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An integrated North Florida dairy farm model to reduce environmental impacts under seasonal climate variability

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Abstract

Dairies are challenged to comply with stricter environmental regulations and remain economically viable. This paper studies the potential use of ENSO-based climate forecasts to reduce N leaching without reducing profits on North Florida dairies. A model was created to perform the analyses, the Dynamic North Florida Dairy Farm Model (DyNoFlo). DyNoFlo is an integrated dynamic model that incorporates Markov-chain simulation of cow flows and crop model simulations for historical climatic years (El Niño, La Niña, and Neutral years). It also includes optimization of managerial options. It responds to dairy-specific environment (climate and soils) and management (livestock management, waste management, crop systems management). The DyNoFlo model was designed to be a tool for producers, regulatory agencies, and extension services in addition to a research tool. Analyzing a typical North Florida dairy farm, it was found that N leaching was highest during winter El Niño years. Sandy soils were substantially more prone to leach N, and perennial grasses were better to prevent N leaching. The typical farm could decrease N leaching up to 23% in an El Niño year and still maintain profit by adjusting protein in the diet, confinement time for milking cows, and combining perennial grasses and forages in pastures and sprayfields. Application of the DyNoFlo model to small, medium, and large dairy farms showed that they could decrease their N leaching by 9, 20, and 25%, respectively, without reducing profits by varying management strategies according to ENSO phases.

Keywords: El Niño Southern Oscillation (ENSO); Water pollution; Nitrogen leaching; Dairy farm modeling; Ecologic simulation; Economic simulation

1. Introduction

Environmental degradation resulting from nitrogen (N) leaching from dairy farms in North Florida must be considered in dairy design and management (Cabrera, 2004). Because of the increasing concerns regarding N concentration in water in the Suwannee River Basin, North Florida dairy farms are being more closely scrutinized by regulatory agencies (Giesy et al., 2003). Effective tools to estimate the potential pollution of specific dairy operations as well as potential ways to mitigate the problem inside the farm gate are critical needs (Van Horn et al., 2001). It is thought that the use of ENSO-based climate forecasts may enable reductions in N leaching without reducing profits. Several applications have been created to provide guidelines to manage nutrients and to assist dairy producers to reduce environmental impacts. Some applications consist of spreadsheets of nutrient balances with emphasis on manure management and farm nutrient utilization based on published standards. A common procedure is to estimate gross amounts of manure N excreted and compare them with the capacity of the plants and soils to absorb them (Van Horn et al., 1994). Neither the standards nor the gross manure N

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calculations in these applications reflect the feed selection and animal or plant performance.

In Van Horn et al. (1994) and successive improvements (Van Horn et al., 1998, 2001), standards from several sources such as the National Research Council and the USDA are used in order to perform sink source balances of nutrients. This application estimates the amount of N excreted as the difference between the quantities of N consumed and N utilized in milk production, weight gain, and body maintenance. This relatively simple approach bases its calculations on only two major cow categories: milking cows and dry cows. This approach estimates the amount of N entering the dairy as the mass of feed stock consumed multiplied by an average N content factor, and the amount leaving the system as the amount of milk produced multiplied by an N content factor. The difference between feed N input and milk N output provides an estimate of excreted N, but also includes errors in starting and ending inventories and the individual nutrient content of feedstuffs and milk (Nennich et al., 2003). The Van Horn methodology does not account for seasonality due to weather-based differences in uptake of N by crops and therefore potential of N leaching. Also, it does not include manure N excreted by heifers.

Another example is the USDA-NRCS, a spreadsheet called Water Budget and Nutrient Balance for Florida, WATNUTFL Version 2.0 (NRCS, 2001), which is based on body weight of ruminants and standard N excretion factors. This application uses standardized estimations of N excretion based on live weight of animals according to the agricultural waste management field handbooks from the USDA. This approach disregards the level of milk production and the intra-annual seasonality of dairy farms. Also, this methodology bases its estimates on averages of at most three cow states.

Parallel research in dairy nutrition using process-based modeling creates an opportunity to integrate modeling procedures and improve overall nutrient flow estimates, and ultimately provides a means to examine the potential of reducing N contamination through manipulation of dairy feeding practices. An example is the state of the art Cornell Net Carbohydrate and Protein System model (CNCPS, Fox et al., 1992) that formulates diets for given production goals and simulates the biophysical partition of nutrients into milk, animal body weight, feces and urine. However, a dairy farm is composed of several other components and the flow of N is determined by the interaction of all these components inside an integrated system.

The capability of simulating whole dairy farm systems is a challenge that has long been recognized. The complexity of dairy farms that include livestock, waste, feed, crops, and their interactions, justifies the creation of a whole-farm model, integrating several disciplines and modeling approaches, in order to better analyze these systems (Herrero et al., 2000). An integrated approach has been demonstrated in the dairy forage system, DAFOSYM (Rotz et al., 1989) and successive improvements (Rotz et al., 1999, 2002; Soder and Rotz, 2001). The DAFOSYM is a whole farm simulation model of dairy production that simulates the farm system for many years of weather to determine long-term performance, environmental impact, and economics of the farm. However, DAFOSYM is regionally adapted to the North East United Sates and does not include an optimization procedure. Nevertheless, it is widely used as a research tool, but not intended to be user friendly to extensionists and farmers.

If model simulation software is created for farmers, extension agents, and farm advisers in addition to the scientific community, it must be designed to be user friendly. It is important not only that the model be able to simulate existing conditions, but also to make the simulation quickly and easily, in a readily accessible form, for site specific conditions, in real time (Archer et al., 2002). Such a model should also incorporate the capability of optimizing the dairy operation in such a way that profitability is maintained while N leaching is reduced.

The Dynamic North Florida Dairy Farm Model, DyNoFlo model, described in this paper integrates N nutrient budget, crop, livestock, and optimization models to assess N leaching from North Florida dairy farms and the economic impacts on these farms resulting from reducing N leaching under different climatic conditions. Previous dairy modeling approaches used in Florida, Van Horn et al. (2001) and NRCS (2001), estimated yearly N leaching assuming static conditions of livestock, crops, and waste systems, and disregarded seasonal climatic conditions. The DyNoFlo model incorporates Markov-chain simulations of cow flows (St-Pierre et al., 2003; Jalvingh et al., 1994), crop simulation models (Jones et al., 2003) and historical climatic years for El Niño Southern Oscillation (Mavromatis et al., 2002) to account for seasonal effects under different climate conditions.

Climatic conditions (i.e., temperature, rainfall, solar radiation), which are influenced by El Niño Southern Oscillation (ENSO phases, Hansen et al., 1998) impact N leaching from dairy farms. Consequently, dairy operations could include different management strategies for varying seasonal climate forecasts based on ENSO phase in order to decrease their environmental impacts.

The DyNoFlo model was created in collaboration with stakeholders to fill gaps found for North Florida dairy farm system modeling and it has fundamental differences from the above mentioned DAFOSYM model. The DyNoFlo is rooted in regional North Florida conditions of herd and crop performances, accounts for intra and inter annual climate variability, includes optimization routines, and it was created as a user-friendly application. The DyNoFlo model and its documentation are available at the Southeastern Climate Consortium Website, http://www.agclimate.org/, under the path: livestock/dairy/N leaching.

The objectives of this paper are: (1) to describe the Dynamic North Florida Dairy Farm Model (DyNoFlo); (2) to demonstrate its use with ENSO-based climate forecasts. The tested hypothesis was that the North Florida dairy farms can reduce N leaching maintaining profitability by selecting practices based on ENSO-based climate forecasts.

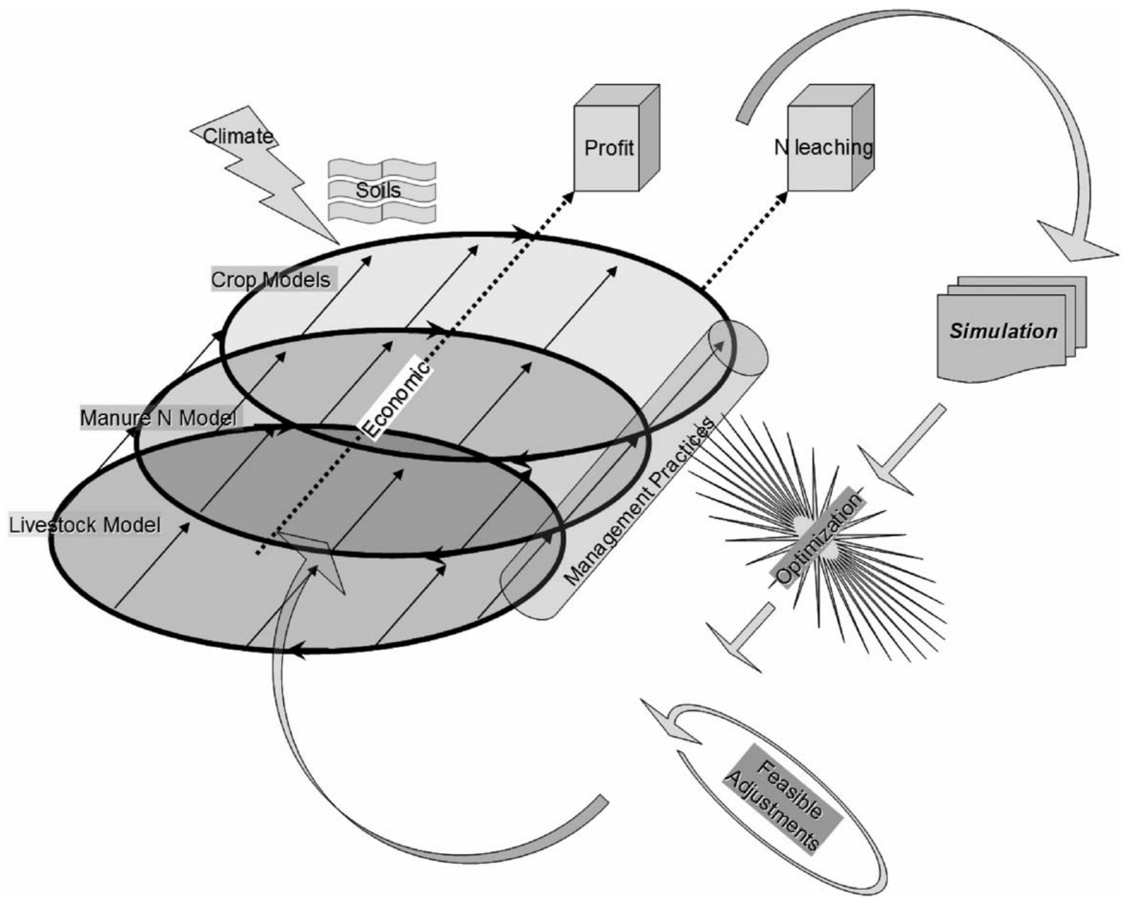

Fig. 1. Schematic representation of the Dynamic North Florida dairy farm model (DyNoFlo).

2. Materials and methods

2.1. The DyNoFlo model

The main components of DyNoFlo are shown in Fig. 1. The livestock model simulates aging and distribution of cows, and manure N excretion. The manure N model receives inputs from the livestock model and simulates the manure N flow through the manure handling system. The crop models receive inputs from the manure N model to simulate N leaching, crop biomass accumulation, and N uptake in the crop fields. The crop models are run on a daily basis and then summarized in monthly outcomes to run dynamically in monthly steps with the livestock and manure N models. An economic module interacts with all other models. Each component responds to a set of management practices. Below are the description and equations that define each DyNoFlo component. All variables are defined in Table 1.

2.1.1. The livestock model

The livestock model calculates the number of animals in each of 3200 cow states by Markov-chain simulation. A cow state is characterized by three features; i is months producing milk after calving (cows) or age of animals after birth (heifers), j is pregnancy state, and k is lactation or parity. A group of cows ($C_{i,j,k}$) is described by months producing milk after calving (adults, i = 1–20) or months of age after birth (heifers, i = 1–32), months of pregnancy (unbred or up to 9 months pregnant, j = 0–9), and number of lactations (heifers or up to nine lactations, k = 0–9). For example, a group of cows can be characterized as being in the ninth month of milk production, third month of pregnancy, and in the second lactation (i = 9, j = 3, k = 2, $C_{9,3,2}$). Non-possible combinations are excluded; for example a group of cows cannot be producing milk 4 months and be 6 months pregnant because cows can become pregnant only after the second month of producing milk. We distinguish between cows as those in lactation numbers k = 1–9 and heifers (k = 0).

The variables $X_{i,m,k}$, $Y_{i,m,k}$ and $M_{i,m,k}$ represent three dimensional matrices that include the monthly probabilities of culling, reproduction, and milk production rates for cows, respectively, for North Florida dairy farm conditions (de Vries, 2004). The variables $X_{i,m,k}$, $Y_{i,m,k}$ and $M_{i,m,k}$ introduce the stochastic parameters into the Markov-chain framework. The sub-indices i and j are defined as previously and m is the month of the year (1–12 from September to August). Culling and reproduction rates for heifers are different from those for cows and they are contained in different matrices, but with the same notation.

Table 1
Variables of the DyNoFlo model in alphabetical order

Variable (unit-month^{-1})[a]	Definition
ACP (%)	Amount of crude protein in diet
BA (kg)	Overall farm biomass accumulation
BAV (US\$ kg^{-1})	Value as forage of accumulated biomass
$Ba_{m,e,s,f,n}$ (kg ha^{-1})	Biomass accumulation in month *m*, for ENSO phase *e*, for soil type *s*, for forage system *f*, and for manure N applied *n*
$C_{1,0,k}$ for $k \geq 1$ (head)	Cows in first month of lactation
$C_{i,0,0}$ for i = 1–32 (head)	Unbred heifers
$C_{i,0,k}$ for i = 1–20, k = 1–9 (head)	Unbred cows
$C_{i,9,0}$ for $i \geq 20$ (head)	Heifers in delivery month
$C_{i,9,k}$ for $i \geq 11$, $k \geq 1$ (head)	Cows in delivery month
$C_{i,j,0}$ (head)	Heifers with *i* months of age and *j* months of pregnancy
$C_{i,j,0}$ for i = 12–32, j = 1–9 (head)	Pregnant heifers
$C_{i,j,k}$ for i = 3–20, j = 1–9, k = 1–9 (head)	Pregnant cows
$C_{i,j,k}$ for $k \geq 1$ (head)	Cows with *i* months producing milk, *j* months of pregnancy, and *k* lactation
CE (US\$ kg milk^{-1})	Expenses by raising crops
DMI (kg)	Herd dry matter intake
DRY (head)	Dry cows (D)
e (code)	ENSO phase (1–3; La Niña, Neutral, El Niño; Table 2)
E (US\$)	Overall farm expenses per kg of milk in month *m*
FP (US\$ kg milk^{-1})	Expenses by feed purchasing
f (code)	Forage system (1–11, Table 2)
HEIFERS (head)	Heifers (young livestock) (H)
i (number)	Months of milk production after calving (1–20, mature cows) or months of age (1–32, heifers)
j (number)	Months of pregnancy (0–9, unbred or up to 9 months pregnant)
k (number)	Lactation cycle (0–9, heifer or up to nine lactations)
m (month)	Month of the year (1–12, from September to August)
M_c (kg)	Manure excreted in concentrated areas
$M_{i,m,k}$ (kg day^{-1})	Milk production for cows with *i* months producing milk, *m* months of the year, and *k* lactation
MILK (kg)	Herd milk production
MILKING (head)	Milking cows, cows producing milk (M)
MM (US\$ kg milk^{-1})	Expenses by marketing of milk
M_p (kg)	Manure excreted in pasture fields
MP (US\$ kg^{-1})	Milk price
M_w (kg)	Manure excreted in manure handling system
n (kg ha^{-1})	Manure N applied in fields
N_c (kg)	Nitrogen excreted in concentrated areas
N_f (kg)	Nitrogen in the feed
$NITROGEN_B$ (kg)	Manure N excreted by BULLS
$NITROGEN_D$ (kg)	Manure N excreted by DRY
$NITROGEN_H$ (kg)	Manure N excreted by HEIFERS
$NITROGEN_M$ (kg)	Manure N excreted by MILKING
$\overline{NL}$ (kg)	Average N leaching for scenarios *r* in an optimization
NL (kg)	Overall N leaching
NL_{mr} (kg)	Nitrogen leaching in month *m* and scenario *r*
$Nl_{m,e,s,f,n}$ (kg ha^{-1})	Nitrogen leaching in month *m*, for ENSO phase *e*, for soil type *s*, for forage system *f*, and for manure N applied *n*
N_p (kg)	Nitrogen excreted in pasture fields
NPF (kg)	Manure nitrogen in pasture field available for plant uptake or leaching
NSF (kg)	Manure nitrogen in sprayfield available for plant uptake or leaching
NV (US\$ kg^{-1})	Value as fertilizer of nitrogen leaching
N_w (kg)	Nitrogen excreted in manure handling system
OE (US\$ kg milk^{-1})	Expenses by other purchases and services
OS (US\$ kg milk^{-1})	Net income by other sales and services
PCT_m (%)	Percent of confined time of milking cows
PFa_t (ha)	Area of pasture field *t*
PHR (%)	Percent of heifers raised on farm
POS (%)	Seasonality of milk production (100 = maximum)
PP (US\$ kg milk^{-1})	Expenses by personnel payment
$\bar{\Pi}$ (US\$)	Average profit for scenarios *r* in an optimization
Π (US\$)	Overall farm profit in month *m*
Π_{mr} (US\$)	Profit in month *m* and scenario *r*
q (number)	Number of sprayfields
r (number)	Scenario number simulated for optimization
rr (number)	Total number of scenarios in an optimization
R (US\$)	Overall farm revenue per kg of milk in month *m*
RHA (kg year^{-1})	Rolling herd average, 12-months moving herd average of milk production
s (code)	Soil type (1–10, Table 2)
SC (%)	Solids collected
SLC (US\$ kg milk^{-1})	Net income by selling cows
$SFat_q$ (ha)	Area of sprayfield *q*
SH (US\$ kg milk^{-1})	Net income by selling calves and heifers
SS (%)	Sedimentation in sludge
T (number)	Number of pasture fields
TAC (head)	Total adult cows
TCA (%)	Time milking cows spend in concentrated areas
TNB (head)	Total number of bulls (B)
VEAc (%)	Volatilization after excretion in concentrated areas
VBF (%)	Volatilization of N before flushing
VECp (%)	Volatilization of N after excretion in pastures
VI (%)	Volatilization of N during irrigation
VL (%)	Volatilization of N in the lagoon
VP (%)	Volatilization of N in the storage pond
VS (%)	Volatilization of N in soil
W_c (m^3)	Water used in manure handling system
W_m (days)	Number of days in month *m*
$X_{i,m,k}$ (%) for $k \geq 1$	Probability of culling cows with *i* months producing milk during month *m* of the year and *k* lactation
$X_{i,m,0}$ (%)	Probability of culling heifers with *i* months of age during month *m* of the year

Table 1 (*Continued*)

Variable (unit-month^{-1})[a]	Definition
$Y_{i,m,k}$ (%) for $i \geq 3$, $k \geq 1$	Probability of pregnancy for cows with i months producing milk during month m of the year and k lactation
$Y_{i,m,0}$ (%) for $i \geq 12$	Probability of pregnancy for heifers with i months of age during month m of the year
Z_{mr} (%)	Selected activity in an optimization for a month m and scenario r

[a] Unless otherwise stated.

The reproduction program for cows starts in the second month after calving; therefore, cows passing from month 1 to month 2 of milk production do not have a probability of becoming pregnant, Eq. (1). However, cows in months 2–12 of milk production can become pregnant (Eq. (2)) or can remain unbred (Eq. (3)). Cows that are still not pregnant after 12 months are culled. Pregnant cows are updated both by months in milk production and months in pregnancy as noted in Eq. (4) and cows and heifers 9-months-pregnant calve and enter higher lactation, Eq. (5). Notice that cows and heifers have, at any stage, a probability of being culled during month m from unforeseen situations

$$C_{i+1,0,k} = (C_{i,0,k})(X_{i,m,k}) \quad \text{for } i = 1,\ k = 1\text{–}9,\ m = \text{any month} \tag{1}$$

$$C_{i+1,1,k} = (C_{i,0,k})(X_{i,m,k})(Y_{i,m,k}) \quad \text{for } i = 2\text{–}12,\ k = 1\text{–}9,\ m = \text{any month} \tag{2}$$

$$C_{i+1,0,k} = (C_{i,0,k})(X_{i,m,k})(1 - Y_{i,m,k}) \quad \text{for } i = 2\text{–}12,\ k = 1\text{–}9,\ m = \text{any month} \tag{3}$$

$$C_{i+1,j+1,k} = (C_{i,j,k})(X_{i,m,k}) \quad \text{for } i = 2\text{–}19,\ j = 1\text{–}8,\ k = 1\text{–}9,\ m = \text{any month} \tag{4}$$

$$C_{1,0,k+1} = \left(\sum_{i=11}^{20} C_{i,9,k}\right)(X_{i,m,k}) \quad \text{for } i = 0\text{–}8,\ m = \text{any month} \tag{5}$$

For example, Eq. (2) simulates the cows that become pregnant in any month by multiplying the number of cows in reproduction stage ($C_{i,0,k}$) by the probability of becoming pregnant ($Y_{i,m,k}$) and by the probability of being culled ($X_{i,m,k}$), where the probabilities are affected by the month of the year, m.

Heifers start their reproduction program when they are 12 months old; therefore, heifers from months 1 to 11, simulated by Eq. (6), do not include a probability of pregnancy. Heifers can become pregnant between 12 and 24 months, Eq. (7), or they can remain unbred, Eq. (8). Unbred heifers 25 months old are culled. Eq. (9) simulates the growth of pregnant heifers

$$C_{i+1,0,0} = (C_{i,0,0})(X_{i,m,0}) \quad \text{for } i = 1\text{–}11,\ m = \text{any month} \tag{6}$$

$$C_{i+1,1,0} = (C_{i,0,0})(X_{i,m,0})(Y_{i,m,0}) \quad \text{for } i = 12\text{–}24,\ m = \text{any month} \tag{7}$$

$$C_{i+1,0,0} = (C_{i,0,0})(X_{i,m,0})(1 - Y_{i,m,0}) \quad \text{for } i = 12\text{–}24,\ m = \text{any month} \tag{8}$$

$$C_{i+1,j+1,0} = (C_{i,j,0})(X_{i,m,0}) \quad \text{for } i = 12\text{–}31,\ j = 1\text{–}8,\ m = \text{any month} \tag{9}$$

The number of milking cows, those producing milk of first or higher lactation, non-pregnant or up to the seventh pregnancy month, is calculated by Eq. (10). The number of dry cows, those in the last 2 months of pregnancy, is calculated by Eq. (11). The number of heifers includes all animals in lactation 0 plus female calves (50% of calves born), Eq. (12). Depending upon management of specific farms, none, part, or all heifers are kept on-farm; therefore, the number of heifers is adjusted by the percent of heifers raised on the farm, PHR

$$\text{MILKING} = \sum_{k=1}^{9}\sum_{j=0}^{7}\sum_{i=1}^{18} C_{i,j,k} \tag{10}$$

$$\text{DRY} = \sum_{k=1}^{9}\sum_{j=8}^{9}\sum_{i=1}^{18} C_{i,j,k} \tag{11}$$

$$\text{HEIFERS} = \left(\sum_{j=0}^{9}\sum_{i=1}^{32} C_{i,j,0}\right)(\text{PHR}) + \frac{\sum_{i=11}^{32}(C_{i,9,k})(X_{i,m,k})}{2} \quad \text{for } k = 1\text{–}9,\ m = \text{any month} \tag{12}$$

Herd milk production is estimated by the productivity rates of milking cow groups, $M_{i,m,k}$, and the number of cows in each state of productivity. Milk production is adjusted by the number of days in each month of the year W_m, including a differentiation between regular and leap years, Eq. (13)

$$\text{MILK} = \left(\sum_{k=1}^{9}\sum_{j=0}^{7}\sum_{i=1}^{18} C_{i,j,k} M_{i,m,k}\right)(W_m) \quad \text{for } m = \text{any month} \tag{13}$$

Climatic conditions influence the proportion of cows by categories and in milk productivity (i.e., lower reproduction rates in summer and higher milk production rates in winter), which ultimately impact overall monthly milk production. Some farmers perform management practices in order to decrease this seasonality. Therefore, any farm can be categorized as 100% seasonal, when maximum fluctuations are observed; 0% seasonal, when minimum fluctuations are observed; or any range in between. The function of seasonality is embedded in the model through the matrices of reproduction rates and milk production rates, which are adjusted by a percent of seasonality (POS), de Vries (2004).

Calculations of manure excreted, manure N (NITROGEN) excreted and dry matter intake (DMI) by different groups of animals are based on parameters estimated from book values for Florida conditions (NRCS, 2001; Van Horn et al., 1998; USDA, 1992). For brevity, equations that estimate manure excreted are similar to manure N excreted and are not presented. The excretion of manure N for milking cows is estimated by a third order function based upon milk productivity, Eq. (14); for dry cows, by a constant rate, Eq. (15); for heifers, by a function based on their age, Eq. (16); and for bulls, by a constant function, Eq. (17). Coefficients in Eqs. (14)–(17) about manure N excretion are parameterized using book values for Florida from USDA (1992, Table FL4-5) and a compilation of several field experiments presented by Van Horn et al. (1998, Table 1)

$$\mathrm{NITROGEN_M} = \left(\sum_{k=1}^{9}\sum_{j=0}^{7}\sum_{i=1}^{18}(0.36 + 2.4^{-3}(M_{i,m,k}) + 6^{-5}(M_{i,m,k})^2 - 3^{-7}(M_{i,m,k})^3)(C_{i,j,k})(W_m)\right) \quad \text{for } m = \text{any month} \tag{14}$$

$$\mathrm{NITROGEN_D} = \left(\sum_{k=1}^{9}\sum_{j=8}^{9}\sum_{i=1}^{18}(0.36)(C_{i,j,k})(W_m)\right) \quad \text{for } m = \text{any month} \tag{15}$$

$$\mathrm{NITROGEN_H} = \left(\sum_{j=0}^{9}\sum_{i=1}^{32}(2.8^{-2}) + i(1.2^{-2})(C_{i,j,0})(\mathrm{PHR})(W_m)\right) \quad \text{for } m = \text{any month} \tag{16}$$

$$\mathrm{NITROGEN_B} = (0.364)(\mathrm{TNB})(W_m) \quad \text{for } m = \text{any month} \tag{17}$$

Nitrogen excreted by milking and dry cows is additionally adjusted by a factor depending on the amount of crude protein in the diet (ACP). Based upon NRC standards (NRC, 2001), average crude protein can be categorized as ‘‘low’’ (13.9370%) or ‘‘high’’ (15.0342%) and these are used to correct the N excretion prediction, as seen in Eq. (18) for milking cows. A similar correction is performed for dry cows.

$$\mathrm{NITROGEN_M} = \mathrm{NITROGEN_M}(1 + (\mathrm{ACP} - 13.9370)(0.0956)) \tag{18}$$

The N excreted that goes to the waste system is the sum of the manure N produced by the milking cows and the bulls during confined time (percent of confined time, PCT_m) and is expressed by Eq. (19). The N excreted that goes to the concentrated areas is the sum of the manure N produced by milking cows and bulls during time spent in concentrated areas (time in concentrated areas, TCA), expressed in Eq. (20). The N excreted in pastures is the sum of the manure N produced by the milking cows and bulls during time spent in pastures and the manure N produced by heifers and dry cows, expressed in Eq. (21). The partitioning of the manure excreted was calculated in a similar way

$$N_\mathrm{w} = (N_\mathrm{M} + N_\mathrm{B})(\mathrm{PCT}_m) \quad \text{for } m = \text{any month} \tag{19}$$

$$N_\mathrm{c} = (N_\mathrm{M} + N_\mathrm{B})(1 - \mathrm{PCT}_m)(\mathrm{TCA}) \quad \text{for } m = \text{any month} \tag{20}$$

$$N_\mathrm{p} = (N_\mathrm{M} + N_\mathrm{B})(1 - \mathrm{PCT}_m)(1 - \mathrm{TCA}) + N_\mathrm{H} + N_\mathrm{D} \quad \text{for } m = \text{any month} \tag{21}$$

Dry matter intake (DMI) is the sum of DMI consumed by milking cows (M), dry cows (D), heifers (H), and bulls (B). As in the previous case, estimates for milking cows are based on milk productivity, estimates for dry cows and bulls are based on constant rates, and estimates for heifers are based on age. Coefficients in Eqs. (22)–(25) are based on book values published by USDA (1992, Table FL4-5) and Van Horn et al. (1998, Table 1)

$$\mathrm{DMI_M} = \sum_{k=1}^{9}\sum_{j=0}^{7}\sum_{i=1}^{18}(25.2 + 0.16M_{i,m,k} + 3.3^{-3}M_{i,m,k}^2 - 2^{-5}M_{i,m,k}^3)(C_{i,j,k})(W_m) \quad \text{for } m = \text{any month} \tag{22}$$

$$\mathrm{DMI_D} = \sum_{k=1}^{9}\sum_{j=8}^{9}\sum_{k=1}^{9}(25.2)(C_{i,j,k})(W_m) \quad \text{for } m = \text{any month} \tag{23}$$

$$\mathrm{DMI_H} = \left(\sum_{j=0}^{9}\sum_{i=1}^{32}(2.7 + i(0.70))(C_{i,j,0})\right)(\mathrm{PHR})(W_m) \quad \text{for } m = \text{any month} \tag{24}$$

$$\mathrm{DMI_B} = (25.2)(\mathrm{TNB})(W_m) \quad \text{for } m = \text{any month} \tag{25}$$

Assuming 33% N digestibility (Van Horn et al., 1998), manure N is estimated as 67% of N in the feed, N_f, Eqs. (14)–(18). The model also estimates the amount of water consumed by the manure handling system (W_c) as a seasonal function based upon specific farm information and field experiences reported by farmers. It was found that July is the month with maximum water usage. Other months can be represented as fraction of July usage. From September to August these fractions were: 0.86, 0.79, 0.72, 0.65, 0.58, 0.65, 0.72, 0.79, 0.86, 0.93, 1.00, and 0.93.

Minimum data required as initial conditions to run the livestock model are: total adult cows (TAC), total number of bulls (TNB), percent of heifers raised (PHR), milk rolling herd average (RHA), percent of seasonality (POS), amount of crude protein fed in the diet (ACP), percent of confined time per month (PCT_m), time spent in concentrated areas (TCA), and water usage in July (W_c).

The livestock model starts by assigning the number of total adult cows (TAC) to the cow category $C_{1,0,1}$ (first month, non-pregnant, first lactation) and then populating all cow and heifer categories. After 132 months, it finds the seasonal steady state of cow flows. After the steady state is achieved, the model dynamically compares the target rolling herd average (inputted RHA) with the estimations performed by the model, and adjusts milk production rates ($M_{i,m,k}$) to match the RHA. The adjustment stops when the difference between the calculated and the target RHA is less than 1%.

2.1.2. The manure N model

The manure N model accounts for the flow and keeps track of the manure N losses in the concentrated areas, the pasture fields, and in the manure management system, following a dynamic adaptation of the framework developed by Van Horn et al. (1998, 2001). All the loss rates are user inputs. The manure management system accounts for the N that is available for either plant uptake or leaching in the sprayfields after losses in different parts of the system (fraction of successive losses): volatilization before flushing (VBF), N in solids collected (SC), volatilization in the lagoon (VL), volatilization in the storage pond (VP), N in the sedimentation sludge (SS), volatilization during irrigation (VI), and volatilization in the soil after being applied (VS). Similarly, part of the manure N deposited in concentrated areas and in pastures is volatilized in the soil after excretion (VAE). The final amounts of N in the soil are represented by NPF and NSF for the pasture and sprayfields, respectively.

2.1.3. The crop models

Crop models contained in the Decision Support System for Agrotechnology Transfer, DSSAT (Jones et al., 2003) were used to translate climate, soil, and farmer management practices into agricultural and environmental outcomes (Phillips et al., 1998). For the soil component, the Century model (Parton et al., 1979) implemented in the DSSAT by Gijsman et al. (2002) was used. Specific data for each of the soil types were converted to the DSSAT v4.0 system using SBuild® software (Uryasev et al., 2003). The drained upper limit values were estimated using Saxton et al. (1986). All crop models were previously calibrated and validated for North Florida dairy farm conditions (Rymph et al., 2004; Cabrera, 2004).

Table 2
Coding of ENSO phases, soil types, and forage systems for crop models

ENSO phase, e		
1	La Niña	
2	Neutral	
3	El Niño	
Soil types, s		
1	Arredondo-Gainesville-Millhopper	
2	Arredondo-Jonesville-Lake	
3	Bonneau-Blanton-Eunola	
4	Penney-Otela	
5	Penney-Kershaw	
6	Millhopper-Bonneau	
7	Otela-Jonesville-Seaboard	
8	Blanton (high)-Lakeland	
9	Blanton (low)-Lakeland	
10	Blanton-Ortega-Penny	
Forage systems, f[a]		
1	Bermudagrass	Bermudagrass
2	Corn	Sorghum
3	Millet	Corn
4	Sorghum	Corn
5	Millet	Sorghum
6	Sorghum	Millet
7	Corn	Corn
8	Corn	Millet
9	Corn	Bahiagrass
10	Corn	Bermudagrass
11	Bahiagrass	Bahiagrass

[a] Forage systems have typical three-season rotations in North Florida. Spring–summer, summer–fall, and fall–winter. The table only shows the rotations for spring–summer and summer–fall, since the rotation in fall–winter is always the same: a combination of winter forages consisting of rye, oats, wheat, and ryegrass.

The crop systems were simulated in dairy sprayfields for 10 types of soil found in the study area (Table 2), for 43 years of daily weather data (1956–1998, of which nine were La Niña, 23 were Neutral, and 11 were El Niño), and four levels of applied manure N (10, 20, 40, and 80 kg ha^{-1} (1/2)month^{-1}). Leached N and biomass (kg ha^{-1} month^{-1}) were compiled for the whole study period (1956–1998) and classified by ENSO phase (Mavromatis et al., 2002, p. 131), because the ENSO phase (climate) affects weather and weather affects yields, leaching, and biomass.

Two matrices were created from outputs of the crop models (kg ha^{-1} month^{-1}), one for N leaching $Nl_{m,e,s,f,n}$ and the other for biomass accumulation $Ba_{m,e,s,f,n}$, in order to couple crop models with the other models. These matrices describe the amounts of N leaching and biomass accumulation by month of the year m (as previously defined), ENSO phase e, soil type s, forage system f, and manure N applied n. The values for e, s, and f are user inputs while m and n are dynamically estimated by the model. For example $Nl_{5,3,4,10,40}$ is the estimated amount of N leached for January, in El Niño phase, for Penney-Otela soil, with corn–bermudagrass–winter forage crop system, and receiving 40 kg ha^{-1} (1/2)month^{-1} of manure N effluent.

Because it is not possible to simulate the impacts of direct manure deposition on pasture with DSSAT, an assumption was required to simulate N leaching and biomass in pasture fields. The impacts of this assumption are not critical to overall farm N leaching, because major concerns of N leaching are mostly from sprayfields. We adjusted the two previous matrices of N leaching and biomass in sprayfields and corrected them to represent N leaching and biomass accumulation in pasture fields based on the fact that pasture fields receive direct deposits of manure and no irrigation. These facts decrease N leaching and biomass accumulation. According to a local panel of experts (W.C. Hart, C.W. Starling, C. Vann, personal communications), it was estimated that N leaching would be reduced by 25% and biomass by 40% in the pasture fields. These values were used as default; however users have the option to adjust them.

The manure N model estimates continuous amounts of manure N applications to the pastures (NPF) and to the sprayfields (NSF); however the crop models used discrete amounts of applied manure N. In order to match these two, an interpolation is performed for N leaching (Nl) and biomass accumulation (Ba) according to the actual rates of manure N application.

Monthly farm estimates of N leaching (NL) and biomass accumulation (BA) are the sum of N leaching in all pasture and sprayfields (Eqs. (26) and (27)); t is the number of pasture fields, q is the number of sprayfields, and PFa and SFa represent the area of the pasture and sprayfields, respectively

$$\mathrm{NL} = \sum_{t=1}^{t}(\mathrm{Nl}_{m,e,s,f,n})(\mathrm{PFa}_t) + \sum_{q=1}^{q}(\mathrm{Nl}_{m,e,s,f,n})(\mathrm{SFa}_q) \quad (26)$$

$$\mathrm{BA} = \sum_{t=1}^{t}(\mathrm{Ba}_{m,e,s,f,n})(\mathrm{PFa}_t) + \sum_{q=1}^{q}(\mathrm{Ba}_{m,e,s,f,n})(\mathrm{SFa}_q) \quad (27)$$

2.1.4. The economic module

This module estimates the monthly overall profit Π (US\$ month^{-1}) as the net income per kg of milk produced multiplied by the monthly milk production (MILK) plus the forage value of the estimated biomass accumulated (BA) minus the value of the estimated nitrogen leaching (NL), Eq. (28)

$$\Pi = (\mathrm{MP} + R - E) \times \mathrm{MILK} + (\mathrm{BA} \times \mathrm{BAV}) - (\mathrm{NL} \times \mathrm{NV}) \quad (28)$$

$$R = \mathrm{SLC} + \mathrm{SH} + \mathrm{OS} \quad (29)$$

$$E = \mathrm{FP} + \mathrm{PP} + \mathrm{MM} + \mathrm{CE} + \mathrm{OE} \quad (30)$$

The net income per kg of milk produced (US\$ kg milk^{-1}) is calculated by adding the milk price (MP) to the per kg of milk revenues (R) and subtracting the per kg of milk expenses (E). Revenues per kg of milk are calculated by adding the net income (US\$ kg milk^{-1}) obtained by selling cows (SLC), sale of calves and heifers (SH), and other sales and services (OS), Eq. (29). Expenses per kg of milk produced are calculated by adding the net expense (US\$ kg milk^{-1}) incurred by feed purchasing (FP), personnel payment (PP), marketing of milk (MM), crop expenses (CE), and other expenses (OE), Eq. (30). The milk price (MP) and all variables included in the revenues (R) and expenses (E) per kg of milk are user defined. Monthly milk production (MILK) is calculated by the livestock model.

The forage value of the biomass accumulated is calculated by multiplying the amount (kg) of biomass accumulated (BA) that is estimated by the crop models by its value (BAV, US\$ kg^{-1}) that is user defined. The value of the nitrogen leached is calculated by multiplying the amount (kg) of N leached (NL) that is estimated by the crop models by its value as fertilizer (NV, US\$ kg^{-1}) that is user defined.

More than 90% of the overall income on North Florida dairy farms comes from milk sales (de Vries et al., 2002); therefore the model is highly sensitive to the milk price (MP) factor.

2.1.5. The optimization module

The optimization module is a linear programming model (Hardaker et al., 2004) that maximizes profit (Π) or minimizes N leaching (NL) using multiple scenario simulation runs rr under restrictions of at most average N leaching ($\overline{\mathrm{NL}}$) or at least average profit ($\bar{\Pi}$), respectively, as defined in Eqs. (31) and (32). The optimization uses the simplex algorithm with bounds on the variables, and the branch-and-bound method, implemented by Watson and Fylstra, Frontline Systems, Inc. (Fylstra et al., 1998) included in the Microsoft Excel (2003) spreadsheet software

$$\max \Pi = \sum_{r=1}^{rr}\sum_{m=1}^{12}\Pi_{mr} \times Z_{mr} \text{ subject to } \sum_{m=1}^{12} Z_{mr} \times \mathrm{NL}_{mr} \leq \overline{\mathrm{NL}} \quad \text{and} \quad Z_{mr} \geq 0 \quad (31)$$

$$\min \mathrm{NL} = \sum_{r=1}^{rr}\sum_{m=1}^{12}\mathrm{NL}_{mr} \times Z_{mr} \text{ subject to } \sum_{m=1}^{12} Z_{mr} \times \Pi_{mr} \geq \bar{\Pi} \quad \text{and} \quad Z_{mr} \geq 0 \quad (32)$$

Here, Z_{mr} is the relative fraction of scenario r chosen in month m. A scenario is a set of management practices (i.e., ‘‘high’’ crude protein in the diet, corn–sorghum–winter forage rotation in sprayfields, bahiagrass in pasture fields,

Table 3
Principal management characteristics on the ''typical'' farm and on farms in which the DyNoFlo model was applied

Management characteristics	Typical small farm for analyses	Selected farms for model application		
		Small	Medium	Large
TAC (head)	400	420	521	3000
TNB (head)	16	10	0	120
PHR (%)	100	0	100	100
RHA (kg head^{-1} year^{-1})	7711	6804	10157	9072
POS (%)	100	100	100	100
ACP (unit)	High	High	High	High
PCT (%)	80	17	100	80
Total N lost (%)	29	31	35	40
N volatilization sprayfields (%)	30	30	30	30
N volatilization pastures (%)	40	40	40	40
Sprayfields (ha)	28.3	16.2	62.7	182.1
Pasture (ha)	32.4	80.9	121.4	323.7
Soil type	Average	2	1	4
Overall profit (US$ Mg milk^{-1})	19.6	0.0	21.3	20.1

Note: TAC: total adult cows, TNB: total number of bulls, PHR: percentage of heifer raised, RHA: rolling herd average of milk production, POS: percentage of seasonality, ACP: amount of crude protein, PCT: percentage of confined time. Soil type 1: Arredondo-Gainesville-Millhopper, soil type 2: Arredondo-Jonesville-Lake, soil type 4: Penney-Otela.

and 80% confinement time). Scenarios are formed by combining levels of selected management practices. Previous models estimate monthly N leaching and profit, which are saved independently for each ENSO phases as technical coefficients in the optimization matrix. $\overline{\text{Nl}}$ and $\bar{\Pi}$ are average N leaching and average profit for the entire dairy farm for all scenarios selected in an optimization process. Optimization was repeated for each ENSO phase to evaluate the potential value of using ENSO-based seasonal forecasts; therefore, management strategies selected by the optimizer were a function of seasonal climatic conditions.

Dual optimization was performed by relaxing $\bar{\Pi}$ or $\overline{\text{Nl}}$ while optimizing its counterpart. Levels of relaxation allowed increasing N leaching (NL) or decreasing profit (Π) by a proportion of their standard deviation, until no further changes were encountered in the objective function.

2.2. Typical farm for analyses

A ''typical'' small farm was created using real data and combining characteristics of dairies in the study area without disclosing any specific farm information (Cabrera, 2004). This typical farm had 400 adult cows (TAC), 16 bulls (TNB), and raised 100% of its heifers (PHR). The rolling herd average of milk production (RHA) was 7711 kg year^{-1}, the farm operated 100% seasonal (POS = 100%), and the amount of crude protein in the diet (ACP) was ''high''. The milking cows spent 80% of their time confined all year (PCT). The total N lost through its waste management system was 29% and there was an extra 30% N volatilized from the soil when applied in sprayfields; the volatilization by direct deposition in soils was 40% (Table 3). The farm had 28.3 ha of sprayfields and 32.4 ha of pasture fields with diverse crops as indicated in Table 4. This farm had an overall profit (Π) of US$ 19.60 per Mg of milk produced. These management characteristics were used in subsequent analyses.

2.3. Simulation experiment design

The DyNoFlo model was used first to simulate current management and then to optimize management strategies for the typical farm to test the hypothesis that the ENSO-based climate forecasts could be used to reduce N leaching

Table 4
Crops in different fields in the ''typical'' farm

Field	Area (ha)	Type	Spring	Summer	Winter
1	4.05	Sprayfield	Corn	Sorghum	Rye
2	8.10	Sprayfield	Corn	Millet	Ryegrass
3	4.05	Sprayfield	Sorghum	Millet	Wheat
4	8.10	Sprayfield	Bahiagrass	Bahiagrass	Oats
5	4.05	Sprayfield	Millet	Sorghum	Rye
6	8.10	Pastureland	Bahiagrass	Bahiagrass	Rye
7	4.05	Pastureland	Bermudagrass	Bermudagrass	Ryegrass
8	8.10	Pastureland	Bahiagrass	Bahiagrass	Wheat
9	4.05	Pastureland	Bermudagrass	Bermudagrass	Oats
10	8.10	Pastureland	Bahiagrass	Bahiagrass	Rye

on North Florida dairies without reducing profits. The typical farm was simulated for a series of scenarios and for all ENSO phases.

Graphical analyses were used to visualize the trade-offs between N leaching and profit under different scenarios that were simulated. Optimization analyses were used to study management strategies the typical farm might implement to decrease N leaching while maintaining profitability. The optimization process varied levels of crude protein in the diet (CP), confinement time (CT), crop sequences in pastures and crop sequences in sprayfields. These management options were selected because they are practical ways North Florida dairy farm managers could decrease N leaching and maintain profitability. Dual optimization was used to study the sensitivity of the typical dairy farm to changes in N leaching and profit as an aid for decision making.

The concept of ‘‘feasible adjustment’’ was introduced because farmers may not be able to change all practices proposed by the optimization. Based on their specific systems, they may be able to implement packages similar to the proposed optimum practices. Using these ‘‘feasible’’ combinations, which are practical management changes farmers agree are possible, the DyNoFlo model was re-run and results were compared with both the original and the optimized outcomes.

Finally, DyNoFlo was applied to selected farms in the study area (a small, a medium, and a large farm). Each farmer collaborated, first by inputting detailed data on their operations and, secondly by validating model outputs. Principal management characteristics of farms that participated in this process are presented in Table 3 contrasted with those of the typical farm. For anonymity reasons, detailed farm characteristics and complete results are not disclosed.

3. Results and discussion

3.1. Typical farm

Simulation of the typical farm indicated that overall annual N leaching would be the lowest for La Niña phases (6136 kg), followed by Neutral years (7% higher) and by El Niño phases (13% higher). Profit was inversely related to N leaching, La Niña years had the highest profit and El Niño years the lowest (Fig. 2A).

On a monthly basis, overall N leaching varied from 68 kg in April for La Niña years to 2737 kg in January for El Niño years with January and February having with the highest leaching rates (Fig. 2B). Accumulated biomass increased, as expected, in the summer months (Fig. 2C) when higher

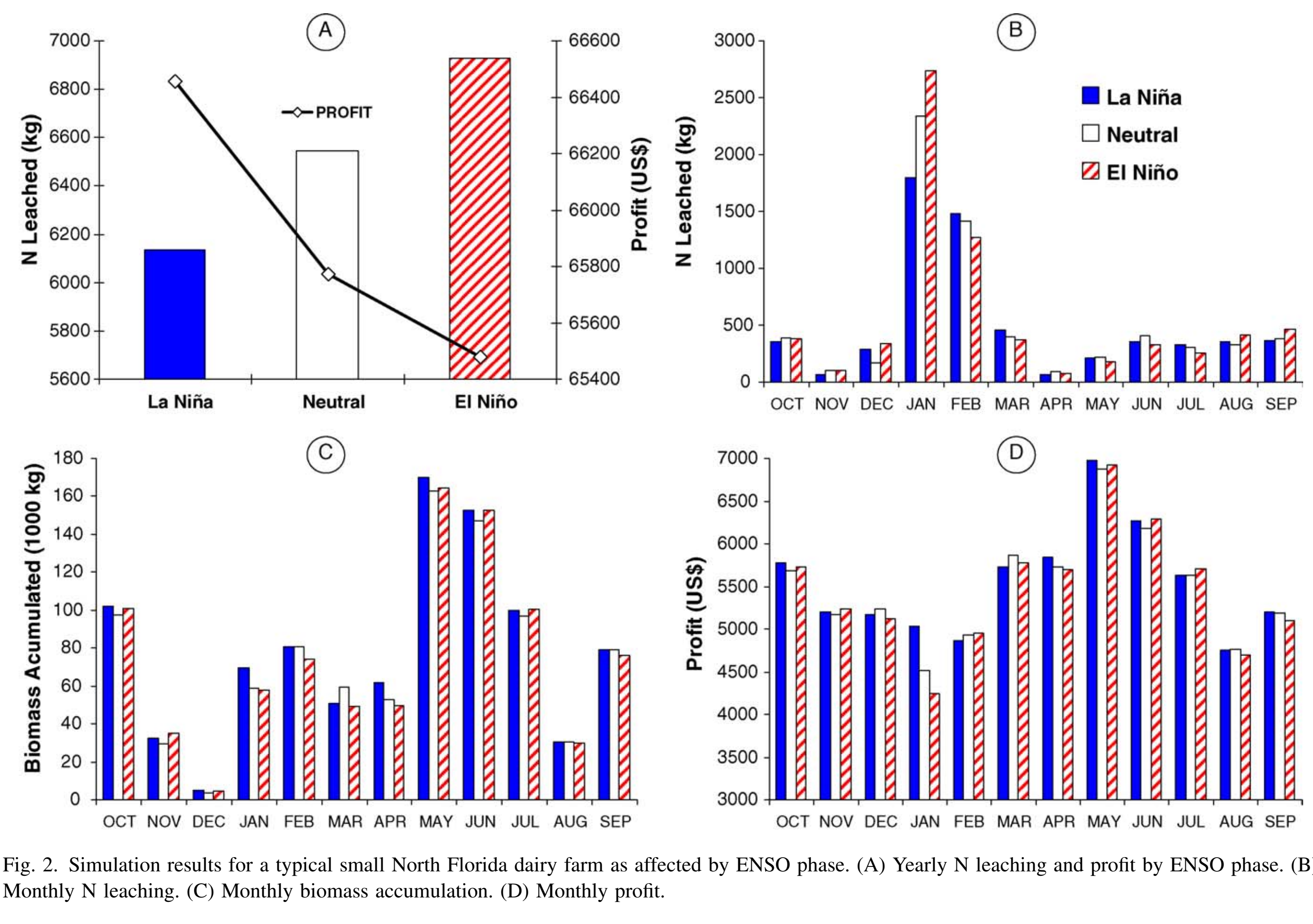

Fig. 2. Simulation results for a typical small North Florida dairy farm as affected by ENSO phase. (A) Yearly N leaching and profit by ENSO phase. (B) Monthly N leaching. (C) Monthly biomass accumulation. (D) Monthly profit.

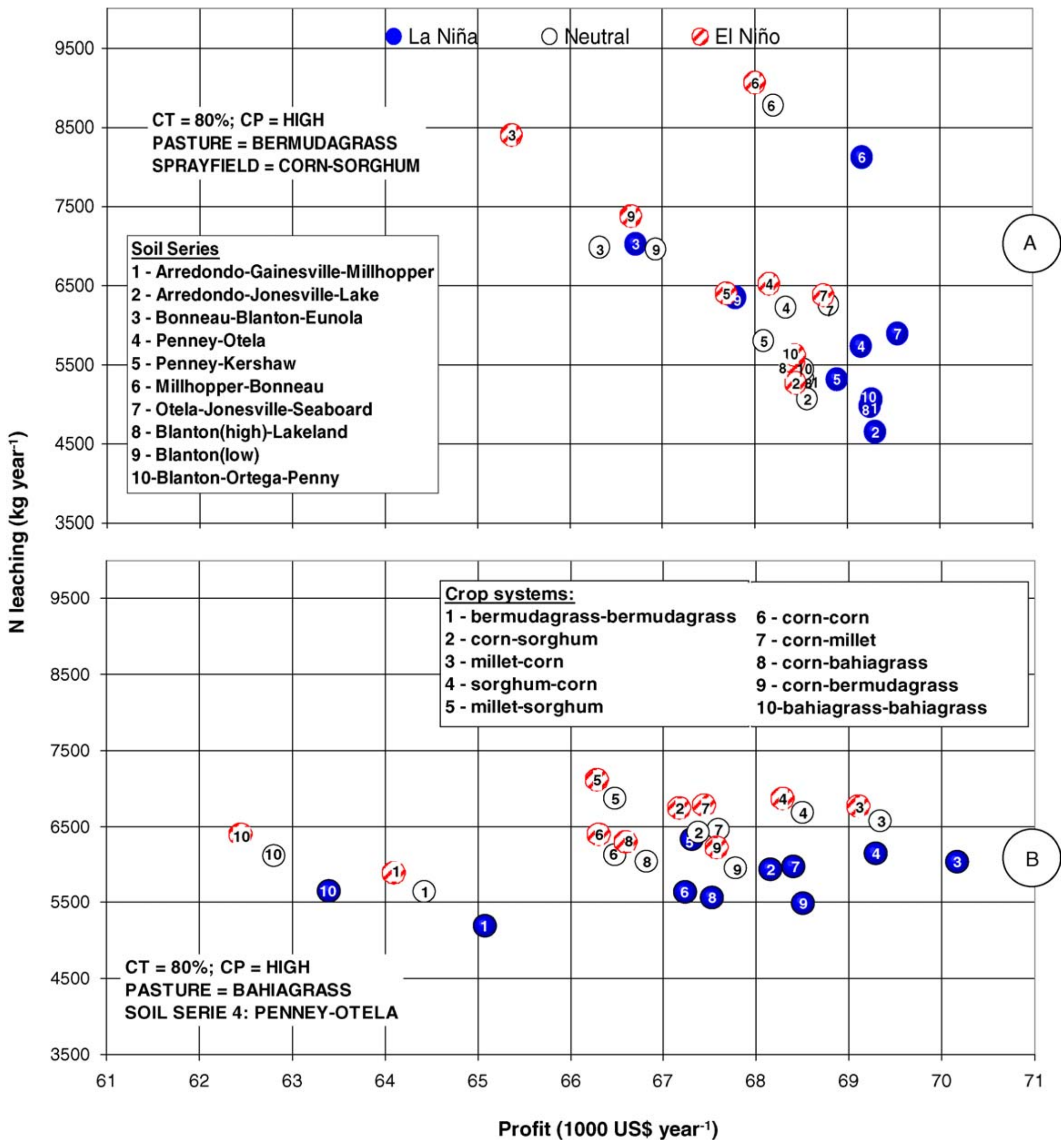

Fig. 3. Trade-off of N leaching and profit for different ENSO phases in typical North Florida dairy farm. (A) Soil series and (B) crop systems in sprayfields. Note: CT is confined time and CP is crude protein in diet.

temperatures determine greater plant growth. Profit was highest between the months of April and July (maximum in May for La Niña years) because of more recycled N and higher biomass accumulation (Fig. 2D).

3.1.1. Soil series

Fig. 3A illustrates N leaching and profit for the 10 soil types in the study area. Soils of type 6 (Millhopper-Bonneau) were those that leached the most, but with a medium-low profit level. Soils of type 3 (Bonneau-Blanton-Eunola) were the second highest in N leaching and those with the lowest net return. Mavromatis et al. (2002) also reported a higher N leaching potential on the sandier soils in North Florida.

Soils 6 and 3 are very sandy and with very low water holding capacity; soil type 6 is the shallowest and, probably because of that, it had the highest N leaching. This fact, however, was favorable for plant growth and because of that profit was not as low as with soil type 3.

The circles with the same number (same soil type) show greater differences between La Niña and Neutral years than between El Niño and Neutral years, meaning that N leaching in la Niña years (profit) was substantially lower (higher) than in Neutral years.

3.1.2. Crop systems in sprayfields

Fig. 3B displays the relationships among 10 different crop systems for spring–summer to summer–fall in the

Table 5
Management strategies selected by the optimizer for the ‘‘typical’’ farm

Crude protein	CP	Low	
Confined time	CT	60%	59% of the pasture
		80%	41% of the pasture
Pasture	Bermudagrass–bermudagrass–winter forage		
ha			
Sprayfields			
La Niña			
9.19	Corn–corn–winter forage		
6.25	Bermudagrass–bermudagrass–winter forage		
5.47	Corn–bermudagrass–winter forage		
3.87	Millet–corn–winter forage		
3.54	Corn–bermudagrass–winter forage		
Neutral			
8.46	Corn–corn–winter forage		
6.77	Bermudagrass–bermudagrass–winter forage		
4.95	Corn–bermudagrass–winter forage		
4.54	Millet–corn–winter forage		
3.61	Corn–bermudagrass–winter forage		
El Niño			
8.71	Corn–corn–winter forage		
6.46	Bermudagrass–bermudagrass–winter forage		
5.26	Corn–bermudagrass–winter forage		
4.53	Millet–corn–winter forage		
3.37	Corn–bermudagrass–winter forage		

sprayfields. Rotation consisting of bermudagrass–bermudagrass outperformed the others with the least N leaching and medium-low profit. It is followed by corn–bermudagrass, which had medium-to-high profit. The rotation of bahiagrass–bahiagrass had low-medium N leaching, but the lowest profit of all. The most profitable crop system was millet–corn with a medium level of N leaching.

Long-term field studies conducted in the same area (Woodard et al., 2002, 2003; Macoon et al., 2002) corroborate these results.

3.1.3. Optimum management strategies

The more environmentally friendly management strategies selected by the optimization process were: (1) a ‘‘low’’ crude protein level; (2) a variable level of confined time, 60% of confined time for cows that use 59% of the pasture and 80% of confined time for cows that use 41% of the pasture; (3) a bermudagrass–bermudagrass–winter forage sequence for all pasture land; (4) variable areas of crop rotations for sprayfields for different ENSO phases (Table 5).

With these combinations, the optimizer estimated that N leaching would decrease to 4602 kg $year^{-1}$ for a La Niña year and to 5215 kg $year^{-1}$ for an El Niño year. A decrease to 4916 kg $year^{-1}$ was the outcome for a Neutral year. Comparing these values with the current practice of the farm, substantial variations are noticed. N leaching could be decreased up to 25% and profit could still be increased by approximately 3.15%, in each ENSO phase with different management strategies.

Several studies (Van Horn et al., 1998, 2001; Wu et al., 2001; Jonker et al., 2002; Børsting et al., 2003) have also found that N leaching can be reduced without reducing productivity by decreasing crude protein in the diet.

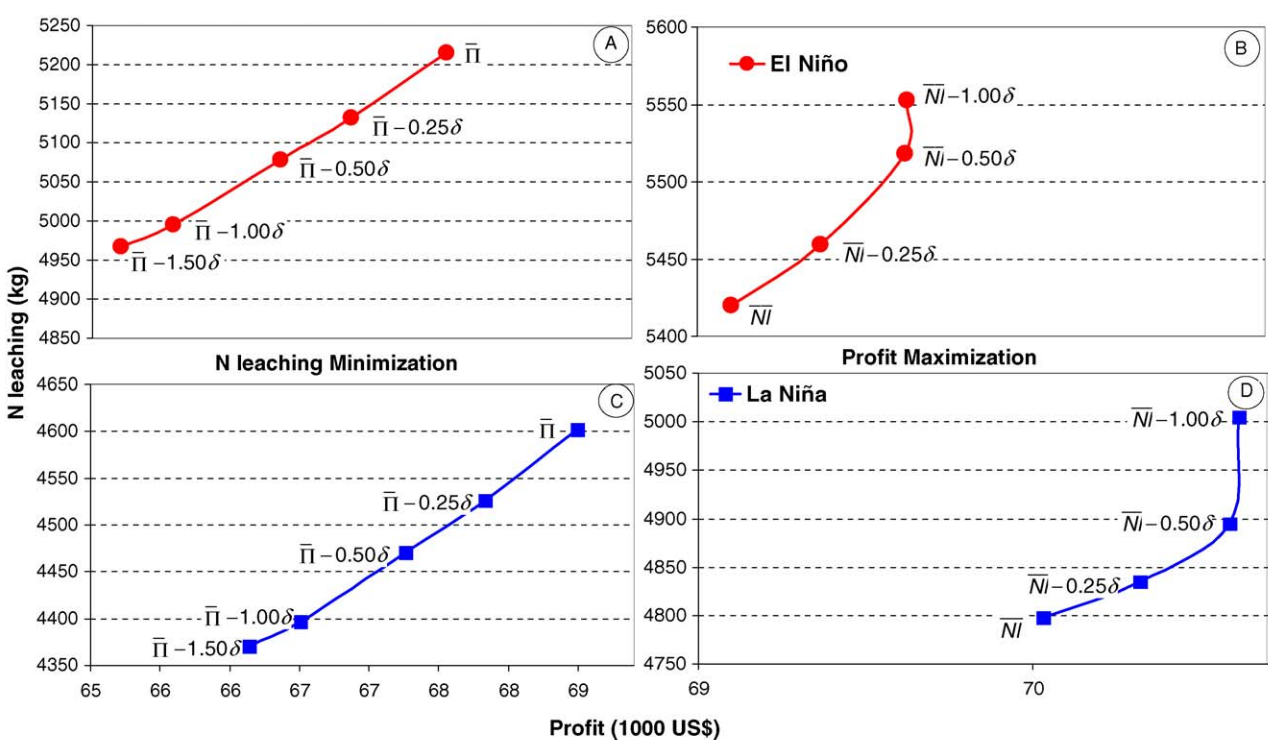

Fig. 4. Dual optimization of N leaching minimization and profit maximization. N leaching minimization relaxing profit for (A) El Niño years and (C) La Niña years. Profit maximization relaxing N leaching for (B) El Niño years and (D) La Niña years. Note: $\bar{\Pi}$ represents average profit, $\overline{\text{Nl}}$ denotes average N leaching, and δ is standard deviation of corresponding profit Π or N leaching Nl.

Table 6
Feasible crop systems in the ‘‘typical’’ dairy farm for El Niño years

ENSO phase	Sprayfield	Area (ha)	Spring	Summer	Winter
EL Niño	1	9.31	Corn	Corn	Rye
	2	6.07	Bermudagrass	Bermudagrass	Ryegrass
	3	5.67	Corn	Bermudagrass	Wheat
	4	7.29	Corn	Corn	Oats
Neutral	1	9.31	Corn	Corn	Rye
	2	6.07	Bermudagrass	Bermudagrass	Ryegrass
	3	5.67	Corn	Sorghum	Wheat
	4	7.29	Millet	Corn	Oats
La Niña	1	9.31	Millet	Corn	Rye
	2	6.07	Bermudagrass	Bermudagrass	Ryegrass
	3	5.67	Corn	Corn	Wheat
	4	7.29	Millet	Sorghum	Oats

Note: For pasture (32.40 ha) a rotation of Bermudagrass–Bermudagrass–Oats for all ENSO phases were considered feasible.

By relaxing profit (decreasing minimum profit every month) N leaching decreased when minimized. For El Niño years it decreased from ~5200 to 4950 kg and for La Niña it decreased from 4600 to 4350 kg. The profit in these cases changed (US$) from ~67,560 to 65,202 for El Niño years and from ~68,500 to 66,140 in La Niña years (Fig. 4A and C). Nitrogen leaching did not decrease beyond those levels even if profit was further relaxed.

By relaxing N leaching (increasing the limit allowed to leach every month) profit increased when maximized. For El Niño years it increased from (US$) ~69,100 to 69,600 and for La Niña years it increased from ~70,000 to 70,600. The N leaching in these situations changed from ~5400 to 5550 kg and from ~4800 to 5000 kg for El Niño and La Niña years (Fig. 4 B and D). Profit did not increase beyond those points even when N leaching was further relaxed.

3.1.4. Feasible practices

The optimizer proposed a decrease in CP in the diet from ‘‘high’’ to ‘‘low’’. We assumed this to be a feasible change for a dairy farmer to make. Next, the optimizer proposed to vary the confined time (CT) between 80 and 60% for different groups of cows. It would be difficult for the farmer to implement this specific change, so CT levels would remain at 80%. Finally, the optimizer proposed a series of crops for different ENSO phases. It was assumed that the farmer can rather easily implement similar, though not identical, changes to these management practices. Crop systems considered feasible for the farm are shown in Table 6. This includes bermudagrass instead of bahiagrass in pastures and sprayfields, and more corn than sorghum and/or millet in sprayfields.

Results of these feasible practices estimated that the N leaching would be reduced (kg year^{-1}) to 4722 for La Niña years and to 5361 for El Niño years. A Neutral year would result in 5048 kg year^{-1} N leaching. Consequently, comparing these N leaching values with the original, farm ‘‘as is’’, N leaching could be greatly reduced by using a ‘‘feasible’’ set of practices instead of the ‘‘as is’’ practices in each specific ENSO phase. N leaching would be reduced approximately 23% and profit could still increase by 2.5% by slightly adjusting management strategies in each ENSO phase (Fig. 5).

The forecast ENSO phase does not always occur, and even if the ENSO phase that is forecast occurs, there is still uncertainty within a phase (Letson et al., 2005). Using the feasible practices for each of the phases for the typical farm, the model was run to show what would result if other phases actually occurred. Table 7 shows N leaching and profit for each of the three forecast ENSO phases and the result if another phase occurs. For example, if a La Niña year is forecast and occurs, and the farmer follows the feasible practice for a La Niña year, it would result in 4722 kg year^{-1} N leaching and $68,712 annual profit. However, if in the same situation a Neutral year occurs, N leaching would increase to 5433 kg year^{-1} and profit would decrease to $68,003. If an El Niño year occurs when La Niña has been forecast, N leaching would increase to 5717 kg year^{-1} and profit would decrease to $67,748. However, each of these results for estimated N leaching would still be substantially lower than the original simulation of the farm ‘‘as is’’: 6136, 6566, and 6934 kg N year^{-1}, respectively. Likewise, profit would still be substantially

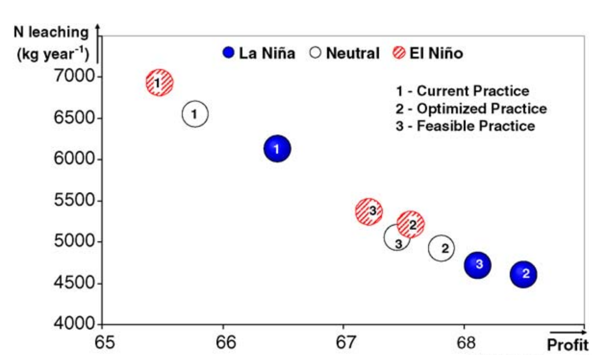

Fig. 5. Comparison of N leaching and profit of current, optimized and feasible practices of the typical farm for different ENSO phases.

Table 7
Leaching of N and profit for feasible practices in the "typical" dairy farm according to forecast and occurring ENSO phases

Actual ENSO phase	ENSO phase forecast					
	La Niña practices		Neutral practices		El Niño practices	
	N leaching (kg year^{-1})	Profit (US$ year^{-1})	N leaching (kg year^{-1})	Profit (US$ year^{-1})	N leaching (kg year^{-1})	Profit (US$ year^{-1})
La Niña	4722	68712	4927	68666	5068	68005
Neutral	5433	68003	5048	67976	5274	67345
El Niño	5717	67748	5580	67725	5361	67106

higher than in the original simulation "as is": $66,455, $65,773, and $65,480, respectively. Similar comparisons can be done for the other phases.

Notice that when El Niño is forecast and El Niño practices are used, and Neutral or La Niña occurs, or when Neutral is forecast and Neutral practices are used, and La Niña occurs, N leaching would decrease and the profit would increase. If the farm is prepared for El Niño and La Niña occurs, the farm would be better off, but not as well off as if a La Niña had been forecast and prepared for.

3.2. Applications of DyNoFlo to selected farms

Each one of the farmers with whom the DyNoFlo was applied mentioned that the model was "about right" in the way it reflected their own farm. Results of changing practices thought to be feasible showed that N leaching could be decreased up to 9, 20, and 25% in the small, medium, and large operations, still maintaining their profit levels.

For the small farm, optimal results suggested a switch from bahiagrass planted in pastures to bermudagrass and to replace sorghum in the sprayfields with sequences that included bermudagrass, corn and millet. On this small farm, decreasing the amount of crude protein in the diet or decreasing the time cows spend confined would not help to substantially reduce N leached. This small farm is mostly a grazing farm located on retentive soils with low risk of N leaching. Because of that, optimal results showed only limited room for improvement, mostly through crop rotations. For El Niño years the optimization tended to select more bermudagrass in both pastures and sprayfields and reduce the amount of crude protein in the diet.

The medium farm was also located on soils less prone to N leaching, but it had much more pressure on the sprayfields because cows were mostly confined and they were higher milk producers. The optimal results suggested that this farm should decrease the crude protein in the diet, try to graze milking cows whenever possible, replace pastures with bahiagrass and other crops with bermudagrass, and try to sod plant the bermudagrass in the sprayfields with corn and millet. These practices would be critical in El Niño phases, but could be relaxed during La Niña phases.

The large farm presented high N leaching risks not only because of a lower land/cow ratio, but also because it was an intense system located on a soil with medium N leaching risk. The optimal results suggested for this farm to decrease the amount of protein in the diet, reduce the confined time of milking cows, and change crop patterns in both pastures and sprayfields. For pastures, the results from optimization identified bermudagrass as the best option, and for sprayfields a combination of bermudagrass with millet in El Niño years or bermudagrass with corn in La Niña years.

4. Conclusions

Nitrogen leaching was the lowest and profit the highest for La Niña ENSO years. The opposite occurred in El Niño years because climatic conditions are cooler and wetter. Winter is the critical season with much higher N leaching due to lower N plant uptake and higher manure N application. There were marked differences in N leaching by soil types, with Millhopper, Bonneau, Blanton, and Eunola soil series more prone to leaching and having less profit. Arredondo, Jonesville, Lake, Ortega, and Penny soil series were less prone to leach N. Crop systems that included bermudagrass, corn, and bahiagrass leached less N, and crop systems that included millet and sorghum tended to leach more. Decreasing the amount of crude protein in the diet decreased N leaching, did not reduce productivity, and increased profit. Therefore, N leaching can be reduced without reducing productivity by decreasing crude protein in the diet. Reducing the confinement time decreased N leaching on the typical farm, but this effect will vary depending on the land/livestock ratio on any individual farm.

Dairy farms in North Florida can reduce N leaching maintaining profitability by selecting practices based on ENSO-based climate forecast. Adjusting the "optimization" practices to those the farmer deems "feasible" demonstrated the power of the model to propose ecologically and economically sound alternatives that are realistic according to ENSO phases. For a typical farm, it was potentially possible using feasible practices to decrease N leaching up to 23% while maintaining farm profitability. Using the model for three selected farms it was potentially possible to reduce N leaching by 9, 20, and 25% on the small, medium, and large farm, without decreasing profitability. The feasible adjustments reduced N leaching and improved profit even in the event that the forecast ENSO phase did not occur.

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