Soil & Tillage Research 166 (2017) 76–83

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Environmental benefits of reducing N rates for coffee in the Cerrado

Victor Meriguetti Pinto[a,*], Isabeli Pereira Bruno[b], Quirijn de Jong van Lier[a], Durval Dourado-Neto[c], Klaus Reichardt[a]

[a] Soil Physics Laboratory, University of São Paulo, Center for Nuclear Energy in Agriculture, P.O. Box 96, 13416-970 Piracicaba, SP, Brazil
[b] Agronomic Institute of Paraná, IAPAR, 86047-902, Rodovia Celso Garcia Cid, km 375 Londrina, PR, Brazil
[c] Department of Crop Science, University of São Paulo, "Luiz de Queiroz" College of Agriculture, P.O. Box 9, 134180-970 Piracicaba, SP, Brazil

ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form 13 October 2016
Accepted 14 October 2016
Available online xxx

Keywords:
Nitrogen management
Nitrate leaching
Coffee
ANIMO model
Cerrado

ABSTRACT

An intensification of agriculture in the Brazilian Cerrado during the last four decades has resulted in unintended consequences such as increased groundwater and surface water pollution due to excessive N fertilization. To address these problems within a coffee (*Coffea arabica* L.) orchard, the process-based ANIMO model was used to simulate nitrate-nitrogen (NO_3-N) leaching and plant nitrogen (N) uptake for several rates of N (200–800 kg h^{-1} y^{-1}). Effects of splitting N applications from three times per year to every other day were also evaluated for a Typic Hapludox within the Cerrado. Statistical analysis of ANIMO outputs showed that simulated soil solution NO_3-N concentrations were in agreement with experimental measurements collected for an entire year. Simulated annual N uptake was also in agreement with average measured N uptake by the coffee plants. An evaluation of the simulation scenarios showed that: i) the most efficient N recovery was associated with N rates between 200 and 400 kg N ha^{-1} y^{-1} that were split into at least seven applications per year; ii) N recovery at rates between 200 and 300 kg N ha^{-1} y^{-1} were efficient with or without split application; and iii) the most environmentally friendly N management strategy was the application of between 200 and 300 kg N ha^{-1} y^{-1} using at least seven splits. Reducing the N rate from 600 to 400 kg N ha^{-1} y^{-1} increased plant N recovery efficiency by 8–12% and reduced NO_3-N leaching by 28 to 47%. Predicted NO_3-N leaching and N plant uptake results confirm that better N management strategies can be developed for coffee plantations and other crops grown in the Cerrado.

1. Introduction

The Cerrado zone in Bahia, one of Brazil's northeastern states, achieved an average 37 bags of coffee per hectare for the 2009–2015 period (Conab, 2014) which is the highest productivity of Arabica coffee bean in the country. Bahia's accomplishment was 24% higher than in Minas Gerais State which had the second highest rate of production during the same period. Coffee production on infertile Cerrado soils in Bahia is feasible by combining irrigation and fertilization practices. However, it is questionable whether fertilizers are being managed efficiently for both crop production and environmental issues in this region. Existing nitrogen (N) management studies for coffee plants cultivated on Cerrado soils do not provide clear answers to these questions. Bruno et al. (2015) obtained uptake efficiency for mature coffee plants in western Bahia using several fertilization rates and concluded that reducing N fertilization from 600 to 200 kg N ha^{-1} y^{-1} could significantly reduce N leaching without reducing crop productivity. A study by the Brazilian Agricultural Research Corporation (EMBRAPA) also showed that a N rate of 200 kg N ha^{-1} y^{-1} resulted the maximum coffee yield on an Oxisol in the central Cerrado (Sanzonowicz et al., 2003), but Neto et al. (2011) reported that a rate of 400 kg N ha^{-1} y^{-1} was needed for maximum coffee productivity in Bahia's Cerrado. These studies document a few achievements related to coffee fertilization and N uptake efficiency, but more are needed to be certain coffee productivity is environmentally sustainable.

Numerical models can be used to understand water and nutrient dynamics in agricultural systems, evaluate sensitivities, suggest strategies for better fertilizer and water inputs, and evaluate new scenarios for an efficient crop management. The hydrological model SWAP (van Dam et al., 2008) and the nutritional model ANIMO (Groenendijk et al., 2005) are two tools

* Corresponding author.
E-mail addresses: meriguett@hotmail.com (V.M. Pinto), isabelibruno@gmail.com (I.P. Bruno), qdjvlier@usp.br (Q. de Jong van Lier), ddourado@usp.br (D. Dourado-Neto), klaus@cena.usp.br (K. Reichardt).

http://dx.doi.org/10.1016/j.still.2016.10.006
0167-1987/

that can be used to simulate water and nutrient dynamics, respectively. SWAP simulates the physical mechanisms associated with water flow, heat flow and solute transport in the soil. ANIMO simulates the cycles of carbon (C), N and phosphorus (P) in the soil, as well as greenhouse gas emissions, nutrient leaching, mineralization and immobilization, nitrification, denitrification, P and N soil sorption. Both simulation models have been accepted by the research community for studies on water (Kumar et al., 2015; Kroes and Supit, 2011; De Jong van Lier et al., 2015) and nutrient dynamics (Farmaha, 2014; Kaufmann et al., 2014; Kistner et al., 2013) with applications worldwide.

In this study, a parameterization of ANIMO for a fertilized Cerrado coffee cropping scenario was performed and scenarios with several N rates and split applications were simulated. The most efficient fertilizer management scenarios were determined using simulations of N plant uptake and NO_3-N leaching below the root zone.

2. Materials and methods

2.1. Field data

Field data used for calibration and model evaluation were obtained from experimental sets described in details in Bruno et al. (2011). They carried out an experiment from August 1, 2008, to July 24, 2009, on a private coffee farm in Barreiras (11°46 S, 45°43′ W), State of Bahia, Brazil. The area has virtually no slope (<1%) and was previously covered by Cerrado vegetation. The soil is classified as Typic Hapludox (Soil Survey Staff, 2010), has low natural fertility (Table 1) and is surrounded by remaining Cerrado ecosystem areas. Local precipitation ranges from 582 to 1687 mm per year with an average of 1082 mm, according to historical data (1961–2013) of the National Institute of Meteorology (INMET). Wind speed, solar radiation, air temperature, and air humidity were used from the INMET weather station of Barreiras. Precipitation was measured at the experimental field using a rain gauge with a collection area of 300 cm^2, installed 1.5 m above the ground level.

Coffee plants (variety 'Red Catuai') were seven years old at the beginning of the experiment. The plant arrangement was circular, allowing irrigation and fertigation by a center pivot with a total irrigated area of 80 ha. Plant spacing was 3.8 m between lines (pivot circles) and 0.5 m between plants. In previous years, urea was applied as fertilizer by fertigation according to the expected crop productivity. The input of mineral N was 600 kg N ha^{-1} y^{-1}. Irrigation was performed by Low Energy Precision Application (LEPA) emitters, which distribute the water according to the circular coffee lines, avoiding water application in the inter-row.

Experimental plots with three plants were randomly distributed along the fourth pivot circle counted from the center (Fig. 1). Sixteen plots received ^{15}N urea at N rates 200, 400, 600 and 800 kg N ha^{-1} y^{-1}. The experimental circle fertigation was discontinued to apply urea manually every 14 days. Four (4) mm of water was applied every other day following farmer's irrigation practice. Crop management included weed and pest control with pesticides, application of P, potassium (K), micronutrients, lime and gypsum and several organic materials.

Soil solution samples were taken in the field using a tubular rod with a vacuum device coupled to a ceramic extraction cup. The extraction cups were installed at 1 m depth and close to the middle plant trunk in the 400 and 800 kg N ha^{-1} y^{-1} plots. Soil solution was sampled every two weeks during the second half of 2008 and once per month during the first half of 2009. Samples taken from plots with the same N rate (replicates) were combined into one sample for the respective day, thus providing a total of 20 soil solution samples for the 400 and 800 kg N ha^{-1} y^{-1} treatments from throughout the experimental year. The nitrogen-nitrate concentrations (C_{NO3-N}) in soil solution samples were analyzed according to Giné et al. (1980) by FIA (Flow Injection Analysis). Only the nitrate concentration was measured; inorganic NH_4-N was not presented in the solution samples above the detection limit of 25 μg L^{-1} (Bortolotto et al., 2013).

2.2. Hydrological simulation with the SWAP model

Daily hydrological data were simulated with the SWAP model (Kroes et al., 2008) using hydraulic parameters for the soil profile to a depth of 1 m. Detailed outcomes of these simulations can be found in Pinto et al. (2015). Soil hydraulic parameters (Table 2) were preserved for N simulations with ANIMO. For the deeper soil layer (1.0–2.0 m), the hydrological parameters were obtained by fitting the van Genuchten (1980) equation with the Mualem parametric restriction to data obtained from disturbed soil samples (R^2 = 0.92) using the RETC software (van Genuchten et al., 1991). The shape parameter λ for the deeper soil layer was obtained by inverse modeling. The constant head method (Reynolds et al., 2002) was employed for obtaining K_s of each soil layer and average values for first/intermediate and deeper layers were obtained for simulations.

Table 1
Chemical characteristics of the Typic Hapludox layers.

Layer depth (m)	pH[a]	OM[b] (g dm^{-3})	P[c] (mg dm^{-3})	S[d] (mg dm^{-3})	K[c] ($mmol_c$ dm^{-3})	Ca[c] ($mmol_c$ dm^{-3})	Mg[c] ($mmol_c$ dm^{-3})	Al[e] ($mmol_c$ dm^{-3})	H + Al[f] ($mmol_c$ dm^{-3})	SB[g] ($mmol_c$ dm^{-3})	CEC[h] ($mmol_c$ dm^{-3})	V[i] (%)	M[j] (%)	N-total[k] (mg kg^{-1})
0–0.2	4.7	25	114	10	2	23	9	3	31	34	65	52	8	1080
0.2–0.4	3.6	20	40	21	1	5	3	9	34	9	43	21	50	620
0.4–0.6	3.8	16	5	60	0.8	4	2	9	31	7	38	18	57	532
0.6–0.8	3.6	14	1	72	0.8	3	1	9	31	5	36	13	65	520
0.8–1.0	3.8	14	1	96	0.8	2	1	10	31	4	35	11	72	505

[a] Active acidity by $CaCl_2$ (0.01 mol l^{-1}) method.
[b] Organic matter by colorimetry.
[c] Phosphorus, potassium, calcium and magnesium by ion exchange resin method.
[d] Sulfur by turbidimetry method.
[e] Exchangeable aluminum by titrimetric method (1 mol l^{-1}).
[f] Potential acidity by pH SMP method.
[g] Sum of bases.
[h] Cation exchange capacity.
[i] Base saturation (100 × SB/CEC).
[j] Aluminum saturation (100 × Al^{3+}/Effective CEC).
[k] Kjeldahl method (Raij et al., 2001).

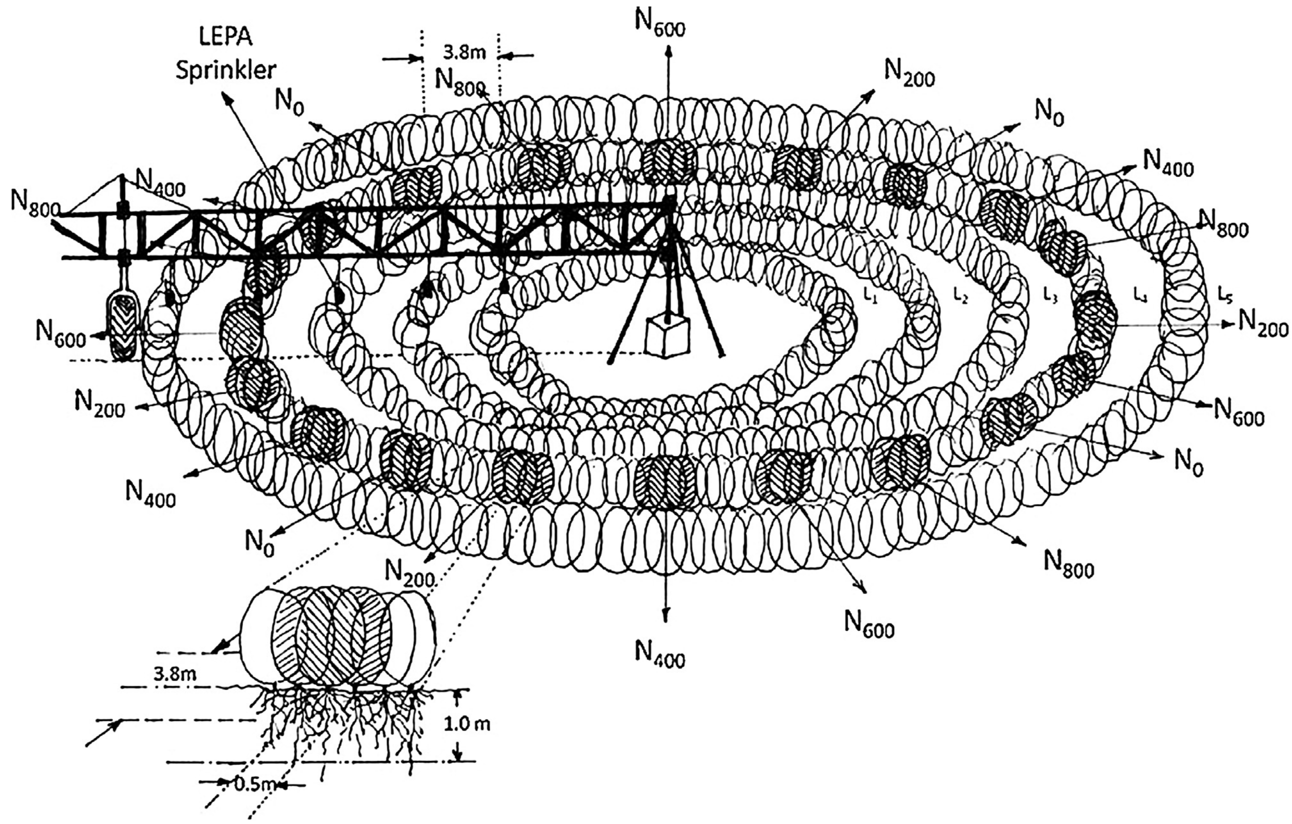

Fig. 1. Schematic representation of the experimental field showing the random distribution of plots in circle L_4 (3 labeled trees each, with different nitrogen rates: N_0 = without nitrogen fertilizer; N_{200} = 200; N_{400} = 400; N_{600} = 600; N_{800} = 800 kg N ha^{-1} y^{-1}); the distance between rows and between coffee plants (3.8 m × 0.5 m); and root system depth (1.0 m).

2.3. Model sensitivity analysis, calibration, and validation

In accordance to the experimental plots of Bruno et al. (2011), four levels of N rates (200, 400, 600 and 800 kg N ha^{-1} y^{-1}) with split application once every two weeks (27 splits during the year) were diagramed for model sensitivity analysis, calibration, and validation. The sensitivity of N leaching, plant uptake and other transport processes simulated with ANIMO to parameters variations was calculated for two N-rate scenarios (400 and 800 kg N ha^{-1} y^{-1}) using the relative partial sensitive index η (Eq. (1)):

$$\eta = \frac{\Delta V/V}{\Delta p/p} = \frac{p\Delta V}{V\Delta p} \qquad (1)$$

To assess η, a selected parameter was changed by 1% ($\Delta p/p = 0.01$) while others were maintained at their default value. Values of $|\eta| \leq 0.5$ were considered equivalent to a low sensitivity for the chosen parameter.

Calibration was performed using the experimental data of NO_3-N concentration in the soil solution measured in the four 400 kg N ha^{-1} y^{-1} replicates. The soil parameters pH, sorption coefficient (s_{NH4}), nitrification rate (k_{nr}), denitrification rate (k_{dr}), stream concentration factor (σ_N^{max}), reference temperature (T_{ref}), the shape parameter λ_{dsl} and the relative root density were optimized by fitting during model calibration. Several combinations of parameters were tested according to the maximum and minimum values for each parameter available in Renaud et al. (2006).

Model simulations were validated using two different output variables, which were measured experimentally: 1) the NO_3-N concentration in the soil solution for the 800 kg N ha^{-1} y^{-1} plots; 2) the overall yearly plant uptake in each experimental management. The best combination of parameters was presented in Table 3.

2.4. Model evaluation

Statistical analysis of the model simulations and consistency with experimental data was performed using the root mean square error RMSE, the index of agreement *d* (Willmott, 1981) and the Nash-Sutcliffe model efficiency NSE (Nash and Sutcliffe, 1970). A full explicative description of these statistical functions and their current use for model validation and calibration can be found in Groenendijk et al. (2014).

2.5. Scenarios of N rates and split application

The N rates 200, 300, 400, 500, 600, 700, and 800 kg N ha^{-1} y^{-1} were evaluated for the following N split application strategies by

Table 2
Van Genuchten-Mualem soil hydraulic parameters used in SWAP simulations.

Soil layer	Depth (m)	θ_r (m^3 m^3)	θ_s (m^3 m^3)	α (m^{-1})	n	K_s (m d^{-1})	λ
Surface and intermediary	0–1.0	0.096	0.387	1.69	1.636	0.266	0.5
Deeper	1.0–2.0	0.115	0.525	1.27	2.040	0.310	0.5

Note: θ_r, residual volumetric soil water content; θ_s, saturated volumetric soil water content; n, α and λ the shape parameters of the retention curve; and K_s the saturated hydraulic conductivity.

Table 3
Soil and plant input parameters used in ANIMO simulations for a Typic Hapludox (Soil Survey Staff, 2010) and *Coffea Arabica* L., variety *Catuaí Vermelho.*

Description	Parameter	Value	Unit
Soil			
Thickness of Surface layer (0–0.1 m)	Δz_1	0.1	m
Thickness of intermediate layer (0.1–1.0 m)	Δz_2	0.9	m
Thickness of deep layer (1.0–2.0 m)	Δz_3	1.0	m
Thickness of top soil compartment	Δz_{top}	0.02	m
Thickness of the reservoir for additions	Δz_{res}	0.05	m
Diffusion coefficient (Surface layer)	p_1	2.00[a]	–
Diffusion coefficient (Intermediate and deeper layers)	p_2	3.00[a]	–
Saturated hydraulic conductivity of the root zone (Surface and intermediate layers)	K_{sr1}	0.266	$m\,d^{-1}$
Dry bulk density (Surface layer)	ρ_{d1}	1790	$kg\,m^{-3}$
Dry bulk density (Intermediate layer)	ρ_{d2}	1580	$kg\,m^{-3}$
Dry bulk density (Deeper layer)	ρ_{d3}	1480	$kg\,m^{-3}$
Soil carbon-nitrogen ratio (Soil profile)	C/N	10	–
Coefficient for organic matter transformations and nitrification	A_n	74,826[a]	$J\,mol^{-1}$
Coefficient for dissolved organic matter transformations	A_d	74,826[a]	$J\,mol^{-2}$
Soil pH (Surface layer)	pH_1	4.3	–
Soil pH (Intermediate and deeper layers)	pH_2	3.8	–
NH_4 sorption coefficient (Soil profile)	s_{NH4}	0.0003	$m^3\,kg^{-1}$
Reference temperature	T_{ref}	25.0	°C
Nitrification rate	k_{nr}	400	y^{-1}
Denitrification rate	k_{dr}	365	y^{-1}
Plant			
Depth of initial root zone	Z_r	1.00	m
Plant residues (roots)	P_r	1426	$kg\,ha^{-1}$
"Sowing" date (in the year of 2008)	t_p	213	Julian day
Harvesting date (in the year of 2009)	t_h	212	Julian day
Transitional data for uptake periods	t_c	365	Julian day
Average cumulative N plant uptake	U_p	491	$kg\,ha^{-1}$
Cumulative transpiration in the first period	T_{a1}	0.59	m
Cumulative transpiration in the second period	T_{a2}	0.60	m
Maximum N transpiration stream concentration factor	σ_N^{max}	3,5	–

[a] According to Groenendijk et al. (2005).

Table 4
Relative partial sensitivity of simulated processes to model parameters.

Parameter	Relative partial sensitivity η[a]				
	Crop uptake	NO_3-N leaching	NH_4-N leaching	NH_4-N nitrified	NO_3-N denitrification
(400 $kg\,ha^{-1}$)					
pH_1	0.82	2.92	1.00	4.70	8.22
pH_2	0.31	5.15	−3.00	3.26	0.00
ρ_{d1}	0.02	0.00	0.00	−0.13	0.00
ρ_{d2}	0.04	−0.17	0.00	−0.17	0.00
s_{1NH4}	0.02	0.00	0.00	−0.13	0.00
s_{2NH4}	0.04	−0.17	0.00	−0.17	0.00
T_{ref}	−0.29	−2.23	1.00	−2.20	−1.37
σ_N^{max}	0.09	−0.52	0.00	−0.17	0.00
U_{p1}	0.18	−0.69	0.00	−0.51	0.00
U_{p2}	0.00	0.00	0.00	−0.08	0.00
T_{a1}	−0.16	0.86	1.00	0.38	0.00
T_{a2}	0.04	0.00	0.00	0.00	0.00
k_{nr}	−0.02	0.52	−1.00	0.55	0.00
(800 $kg\,ha^{-1}$)					
pH_1	0.00	2.87	−1.41	2.17	6.25
pH_2	0.02	3.87	−10.92	2.10	0.00
K_{sr1}	0.00	0.05	0.00	0.00	−2.50
ρ_{d2}	0.00	−0.10	−0.35	−0.02	0.00
s_{2NH4}	0.00	−0.10	−0.70	−0.02	0.00
T_{ref}	0.02	−1.72	3.17	−1.31	−2.50
U_{p1}	0.27	−0.62	−0.35	−0.07	0.00
U_{p2}	0.73	−0.96	−1.06	−0.47	0.00
T_{a1}	−0.23	0.62	0.00	0.03	0.00
T_{a2}	−0.73	0.91	0.70	0.41	0.00
k_{nr}	0.04	0.43	−1.76	0.29	0.00

Note: pH_1, soil pH of surface layer (0–0.1 m); pH_2, soil pH of intermediary (0.1–1.0 m) and deep layers (1.0–2.0 m); K_{sr1}, saturated hydraulic conductivity of the root zone (0–0.1 m); ρ_{d1}, dry bulk density of surface layer; ρ_{d2}, dry bulk density of intermediary and deep layers; s_{1NH4}, sorption coefficient of surface layer; s_{2NH4}, sorption coefficient of intermediary and deep layers; T_{ref}, temperature of reference; σ_N^{max}, maximum N transpiration stream concentration factor; U_{p1} and U_{p2}, expected cumulative uptake in the first and second period, respectively; T_{a1} and T_{a2}, transpiration in the first and second period, respectively; k_{nr}, reference nitrification rate.

[a] Positive/negative value indicates an increase/decrease in the N process simulated in relation to its value when simulated with the standard combinations of parameters; "Zero" means insignificant or no changes in N process simulated with the modified parameter.

fertigation: i) split application every other day (Na_{2d}); ii) once per week (Na_{1w}); iii) once every two weeks (Na_{2w}); iv) once per month (Na_{1m}); v) seven times during the year ($Na_{7/1y}$); and vi) three times during the year ($Na_{3/1y}$). A total of 42 scenarios (7 N rates × 6 split strategies) resulted from the combinations of different annual N rates and split applications during the year.

The N recovery efficiency (NRE) and the NO_3-N leaching were obtained for the 42 evaluated scenarios. NRE was calculated as the ratio between the N plant uptake derived from fertilizer (NU_{ff}) and the mineral N rate applied (Moll et al., 1982). The ratios of the experimentally measured NU_{ff} (Bruno et al., 2015) by the simulated total N taken up from soil, fertilizer and other sources were 0.39, 0.33, 0.44 and 0.38, respectively to the applied N rates 200, 400, 600 and 800 kg N ha^{-1} y^{-1}. The average value of these ratios (0.38) was used to reduce the simulated total N uptake and estimate NU_{ff} for all 42 scenarios. In accordance with experimental data (Bortolotto et al., 2012, 2013), on average 65% of the total NO_3-N leaching originated from N fertilizer (400 and 800 kg N ha^{-1} y^{-1}). This fraction was used to estimate the NO_3-N leachate originating from fertilizer based on the total NO_3-N leachate.

In this way, the annual amount of NO_3-N leaching in a 100 ha circular coffee plantation under a center-pivot (average representative area) was obtained for all N rate scenarios with split application Na_{2w} using three values for annual precipitation: i) 1535 mm (total of the 2008/2009 season), ii) 957 mm (average of the 2003–2013 period) and iii) 582 mm (annual 30 years record minimum precipitation).

The efficiency of the N fertilizing scenario was defined considering the level of NRE and the NO_3-N leaching. The worst-case scenario (which had the lowest NRE and the highest rate of NO_3-N leaching) evaluated with 957 mm of precipitation was used as reference. A management scenario was considered environmentally friendly when NO_3-N leaching was at least 90% lower than the reference. A scenario in which NRE was at least 90% higher than in the reference was considered an efficient recovery management scenario. Classifying the scenarios in this way allowed to establish a recommendation of N fertilization for coffee orchards in the Cerrado region.

3. Results and discussion

3.1. Sensitivity analysis

The evaluated N processes presented high sensitivity to specific parameters, depending on the N rate. The most influential parameters for the simulated N processes with ANIMO model were soil pH, T_{ref}, U_p, T_a, and k_{nr} (Table 4).

An increase in K_{sr} diminished the availability of NO_3-N for denitrification since plant roots absorb preferentially nitrate from the soil surface when N was applied at a rate of 800 kg N ha^{-1} y^{-1}. An increase in σ_N^{max} produced a decrease in NO_3-N leaching but did not significantly change plant uptake for a rate of 400 kg N ha^{-1} y^{-1}. When the N rate 800 kg N ha^{-1} y^{-1} was applied, a large amount of NO_3-N was projected in the soil due to ammonium nitrification, and σ_N^{max} did not regulate plant uptake, nor did it affect N leaching. When the uptake parameter U_p was increased, less nutrient would be expected available for leaching. Less expected was that plant uptake decreased while transpiration T_{a1} increased.

The observed high influence of soil pH on the simulations is related to the high amounts of fertilizer added, and, consequently, high rates of nitrification resulted. Soil pH reduction factor governing the nitrification rates simulated with ANIMO is inversely proportional to the exponential of soil pH level (Renaud et al., 2006), which explains the high sensitivity of nitrification and nitrification-influenced processes to relatively small variations of this soil parameter.

Allowing for a temporal variation of soil pH in the simulation scenarios might improve the simulation results. For fertilized agricultural systems, soil pH is shown to vary temporally due to fertilizer application both on the long-term (Schroder et al., 2011) and on the short-term (Tong and Xu, 2012). With the high rates of N applied to the evaluated coffee orchard, an elevation of soil acidity is expected over time (not measured data). However, simulation of soil pH temporal variation is not possible in the current version of ANIMO.

3.2. Calibration and validation

Calibration achieved the statistical indexes RMSE = $3.9 \cdot 10^{-3}$ kg m^{-3}, NSE = 0.46 and d = 0.80, NSE and d indicating that parameters were well calibrated for the N rate 400 kg N ha^{-1} y^{-1}. The validation simulations of NO_3-N at 1.0 m depth for the N rate 800 kg N ha^{-1} y^{-1} were of good quality as revealed by the NSE = 0.45 and d = 0.80 (RMSE = $7.3 \cdot 10^{-3}$ kg m^{-3}). The relatively high values of RMSE were mainly caused by NO_3-N concentrations measured on day 190, 263 and 321, the peak concentrations in the experimental distribution (Fig. 2). These outliers can be related to the nitrate nature and the NO_3-N soil solution measurement, which averages four spatially remote plots with the same N rate applied (replicates). Considering nitrate is highly mobile in soil, measuring it randomly might result in high RMSE on a given timescale.

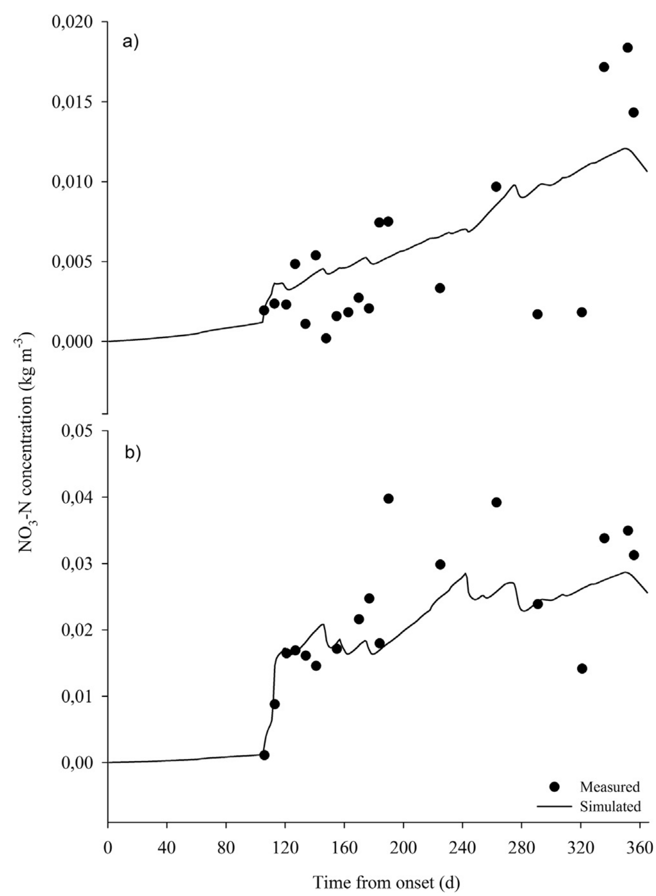

Fig. 2. Daily concentrations of NO_3-N at 1 m depth simulated (lines) and measured (dots) as a function of time from onset of experiments: a) calibration and b) validation.

However, over the experimental season, the model predicted satisfactorily the NO_3-N concentrations in the soil solution.

Simulated annual N uptake was 309, 450, 556 and 562 kg N $ha^{-1} y^{-1}$, for the applications of 200, 400, 600, and 800 kg N $ha^{-1} y^{-1}$, respectively. The experimentally measured N uptakes, from the low to the high N rate, were 481 (σ = 75), 403 (σ = 71), 586 (σ = 90) and 492 (σ = 122) kg N $ha^{-1} y^{-1}$. The ANIMO protocol for modeling N uptake performed well for the scenarios with high N availability, in agreement with conclusions by Wolf et al. (2005). For the 200 kg N $ha^{-1} y^{-1}$ scenario, however, the simulated average N uptake was lower than the observed values and outside the error interval. This discrepancy between model prediction and observation for the N rate 200 kg N $ha^{-1} y^{-1}$ may be explained by mechanisms of nutrient reallocation not accounted for in ANIMO.

The total N taken up by plants predicted by ANIMO can be divided into NO_3-N or NH_4-N preferences. For the N rate 200 kg N $ha^{-1} y^{-1}$, uptake was 41% NO_3-N and 59% NH_4-N. For the N rates 400, 600 and 800 kg N $ha^{-1} y^{-1}$, NO_3-N uptake was predominant (52, 63 and 86% respectively). The preference for NO_3-N by plants when the rate 800 kg N $ha^{-1} y^{-1}$ was applied indicates luxurious consumption of N predicted by the model. Luxurious consumption of N by coffee plants during the experimental sets was detected by Bruno et al. (2011) using isotopic analysis with ^{15}N. The similarity of experimental and simulated uptake results showed that ANIMO can predict the N luxurious demand by coffee plants.

3.3. Scenarios of N rate and split application

Nitrogen recovery efficiency (NRE) decreased with an increase in N rate (Fig. 3a) similarly for all the scenarios of N split application. Differences in NRE were not significant between the N split scenarios Na_{2d}, Na_{1w}, Na_{2w} and $Na_{7/1y}$ simulated with ANIMO. The highest differences (mid 5 and 8%) of NRE resulted with $Na_{3/1y}$ in relation to other scenarios between the N rates 400 and 800 kg N $ha^{-1} y^{-1}$. Increasing the N rate and decreasing the N split application resulted in the maximum rates of NO_3-N leaching simulated (Fig. 3b). Splitting the N rate 400 kg N $ha^{-1} y^{-1}$ into three splits during the year ($Na_{3/1y}$) increased the NO_3-N leaching by 192% in relation to the rate predicted in the scenario with N split application once per two weeks (Na_{2w}). Within each N rate, differences in the results of NO_3-N leaching obtained from the scenarios of split application Na_{2d}, Na_{1w}, and Na_{2w} were very small (Fig. 3b).

The increments on NO_3-N leaching in a pivot area (kg N y^{-1}) correlated exponentially with increasing N rates (Fig. 4). The exponential relations $y = 891 \cdot e^{0.0033x}$ (R^2 = 0.99), $y = 585 \cdot e^{0.0034x}$ (R^2 = 0.98) and $y = 259 \cdot e^{0.0017x}$ (R^2 = 0.92) were obtained from data shown in Fig. 4a,b and c, respectively. Increasing the N rate from 400 to 500 kg N $ha^{-1} y^{-1}$ caused NO_3-N leaching increases by 11% (P = 1535 mm, Fig. 4a), 58% (P = 957 mm, Fig. 4b) and 50% (P = 582 mm, Fig. 4c). Increasing the N rate from 600 to 700 kg N $ha^{-1} y^{-1}$ resulted NO_3-N leaching increases by 57% (Fig. 4a), 131%

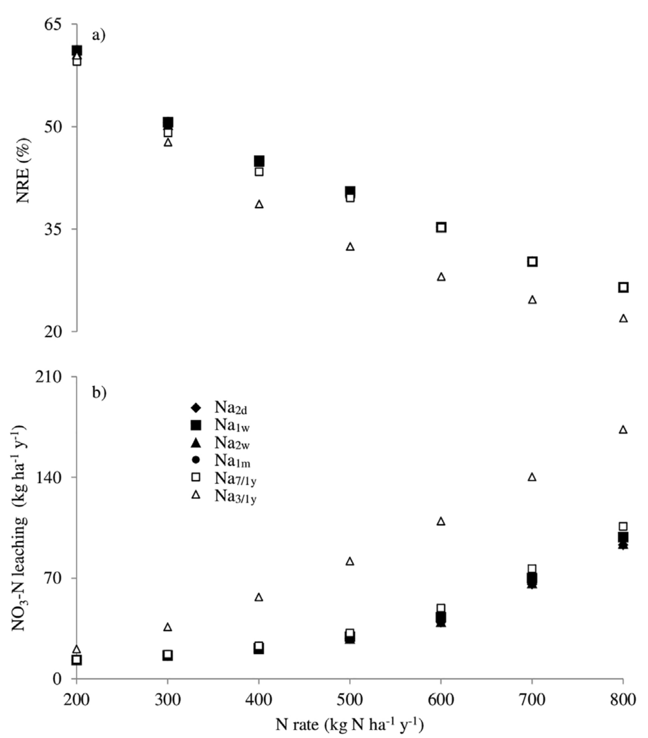

Fig. 3. Nitrogen recovery efficiency (NRE) and N-nitrate (NO_3-N) leaching for different N rates and split applications with 957 mm annual precipitation. Scenarios of split N application: every other day (Na_{2d}), once per week (Na_{1w}), once every two weeks, (Na_{2w}), once per month (Na_{1m}), seven times during the year ($Na_{7/1y}$) and three times during the year ($Na_{3/1y}$).

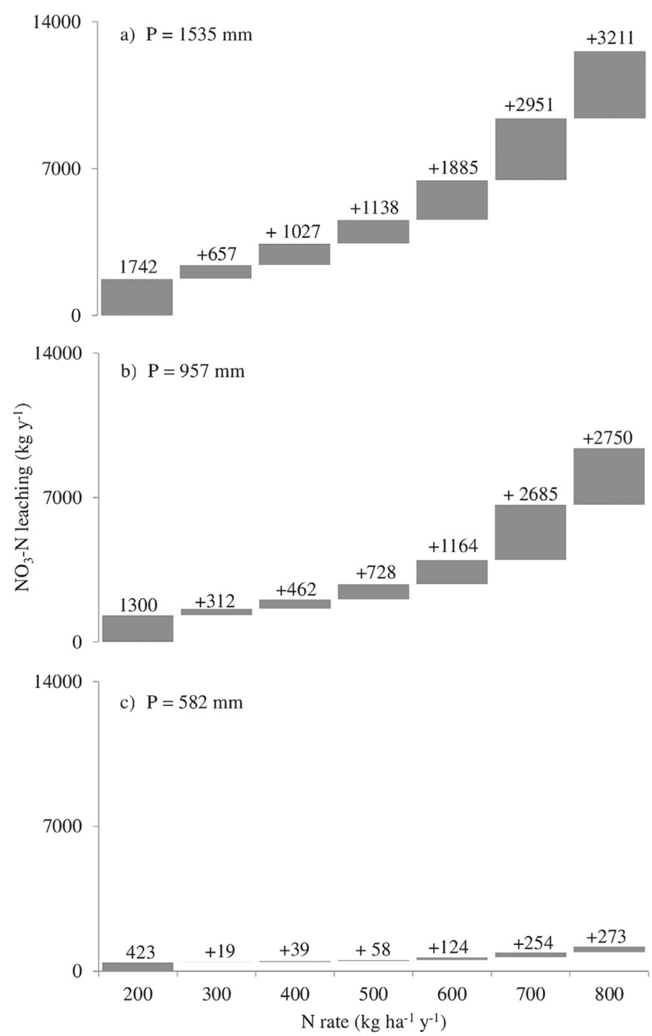

Fig. 4. N-nitrate (NO_3-N) leaching rates resulting from split N application every two weeks (Na_{2W}) during one year in a 100 ha coffee orchard with annual precipitation: a) 1535 mm, b) 957 mm and c) 582 mm.

(Fig. 4b) and 105% (Fig. 4c). The exponential response of NO_3-N leaching to the applied N rates shows that high amounts of mobile NO_3-N can be delivered to soil layers below the rooting zone if N is not properly managed, with a possible negative environmental impact.

The N rate 800 kg N ha^{-1} y^{-1} split into three applications per year was the scenario with lowest NRE percentage and highest NO_3-N leaching rate and was, therefore, considered as the reference. Additionally, as shown by ^{15}N analysis (Bruno et al., 2011) and confirmed by ANIMO simulations, 800 kg N ha^{-1} y^{-1} resulted in luxurious N consumption.

Using this reference, the environmentally friendly managements were found to be those with N rates between 200 and 300 kg N ha^{-1} y^{-1} applied in at least seven times per year. The NO_3-N leaching rate in an average center-pivot area submitted to one of the cited managements will result between 1380 and 1700 kg N y^{-1}. NRE resulted between 49 and 61% for the environmentally friendly N managements. The recommended managements for relative high plant recovery efficiency were N rates between 200 and 400 kg N ha^{-1} y^{-1} with splits at least seven times during one year (NRE between 43 and 61%). The N rates between 200 and 300 kg N ha^{-1} y^{-1} split into three splits in one year are also recommended, with NRE between 60% and 48% (90% lower than NRE from the uncertain N management).

Using N rate 200 kg N ha^{-1} y^{-1} resulted in the highest NRE (61%) and lowest NO_3-N leaching (13 kg N ha^{-1} y^{-1}). However, the corresponding simulated plant uptake could not be validated with experimental data, and any management with this N rate still demands evaluations before being confirmed.

In agreement with the proposed N management classification, farmers commonly employed N rate 600 kg N ha^{-1} y^{-1} with split application of N once every two weeks (averages NRE 35% and NO_3-N leaching rate 39.5 kg N ha^{-1} y^{-1}) is below the standards for a high plant recovery efficiency and environmentally friendly management. The N rate 400 kg N ha^{-1} y^{-1} with split application once every two weeks (Na_{2w}) resulted in an NRE 45% (104% higher than the reference) and NO_3-N leaching rate 28 kg N ha^{-1} y^{-1} (88% lower than the reference). The N rate 400 kg N ha^{-1} y^{-1} with split application Na_{2w} is at the critical limit to be classified as environmentally friendly, and can be recommended for attaining high plant recovery efficiency and environmental quality. Reducing the N rate from 600 to 400 kg N ha^{-1} y^{-1} for coffee plantations on Cerrado soils would increase plant N recovery efficiency from 8 to 12% and decrease the loss of NO_3-N by leaching to the environment from 28 to 47%.

4. Conclusion

Agreement between simulated NO_3-N concentrations in soil solution with experimental data confirmed the model efficiency for predicting N transport by leaching in a coffee orchard on a Cerrado sandy soil of Bahia. ANIMO predicted the average plant uptake for N rates between 400 and 800 kg N ha^{-1} y^{-1}. Simulated N management scenarios were classified according to proposed limits for N recovery efficiency and NO_3-N leaching and results showed: i) the most efficient N recovery managements were N rates between 200 and 400 kg N ha^{-1} y^{-1} with split application at least seven times during one year; ii) N rates between 200 and 300 kg N ha^{-1} y^{-1} were efficient in recovery independent of N split application; iii) the environmentally friendly managements corresponded to N rates between 200 and 300 kg N ha^{-1} y^{-1} with split applitaion at least seven times during the year. Reducing the N rate from 600 to 400 kg N ha^{-1} y^{-1} for Cerrado coffee plantations would increase N recovery efficiency by 8 to 12% and minimize the NO_3-N leaching by 28–47%. For coffee crops grown on Cerrado sandy soils and managed with fragmented N rates under fertigation, a rate of 400 kg N ha^{-1} y^{-1} is recommended for continuing at high productivity and reduced environment impact.

Acknowledgments

The authors are grateful to São Paulo Research Foundation (FAPESP/Grant #:2011/22320-1) for the main financial support. The Coordination for the Improvement of Higher Education Personnel (CAPES/Grant #:8313-12-1) and the National Council for Scientific and Technological Development (CNPq/Grant #:302261/2011-7) also provided financial support for this research. Valuable contributions to this study were made by Dr. Jos C. van Dam and Dr. Piet Groenendijk from WUR/Wageningen-The Netherlands. We thank the anonymous reviewers for their careful reading of our manuscript and their constructive comments and suggestions.

References

Bortolotto, R.P., Bruno, I.P., Reichardt, K., Timm, L.C., Amado, T.J.C., Ferreira, A.O., 2012. Nitrogen fertilizer (^{15}N) leaching in a central pivot fertigated coffee crop. Rev. Ceres 59, 427–432.

Bortolotto, R.P., Bruno, I.P., Dourado-Neto, D., Timm, L.C., Silva, A.N., Reichardt, K., 2013. Nitrate leaching through climatologic water balance in a fertigated coffee plantation. Rev. Ceres 60, 785–792. doi:http://dx.doi.org/10.1590/S0034-737x2013000600006.

Bruno, I.P., Unkovich, M.J., Bortolotto, R.P., Bacchi, O.O.S., Dourado-Neto, D., Reichardt, K., 2011. Fertilizer nitrogen in fertigated coffee crop: absorption changes in plant compartments over time. Field Crops Res. 124, 369–377. doi:http://dx.doi.org/10.1016/j.fcr.2011.07.004.

Bruno, I.P., Reichardt, K., Bortolotto, R.P., Pinto, V.M., Bacchi, O.O.S., Dourado-Neto, D., Unkovich, M.J., 2015. Nitrogen balance and fertigation use efficiency in a field coffee crop. J. Plant Nutr. 38, 2055–2076. doi:http://dx.doi.org/10.1080/01904167.2014.958168.

Conab, 2014. Companhia Nacional de Abastecimento (Conab), Brasília. http://www.conab.gov.br/conteudos.php?a=1252&t=.

De Jong van Lier, Q., Wendroth, O., Van Dam, J.C., 2015. Prediction of winter wheat yield with the SWAP model using pedotransfer functions: an evaluation of sensitivity, parameterization and prediction accuracy. Agric. Water Manage. 154, 29–42. doi:http://dx.doi.org/10.1016/j.agwat.2015.02.011.

Farmaha, B.S., 2014. Evaluating animo model for predicting nitrogen leaching in rice and wheat. Arid Land Res. Manage. 28, 25–35. doi:http://dx.doi.org/10.1080/15324982.2013.801371.

Giné, M.F., Bergamin, H., Zagatto, E.A.G., Reis, B.F., 1980. Simultaneous determination of nitrate and nitrite by flow injection analysis. Anal. Chim. Acta 114, 191–197. doi:http://dx.doi.org/10.1016/S0003-2670(01)84290-21-197.

Groenendijk, P., Renaud, L.V., Roelsma, J., 2005. Prediction of Nitrogen and Phosphorus leaching to groundwater and surface waters; Process descriptions of the ANIMO 4.0 model. Alterra-Report 983, Wageningen, the Netherlands, 116p. ISSN 1566-7197.

Groenendijk, P., Heinen, M., Klammler, G., Fankb, J., Kupfersberger, H., Pisinaras, V., Gemitzi, A., Peña-Harod, S., García-Prats, A., Pulido-Velazquez, M., Perego, A., Acutis, M., Trevisan, M., 2014. Performance assessment of nitrate leaching models for highly vulnerable soils used in low-input farming based on lysimeter data. Sci. Total Environ. 499, 463–480. doi:http://dx.doi.org/10.1016/j.scitotenv.2014.07.002.

Kaufmann, V., Pinheiro, A., Castro, N.M.R., 2014. Simulating transport of nitrogen and phosphorus in a Cambisol after natural and simulated intense rainfall. J. Contam. Hydrol. 160, 53–64. doi:http://dx.doi.org/10.1016/j.jconhyd.2014.02.005.

Kistner, I., Ollesch, G., Meissner, R., Rode, M., 2013. Spatial-temporal dynamics of water soluble phosphorus in the topsoil of a low mountain range catchment. Agric. Ecosyst. Environ. 176, 24–38. doi:http://dx.doi.org/10.1016/j.agee.2013.05.016.

Kroes, J.G., Supit, I., 2011. Impact analysis of drought, water excess and salinity on grass production in The Netherlands using historical and future climate data. Agric. Ecosyst. Environ. 144, 370–381. doi:http://dx.doi.org/10.1016/j.agee.2011.09.008.

Kroes, J.G., van Dam, J.C., Groenendijk, P., Hendrikx, R.F.A., Jacobs, C.M.J., 2008. SWAP version 3.2. Theory Description and User Manual. Alterra, Wageningen Report 1649, 262p..

Kumar, P., Sarangi, A., Singh, D.K., Parihar, S.S., Sahoo, R.N., 2015. Simulation of salt dynamics in the root zone and yield of wheat crop under irrigates saline regimes using SWAP model. Agric. Water Manage. 148, 72–83. doi:http://dx.doi.org/10.1016/j.agwat.2014.09.014.

Moll, R.H., Kamprath, E.J., Jackson, W.A., 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron. J. 74, 562–564.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part 1 — a discussion of principles. J. Hydrol. 10, 282–290. doi:http://dx.doi.org/10.1016/0022-1694(70)90255-6.

Neto, A.P., Favarin, J.L., Almeida, R.E.M., Dias, C.T.S.D., Tezotto, T., Alves, A.G.A., Moraes, M.F., 2011. Changes of nutritional status during a phenological cycle of coffee under high nitrogen supply by fertigation. Commun. Soil Sci. Plant Anal. 42, 2414–2425. doi:http://dx.doi.org/10.1080/00103624.2011.607731.

Pinto, V.M., Reichardt, K., van Dam, J., De Jong van Lier, Q.J., Bruno, I.P., Durigon, A., Dourado-Neto, D., Bortolotto, R.P., 2015. Deep drainage modeling for a fertigated coffee plantation in the Brazilian savanna. Agric. Water Manage. 148, 130–140. doi:http://dx.doi.org/10.1016/j.agwat.2014.09.029.

Raij, B., van Andrade, J.C., Cantarella, H., Quaggio, J.A., 2001. Chemical Analysis for Evaluation of Tropical Soil Fertility. Instituto Agronômico, Campinas.

Renaud, L.V., Roelsma, J., Groenendijk, P., 2006. User's Guide of the Animo 4.0 Nutrient Leaching Model, Alterra Report 224. Alterra, Wageningen 191p.

Reynolds, W.D., Elrick, D.E., Young, E.G., Amoozegar, A., Booltink, H.W.G., Bouma, J., 2002. Water retention and storage: saturated and field-saturated water flow parameters. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 4, Physical Methods. SSSA Book Series N.5. Madison, WI, USA, pp. 797–878.

Sanzonowicz, C., Toledo, P.M.R., Sampaio, J.B.R., Guerra, A.F., Silva, D.T.M., 2003. Nitroger Fertilization in Trimmed Coffee in a Savannah Oxisol. Technical Report 104. Embrapa Cerrados 15p. ISSN1676-918X.

Schroder, J.L., Zhang, H., Girma, K., Raun, W.R., Penn, C.J., Payton, M.E., 2011. Soil acidification from long-term use of nitrogen fertilizers on winter wheat. Soil Sci. Soc. Am. J. 75, 957–964. doi:http://dx.doi.org/10.2136/sssaj2010.0187.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington.

Tong, D., Xu, R., 2012. Effects of urea and $(NH_4)_2SO_4$ on nitrification and acidification of Ultisols from Southern China. J. Environ. Sci. 24, 682–689. doi:http://dx.doi.org/10.1016/S1001-0742(11)60832-2.

van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of modeling water flow in variably saturated soils with SWAP. Vadose Zone J. 7, 640–653. doi:http://dx.doi.org/10.2136/vzj2007.0060.

van Genuchten, M. Th., Leij, F.J., Yates, S.R., 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 1.0. EPA Report 600/2–91/065. U.S. Salinity Laboratory, USDA, ARS, Riverside, CA.

van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2, 184–194. doi:http://dx.doi.org/10.1080/02723646.1981.10642213.

Wolf, J., Hack-ten Broeke, M.J.D., Rötter, R., 2005. Simulation of nitrogen leaching in sandy soils in The Netherlands with the ANIMO model and the integrated modeling system STONE. Agric. Ecosyst. Environ. 105, 523–540. doi:http://dx.doi.org/10.1016/j.agee.2004.07.010.