 963 | 0.97 | 0.389 | 0.000 |
| 964 | 0.01 | 0.381 | 0.169 |
| 980 | 1.7 | 0.319 | 0.139 |
| 985 | 0.01 | 0.294 | 0.126 |
| 1003 | 0.01 | 0.239 | 0.105 |
| 1006 | 0.01 | 0.226 | 0.100 |
| 1013 | 0.01 | 0.206 | 0.098 |
| 1021 | 0.01 | 0.203 | 0.106 |

**Table D.7.** Measured and simulated values of $NH_4$-N in runoff from a plot planted with a rotation of wheat/soybean with treatment No-till for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 6.05 | 0.121 | 3.654 |
| 375 | | 0.000 | 0.000 |
| 380 | 0.38 | 0.000 | 3.368 |
| 381 | 0.22 | 0.000 | 2.814 |
| 411 | 5.38 | 0.000 | 0.000 |
| 418 | 2.53 | 0.000 | 1.092 |
| 426 | 1.25 | 0.000 | 0.793 |
| 449 | 1.62 | 0.000 | 0.000 |
| 452 | 1.76 | 0.000 | 0.000 |
| 468 | 0.43 | 0.013 | 0.152 |
| 473 | 2.34 | 0.000 | 0.356 |
| 474 | 2.05 | 0.000 | 0.488 |
| 490 | 10.33 | 0.000 | 0.800 |
| 536 | 5.1 | 0.019 | 3.497 |
| 542 | 2.24 | 0.000 | 4.185 |
| 543 | 1.4 | 0.000 | 4.019 |
| 547 | 1.12 | 0.000 | 4.041 |
| 551 | 0.6 | 0.000 | 4.050 |
| 558 | 0.5 | 0.000 | 2.979 |
| 570 | 3.08 | 0.041 | 2.589 |
| 592 | 3.78 | 0.043 | 0.000 |
| 595 | 11.62 | 0.000 | 3.379 |
| 605 | 5.88 | 0.013 | 2.365 |
| 618 | 5.46 | 0.000 | 2.112 |
| 620 | 1.82 | 0.016 | 1.516 |
| 621 | 0.7 | 0.000 | 1.297 |
| 623 | 0.84 | 0.000 | 0.945 |
| 648 | 1.02 | 0.062 | 0.849 |
| 652 | 0.84 | 0.371 | 1.002 |
| 665 | 1.68 | 0.608 | 2.276 |
| 683 | 10.72 | 0.459 | 2.701 |
| 700 | 5.6 | 1.529 | 2.714 |
| 711 | 6.83 | 0.840 | 1.731 |
| 716 | 0.67 | 0.540 | 1.298 |
| 721 | 3.25 | 0.466 | 1.123 |
| 724 | 0.9 | 0.000 | 0.000 |
| 739 | 0.28 | 0.048 | 1.386 |
| 750 | 1.4 | 0.140 | 1.246 |
| 761 | 0.13 | 0.193 | 1.107 |
| 767 | 0.62 | 0.090 | 0.947 |
| 781 | 4.97 | 0.000 | 1.185 |
| 830 | | 0.064 | 0.553 |

Table D.7. Continuation

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 0.58 | 17.646 | 18.834 |
| 963 | 4.36 | 4.108 | 0.000 |
| 964 | 11.6 | 2.731 | 3.913 |
| 980 | 3.05 | 0.000 | 1.846 |
| 985 | 0.58 | 0.000 | 1.274 |
| 1003 | 0.48 | 0.000 | 1.054 |
| 1006 | 0.09 | 0.000 | 0.499 |
| 1013 | | 0.000 | 0.432 |
| 1021 | 1.08 | 0.000 | 1.212 |

**Table D.8.** Measured and simulated values of $NO_3$-N in runoff from a plot planted with a rotation of wheat/soybean with treatment No-till for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 2.16 | 0.139 | 0.094 |
| 375 | 3.24 | 0.000 | 0.000 |
| 380 | 3.5 | 0.001 | 0.067 |
| 381 | 0.99 | 0.000 | 0.027 |
| 411 | 2.16 | 0.000 | 0.000 |
| 418 | 0.53 | 0.000 | 0.001 |
| 426 | 2.39 | 0.000 | 0.006 |
| 449 | 1.27 | 0.000 | 0.000 |
| 452 | 1.09 | 0.000 | 0.000 |
| 468 | 13.02 | 0.000 | 0.000 |
| 473 | 4.13 | 0.019 | 0.001 |
| 474 | 2.24 | 0.002 | 0.011 |
| 490 | 2.38 | 0.005 | 0.002 |
| 536 | 1.3 | 0.000 | 0.062 |
| 542 | 0.8 | 0.575 | 0.124 |
| 543 | 9.6 | 0.066 | 0.056 |
| 547 | 1.3 | 0.176 | 0.071 |
| 551 | 1 | 0.180 | 0.135 |
| 558 | 8.12 | 0.001 | 0.001 |
| 570 | 4.06 | 0.034 | 0.019 |
| 592 | 2.8 | 0.038 | 0.000 |
| 595 | 2.66 | 0.033 | 0.092 |
| 605 | 4.62 | 0.000 | 0.006 |
| 618 | 2.52 | 0.000 | 0.012 |
| 620 | 2.38 | 0.001 | 0.000 |
| 621 | 1.12 | 0.000 | 0.031 |
| 623 | 0.84 | 0.000 | 0.000 |
| 648 | 1.68 | 0.000 | 0.001 |
| 652 | 0.43 | 0.000 | 0.000 |
| 665 | 10.5 | 0.017 | 0.010 |
| 683 | 0.34 | 0.007 | 0.115 |
| 700 | 2.2 | 0.022 | 0.024 |
| 711 | 0.34 | 0.005 | 0.005 |
| 716 | 14.45 | 0.002 | 0.001 |
| 721 | 1.01 | 0.019 | 0.062 |
| 724 | 6.72 | 0.000 | 0.000 |
| 739 | 1.57 | 0.000 | 0.025 |
| 750 | 0.95 | 0.000 | 0.003 |
| 761 | 0.06 | 0.000 | 0.054 |
| 767 | 0.62 | 0.000 | 0.003 |
| 781 | 0.63 | 0.031 | 0.045 |
| 830 | | 0.000 | 0.001 |

Table D.8 continuation

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 4.4 | 0.023 | 0.046 |
| 963 | 0.6 | 0.138 | 0.000 |
| 964 | 1.2 | 0.000 | 0.008 |
| 980 | 1.41 | 0.000 | 0.024 |
| 985 | 9.8 | 0.000 | 0.001 |
| 1003 | 0.35 | 0.000 | 0.002 |
| 1006 | 1 | 0.000 | 0.000 |
| 1013 | | 0.005 | 0.001 |
| 1021 | 1.62 | 0.026 | 0.044 |

**Table D9.** Measured and simulated values of $PO_4$-P in runoff from a plot planted with a rotation of wheat/soybean with treatment No-tillage for the Lages plot study.

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 324 | 1.66 | 1.278 | 0.290 |
| 375 | 0.13 | 0.000 | 0.000 |
| 380 | 1.04 | 0.996 | 0.267 |
| 381 | 1.05 | 0.981 | 0.264 |
| 411 | 0.96 | 0.000 | 0.000 |
| 418 | 0.33 | 0.745 | 0.198 |
| 426 | 0.06 | 0.686 | 0.188 |
| 449 | 3.18 | 0.000 | 0.000 |
| 452 | 0.06 | 0.000 | 0.000 |
| 468 | 0.09 | 0.570 | 0.144 |
| 473 | 0.27 | 0.548 | 0.143 |
| 474 | 0.08 | 0.541 | 0.144 |
| 490 | 0.06 | 0.514 | 0.152 |
| 536 | 0.62 | 1.072 | 0.238 |
| 542 | 0.46 | 1.037 | 0.246 |
| 543 | 0.01 | 1.032 | 0.249 |
| 547 | 0.01 | 1.005 | 0.258 |
| 551 | 0.01 | 0.979 | 0.267 |
| 558 | 1.25 | 0.934 | 0.274 |
| 570 | 0.01 | 0.885 | 0.274 |
| 592 | 0.01 | 0.837 | 0.000 |
| 595 | 0.01 | 0.822 | 0.285 |
| 605 | 0.01 | 0.802 | 0.282 |
| 618 | 0.01 | 0.784 | 0.280 |
| 620 | 0.29 | 0.767 | 0.277 |
| 621 | 0.01 | 0.753 | 0.274 |
| 623 | 0.16 | 0.732 | 0.270 |
| 648 | 0.07 | 0.651 | 0.247 |
| 652 | 0.01 | 0.635 | 0.252 |
| 665 | 0.01 | 0.623 | 0.274 |
| 683 | 2.15 | 2.419 | 0.448 |
| 700 | 1.6 | 1.935 | 0.428 |
| 711 | 1.18 | 1.873 | 0.415 |
| 716 | 0.4 | 1.767 | 0.413 |
| 721 | 1.3 | 1.721 | 0.404 |
| 724 | 0.5 | 0.000 | 0.000 |
| 739 | 0.05 | 1.588 | 0.402 |
| 750 | 0.01 | 1.517 | 0.390 |
| 761 | 0.01 | 1.404 | 0.380 |
| 767 | 0.01 | 1.359 | 0.374 |
| 781 | 0.46 | 1.260 | 0.367 |
| 830 | | 0.965 | 0.320 |

Table D9 continuation

| Day | Measured | GLEAMS | TROPGLEAMS |
|---|---|---|---|
| 931 | 0.16 | 0.598 | 0.346 |
| 963 | 1.11 | 0.544 | 0.000 |
| 964 | 0.66 | 0.535 | 0.319 |
| 980 | 0.01 | 0.467 | 0.277 |
| 985 | 0.01 | 0.439 | 0.258 |
| 1003 | 0.39 | 0.376 | 0.224 |
| 1006 | 0.01 | 0.359 | 0.215 |
| 1013 | | 0.337 | 0.206 |
| 1021 | 0.01 | 0.335 | 0.217 |