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The dynamic North Florida dairy farm model: A user-friendly computerized tool for increasing profits while minimizing N leaching under varying climatic conditions

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Abstract

This paper describes the computer implementation of the *Dy*namic *No*rth *Flo*rida *Dairy* farm model (DyNoFlo Dairy). The DyNoFlo Dairy is a decision support system that integrates nutrient budgeting, crop, and optimization models created to assess nitrogen (N) leaching from North Florida dairy farm systems and the economic impacts resulting from reducing it under different climatic conditions. The decision support system, based on Excel® and Visual Basic® software, responds to dairy-specific environmental (climate and soils) and managerial characteristics (livestock management, waste management, crop systems management) and can be used to study the economic and ecologic sustainability of these systems. The DyNoFlo Dairy model is a dynamic adaptation of the framework "balance" of nutrients in dairy farms, commonly used in Florida. The DyNoFlo Dairy model incorporates Markov-chain probabilistic simulation of cow-flows and crop simulation for historical climatic years El Niño southern oscillation (ENSO), automated optimization of managerial options, participatory modeling, and user friendliness. This paper discusses the model components and its computer implementation in a user-friendly application. The model was parameterized for conditions found in North Florida dairy farm systems. It is intended to be a tool for producers, regulatory agencies, and extension services, and because of that, participatory and interdisciplinary work was pursued during model creation, calibration, and validation. A case study for a synthesized North Florida dairy farm using the DyNoFlo

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Dairy model found substantial differences in the N leaching for different ENSO phases and other managerial factors; and the possibility of decreasing N leaching up to 25% while still maintaining profitability levels.

Keywords: Markov chains; Leaching; Optimization; Florida; Dairy; Climate; User friendly

1. Introduction

Reduction of N leaching from dairy farm systems in North Florida is recognized as the most important factor for successful business in the future (Staples et al., 1997; Fraisse et al., 1996; Van Horn et al., 1998). Because of increasing concern with N levels in water in the Suwannee River Basin, North Florida dairy farms are being more closely scrutinized by regulatory agencies (Giesy et al., 2003), and effective tools to estimate the amount of pollution of specific operations as well as potential ways to mitigate the problem inside the farm gate is an imperative need (Van Horn et al., 2001).

The complexity of dairy farms in North Florida justifies the creation of a whole-farm model as a decision support system, integrating several modeling approaches, in order to better analyze these systems (Herrero et al., 2000). Evidence indicates that climatic conditions (i.e., temperature, rainfall, solar radiation), which are influenced by ENSO phases (O'Brien et al., 1999), impact overall N leaching on North Florida dairy farms. Consequently, dairy operations could evaluate different management strategies depending on seasonal forecasts. For example, in North Florida, wetter and colder El Niño winters increases N leaching because of reduced plant N uptake and increased water percolation, while dryer La Niña spring and summers decreases N leaching because of less water percolation.

The objective of this paper is to describe the Excel-based *Dy*namic *No*rth *Flo*rida *Dairy* farm model (DyNoFlo Dairy). The DyNoFlo Dairy model is a decision support system that integrates nutrient budgeting, crop, and optimization models created to assess nitrogen (N) leaching from North Florida dairy farm systems and the economic impacts resulting from reducing it under different climatic conditions. The model responds to specific environmental (climate and soils) and managerial characteristics of dairies (total number of cows, milk production, crop rotations, waste system, etc.) and can be used to study the economic and ecological sustainability of these systems. The DyNoFlo Dairy model is a dynamic adaptation of the nutrient "balance" or "budgeting" framework in dairy farms, commonly used in Florida Van Horn et al. (1991, 1994, 1998, 2001) and NRCS (2001). The DyNoFlo Dairy model incorporates Markov-chain probabilistic simulations of cow flows (DeLorenzo et al., 1992), crop simulation models (Jones et al., 2003) for historical climatic years for El Niño southern oscillation (ENSO) (O'Brien et al., 1999), automated linear programming optimization of managerial options (Hardaker et al., 2004), participatory modeling (Geurts and Joldersma, 2001), and user friendliness. The actual model and complementary documentation are available at the Southeastern Climate Consortium website, http://www.AgClimate.org, in the dairy section.

The Van Horn et al. (1991, 1994, 1998, 2001), NRCS (2001), and Lanyon (1994) approaches were adjusted, modified, and used for keeping track of dynamic N movement in all system components. Agronomic measures of nutrient balance and tracking of inputs and outputs for various farm management units can provide the quantitative basis for management to better allocate manure to fields, to modify dairy rations, or to develop alternatives to on farm manure application (Lanyon, 1994). For instance, identifying where pollutants are being directly discharged and taking measures to reduce these discharges are more easily accomplished than controlling the indirect sources or "non-point" source pollutants (Environmental Literacy Council, 2004). Indeed, historically, scientists have been able to track single, or "point" sources of pollution, but tracking multiple, or "non-point" sources has been difficult (Ondersteijn et al., 2002).

Crop models (Jones et al., 2003; Jones et al., 1998) are process based dynamic simulation models that allow translating biophysical and environmental conditions into agricultural outcomes (Philips et al., 1998). Crop models can be used to estimate monthly biomass accumulation and N leaching by a number of crop and pasture sequences under different climatic conditions, depending on soil conditions, manure applications, and other managerial choices.

Linear programming models (LP) are optimization models that can devise alternative management choices that maximize (minimize) an objective function according to a set of restrictions (Hardaker et al., 2004). Linear programming models have been widely used in analysis of farming systems, beginning about the time of the Heady and Candler book in 1958 (Heady and Candler, 1958).

Optimization methods to decrease manure N excretion are widely reported in the literature (Tedeschi et al., 2003; Ruiz et al., 2001; Wang et al., 1999), however, these mostly focus on diet alterations and do not include economic variables. Fewer studies exist at the farm level involving components of a dairy system. One of them is a study performed in the Netherlands (Jansen et al., 1999) that includes not only dairy farms but also other land uses, on a regional basis, and economic modules. Jansen et al. (1999) use a linear programming model to minimize production costs constraining N leaching; however, it does not have sufficient detail to specifically represent all components of a complex dairy farm system.

Multiple feedback loops were used during a 2-year process of interaction with stakeholders to create the DyNoFlo Dairy model. This iterative process involved creation of prototype models, interaction with stakeholders, and improvement of prototype models according to suggestions and feedback. Many adjustments were made and expert advice was incorporated from farmers, specialists in the government, private, extension, university and production sectors. Detailed information about the participatory process can be found in Cabrera (2004). During this participatory process, every effort was made to create a user-friendly application for the final users.

2. Model description

2.1. Conceptual decision support system

Since a whole dairy farm encompasses environmental, economic, and biophysical components, its analysis is best served by a systems approach that accounts for the interactions of these components, and that can trace the consequences of an intervention through the entire

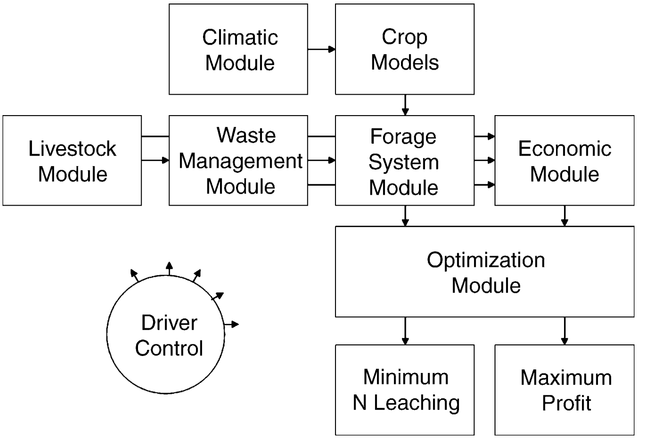


Fig. 1. Schematic representation of the DyNoFlo Dairy model.

system (Kelly, 1995). The systems approach used is farming systems research and extension (FSRE) as described by Hildebrand (1990). "Farm management" (Hazell and Norton, 1986) replaces "farm household" in livelihood systems analyses for commercial or industrial farm dimensions such as North Florida dairy farms. The farming system is composed of an arrangement of subsystems, i.e., biophysical, environmental, and economic components.

In order to assess what would happen with the whole dairy operation and what would happen specifically with nitrate flow under different climate scenarios (i.e., during wet cold years such as El Niño years in contrast to dry warm La Niña years), models of these scenarios are set up (Thornley and Johnson, 1990). The successful planning of an animal waste management system requires the ability to simulate the impact of waste production, storage, treatment, and utilization on the water resources; it must address overall nutrient management for the operation (De et al., 2004; Fraisse et al., 1996).

2.2. Overall characteristics

The DyNoFlo Dairy model consists of the following components (Fig. 1):

1. the driver control,
2. the livestock module,
3. the waste management system module,
4. the forage system module,
5. the climatic module,
6. the economic module,
7. the optimization module.

The DyNoFlo Dairy model is an integrated, whole-dairy farm simulation model that links decision making with biophysical, environmental, and economic processes. The main objective of the DyNoFlo Dairy model is to predict monthly N leaching and profit in response to environmental (climate and soils) and managerial characteristics of farms (livestock management, waste management, and crop management). The DyNoFlo Dairy model can be used to study the economic and ecological sustainability of these systems, as well as to diagnose sources of problems and search for feasible alternative management practices.

The simulation approach includes dynamic (monthly steps) simulation models, crop models, and optimization models integrated by a driver control. The livestock and waste modules follow an adaptation of the budgeting framework that tracks the flow of N through the entire dairy farm system along with production and additional economic variables, according to a pre-defined set of management and climatic conditions. Crop models assess the N recycled (uptake) by plants and the amount of N leached (N below the root zone) according to management, genetic, soil, and climatic specific conditions. The optimization model consists of a linear programming model that either minimizes N leaching for specific farm conditions and profit levels or maximizes profit subject to constrained N leaching levels. The DyNoFlo Dairy model incorporats Markov-chain probabilistic simulation of cow flows and crop simulation for 43 historical climatic years (El Niño southern oscillation), automated optimization of managerial options, participatory modeling, and user friendliness.

The DyNoFlo Dairy model, a decision support system, was developed in Excel® using embedded Visual Basic® in order to produce a user-friendly final product for farmers, Extension services, and regulatory agencies. Users need only open an Excel file and the model is ready to work. Crop models were previously run using the Decision Support System for Agrotechnology Transfer, DSSAT v4.0 (Jones et al., 2003). Crop model outputs were exported to Excel® to be implemented in the DyNoFlo Dairy model. The optimization component is automatically set up and solved taking advantage of the solver tool that ships with Excel.

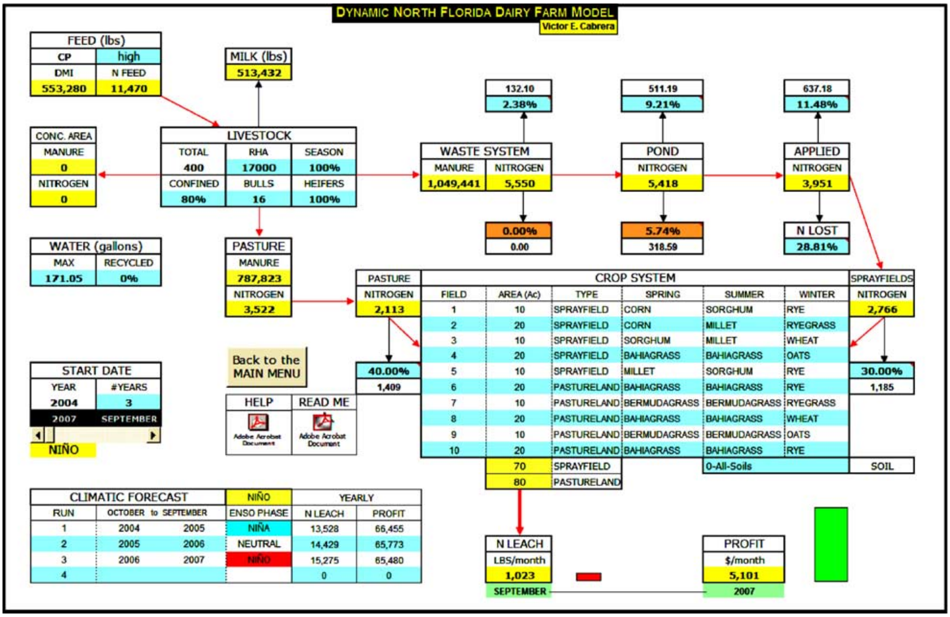
2.3. Components

The livestock model simulates cow flow and manure N excretion. The waste model receives information from the livestock model and simulates manure N flow through the waste handling system. The crop models receive information from the waste model and environmental information on climate and soils to simulate N leaching and biomass accumulation (plant growth) in the crop fields. The livestock, waste, and crop models run in parallel, dynamically in monthly steps. Each one of them is a function of a set of management practices. The crop simulation outputs are measured in monthly estimations of overall N leaching and biomass accumulation on a dairy farm. An economic component goes across the livestock, waste, and crop models to estimate monthly overall profit.

The optimizer, an automated tool, is a linear programming model that solves a matrix built with outputs of monthly N leaching and profit from several simulations with different management scenarios. Management strategies suggested by the optimizer can be compared with feasible farm practices in consultation with the farm manager to find the feasible adjustments in each particular case in an iterative process of adjusting management strategies and rerunning the simulation.

2.3.1. Interface

For user friendliness, all modules and their connections are graphically represented in the starting spreadsheet (Fig. 2). A “menu” appears automatically when the file is first opened



FIELD	AREA (Ac)	TYPE	SPRING	SUMMER	WINTER
1	10	SPRAYFIELD	CORN	SORGHUM	RYE
2	20	SPRAYFIELD	CORN	MILLET	RYEGRASS
3	10	SPRAYFIELD	SORGHUM	MILLET	WHEAT
4	20	SPRAYFIELD	BAHIAGRASS	BAHIAGRASS	OATS
5	10	SPRAYFIELD	MILLET	SORGHUM	RYE
6	20	PASTURELAND	BAHIAGRASS	BAHIAGRASS	RYE
7	10	PASTURELAND	BERMUDAGRASS	BERMUDAGRASS	RYEGRASS
8	20	PASTURELAND	BAHIAGRASS	BAHIAGRASS	WHEAT
9	10	PASTURELAND	BERMUDAGRASS	BERMUDAGRASS	OATS
10	20	PASTURELAND	BAHIAGRASS	BAHIAGRASS	RYE

RUN	OCTOBER	to SEPTEMBER	ENSO PHASE	N LEACH	PROFIT
1	2004	2005	NIÑA	13,528	66,455
2	2005	2006	NEUTRAL	14,429	65,773
3	2006	2007	NIÑO	15,275	65,480
4				0	0

Fig. 2. Main screen of the DyNoFlo Dairy model displays a diagram of a dairy farm with all its main components.

or when it is called by a button inserted in this spreadsheet called “back to main menu.” This menu first shows a tab called “start” with a greeting welcoming the user to the system, briefly explaining the purpose of the application, and suggesting the read-me and help files be read before starting the runs. This welcoming tab also gives contact information to obtain support. The read-me file is in the spreadsheet. Both, the “welcome” page and the “start” spreadsheet have a button to trigger a help file.

The menu (Fig. 3) has eight tabs (top) and a common section (bottom). Besides the welcoming start tab, there are tabs for: livestock, nitrogen, soil, crop, climate, economics and optimize. In each of these the user can navigate for reviewing, inputting and/or selecting specific data. The common section consists of a drop-box menu to select small, medium, or large farm as a template, buttons to interchange the simulation visualization, and a button that makes the model run.

The livestock tab deals with cow-flow and milk production variables; the nitrogen tab refers to waste management system and water usage; the soil tab deals with the farm location and soil type; the crop tab defines all the farm fields, their size and their crops or crop sequences; the climate tab defines the number of years of simulation together with the climatic year (El Niño, La Niña, or neutral climatic years, according to ENSO); the economic tab allows the user to personalize revenues and expenses for specific farms; and the optimization tab allows the user to customize management options a farm could adjust to decrease N leaching.

For all modules there are default values for synthesized small, medium and large farms to start with (the drop-box menu at the bottom allows this customization) as a help to

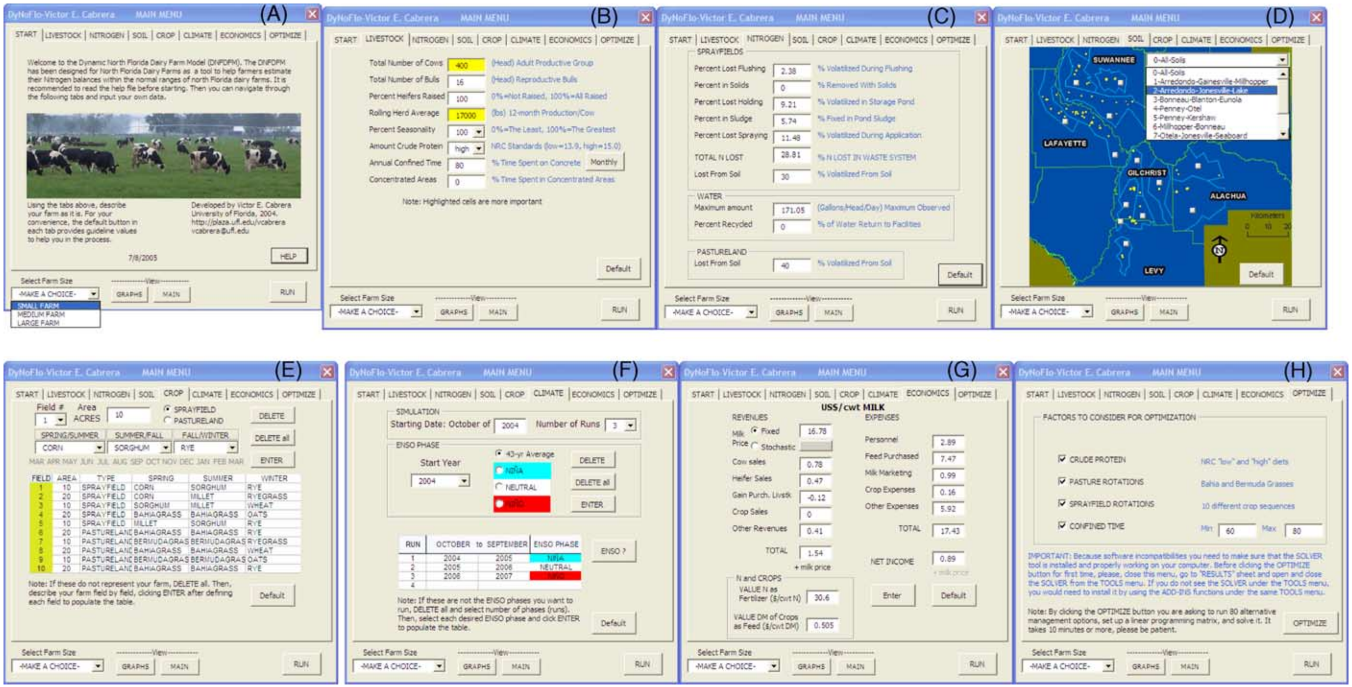


Fig. 3. Screen displays of the DyNoFlo Dairy model: (A) the start greeting menu control; (B) the livestock module control; (C) the waste management control; (D) dairy farm location and soil type by farm component control; (E) forage systems component control; (F) the climatic component control; (G) the economic component control; (H) the optimization control.

the user for introducing information. After the initial information is inputted, the user can press the “run” button and the model will start running. There is an initial time lag to let the model self adjust and then the results are seen in real time as numbers and graphs change on the screen. After running, the user can review the results by moving a scrollbar altering the timeline of the run. The user can also review the database generated by the results by scrolling down the spreadsheet. Excel® software is one of the most widely used computer programs. The DyNoFlo Dairy model takes advantage of this fact and delivers an application that will be easier to adopt for final users as an Excel® file (.xls extension). The DyNoFlo Dairy model does not change any of the normal capabilities of Excel software; it only protects the Visual Basic code and some cell contents from unintended changes, but leaves all other Excel capabilities intact so the users can utilize the Excel as they normally do to perform spreadsheet calculations, printouts, or take any other action together with the farm simulation.

2.3.2. The driver control

The driver control is the dynamic component that integrates and controls the simultaneous run of all other modules. The driver control also summarizes monthly estimations of N leaching and profitability by tracking the nitrogen and profit flows across all other modules.

The livestock module estimates the amount of N entering the system through the feed, as a function of monthly milk production and the level of crude protein in the diet. It estimates the amount of N utilized by the livestock in weight gain, reproductive functions, and milk production, according to the Florida standards and the number of animals in each specific group of the herd. It then calculates the amount of N excreted by each group of livestock and assigns amounts of N going to concentrated areas, pasture and crop land, and to the waste management system, by using differences, user inputs of confined time, seasonality, herd management, and standards for North Florida.

The waste management module continues the N flow to the crop land either in the pastures or in the sprayfields. Pastures receive the N excreted either in the concentrated areas (after they are collected and distributed in the fields) or by direct deposition by grazing animals (dry cows, heifers, and milking cows during non-confined time), while sprayfields receive the N in the effluent collected through the waste management system produced by milking cows during confined time. The waste management module also estimates the amounts of N volatized when the manure is deposited on the soil either as direct deposition or sprayed by an irrigation system by defaulting to North Florida estimations or by user defined values. In the case of the effluent applied in sprayfields, it first passes through a treatment in the waste management system. All farms in the study had some variation of a “flushing” waste management system and the waste management module estimates the amounts of N moving from one to the next component of this waste system until it reaches the soil of the sprayfield.

Whether the N is directly deposited in pastures or applied in sprayfields, pre-run crop simulation models estimate the amounts of N used by the crops as well as the amount of N leached by these fields, according to specific parameters of the amounts and type of manure N received, type of soil, crops present in the fields and detailed climatic characteristics. The user defines the number of years, the farm size, the field size, the crop sequences in each field, the type of soil by farm location, the climatic year (El Niño, La Niña, or neutral year) or the 43 years climate average.

At the end, the economic module estimates the overall monthly profit as the difference between revenues and expenses including the value of the estimated produced biomass and N leaching as revenue and expense, respectively.

2.3.3. The livestock module

The livestock module simulates cow-flows by using a Markov-chain probabilistic approach for a multidimensional matrix that includes cow age, months in milk, months in pregnancy, and lactation stage (lactation is the number of calvings (parity) of a cow). Markov chains for simulation of flow of cows are widely described in the literature of dairy economics (Kennedy and Scott, 1993; DeLorenzo et al., 1992). The livestock module uses number of cows in different states to estimate seasonal rates of culling, reproduction, and replacements of animals, feed requirements, and milk production based upon historical North Florida dairy records from the Dairy Herd Improvement Association (DHIA, www.dhia.org) summarized by de Vries (2004). Details and quantification of relationships of the livestock model can be found in Cabrera (2004).

The manure N excreted by a specific cow state is estimated as a function of milk production, for milking cows (Nennich et al., 2003); and by a function of book values (USDA, 1996, 1992), for dry cows, heifers, and bulls. For example, to estimate the manure N produced by milking cows in a giving month, Eq. (1) was used:

$$\mathrm{N}_{Mm}=\left(\sum_{k=1}^{9}\sum_{j=0}^{7}\sum_{i=1}^{18}(0.36+2.4^{-3}(M_{imk})+6^{-5}(M_{imk})^2-3^{-7}(M_{imk})^3)(C_{ijk})(W_m)\right) \tag{1}$$

where N_{Mm} is the amount of manure N produced by milking cows in month of the year m, i the months in milk after calving, j the pregnancy months, k the lactation cycle, m the month of the year, M_{imk} the milk production rate for a specific cow group determined by the sub indices, C_{ijk} represents the number of cows in a group determined by the sub indices, and W_m is the number of days on the month m. The coefficients in the equation were determined by fitting a curve that estimates the manure N excreted based on milk production based upon Van Horn et al. (1998).

The livestock model uses information of the total number of adults cows (TAC) and the rolling herd average (RHA). For further customization and for other estimations the user can input other layers of information such as the total number of bulls, the percent of heifers raised on the farm, the percent milk production variation through the year, the amount of crude protein in the diet, the percent of confined time, and the percent of time milking cows spend in concentrated areas (Fig. 3B). For the confined time, there is an additional button that allows the user to enter monthly variations of confined time, if desired. Using these initial conditions, the model is capable of self-adjusting to reach a seasonal steady state of cow flow. This is the way North Florida dairy farms operate, and different model runs could account for plans to increase or decrease herd size.

Markov chains represent the states cows go through, as described below. When a female calf is born it gains weight for 12 months. At that age, pregnancies are sought through artificial insemination or by the use of bulls. If the heifer is not pregnant at 24 months, it will be culled. The proportion of culling of heifers for not being pregnant is very low. After 9 months of pregnancy a calf is born and the heifer enters the milking group as a fresh, first lactation, first month, open cow. Local information indicates that not all farmers raise their own replacements or they do not raise all their needed replacements to maintain the herd size. In those cases, the model can be easily adjusted by a percentage estimate of replacements raised on the farm.

During the first lactation cycle, Markov chains divide cows into different categories according to whether or not they are pregnant, how many months they are pregnant and how many months they have been milking. The possible states or categories into which cows stay at any point in time depends on the model dimensions: 10 months for lactations $\times$ 32 months for growing or in milking $\times$ 10 months for pregnancy = 3200 states.

A voluntary waiting period (VWP) of 45–60 days will be observed before starting the reproductive program again in a first lactation cow. An average re-conception rate for Florida is 16%, meaning that only 16% of the cows of first (or higher) lactation will get pregnant in an attempt, but this varies, and the model accounts for these variations (conceptions attempts are repeated every 21 days, following estrous cycle). The pregnancy rate that encompasses heat detection together with conception rate decreases with months in milk and increases with colder months.

If after 12 months in milking the cow is not pregnant, it will be culled from the herd. Fewer cows will arrive at higher lactation cycles because there is always a chance for any cow to be culled for any another reason besides reproduction. The culling rate depends on cow stage: heifer or adult (months in milk) and the season. For example, higher culling rates are expected in warmer months and in the first months of milking (for more details see de Vries (2004)).

Cows produce different amounts of milk depending on lactation stage, months in milk, and season of the year. These milk production rates can be adjusted for every specific farm based on the rolling herd average (RHA, average of milk produced for the entire herd in the last 12 months) by running the model and comparing total milk production with the RHA target. The model self adjusts to reach the RHA for that specific herd with less than 1% of error.

The livestock module communicates directly with the feed component to retrieve information about dry matter intake and protein amounts and yields its outputs to the modules that handle the waste in the concentrated areas, the pasture fields, and the waste management system.

2.3.4. The waste management system module

The waste handling system simulates the N movement through the components of the flushing system, which is common (with some variants) to all North Florida dairy farms (Fig. 3C). The flushing system handles the manure deposited on concrete in confined areas. It consists of water flushing system, storage pond, and an irrigation system. Additionally there may also be a solids screener and a treatment lagoon. The flushing system uses great amounts of water to move the manure (feces and urine) deposited on concrete, the storage pond receives and stores this liquid manure for variable amounts of time, and the irrigation system applies it to the crop systems. Both, the solid screener and the treatment lagoon are designed to separate solids from the flushed manure, the first one by mechanical action and the second one by gravity. Both, if present, are located before the storage pond.

As soon as the manure is deposited on the concrete, variable rates of ammonia will be lost to the air as volatilization. If solids are screened, the manure that reaches the storage pond will be a solution with less than 5% solids. Nitrogen in this liquid manure is ammonium and organic compounds in solution. Extra amounts of ammonia are still lost by volatilization to the air during the holding time in the storage pond and during spraying application in the fields. If solids are not screened, the liquid manure will have greater than 5% solids but it is still sprayed on the fields using high-pressure equipment and an agitator to maintain it as a liquid. For example, the manure N at the final point of utilization in sprayfields is estimated using Eq. (2):

$$\mathrm{N}_{w_f} = (\mathrm{N}_w)(\mathrm{VBF})(\mathrm{SC})(\mathrm{VP})(\mathrm{VI})(\mathrm{VS}) \tag{2}$$

where N_{w_f} is manure N available in the sprayfields; N_w the amount of manure N deposited in concrete, VBF the fraction of N loss by volatilization before flushing, SC the fraction of N in the solids collection, VP the fraction of N volatilized in pond, VI the fraction of N volatilized during irrigation, and VS is the fraction of N lost in the soil after application.

Values vary greatly in different management systems. Van Horn et al. (1998) present an average system for Florida in which there is an estimated total loss (total N lost, TNL) of 29% of N through the waste system with specific characteristics in all components. These values are used as default in the model, but ultimately the users must change them to better mimic their specific conditions. Exporting manure N off the farm is an option that can be accounted for in the model. However, this practice is very limited in the study area.

The waste management system communicates with the livestock model and with the crop models. It uses the estimated amounts of N excreted by confined cows and it estimates monthly N amounts applied to the sprayfields to be used by the crop models.

2.3.5. The forage systems module

The crop models from the decision support systems for agrotechnology transfer (DSSAT, Jones et al., 2003) use daily climatic information of temperature, irradiation, and precipitation along with soil characteristics, manure effluent applied, and other management choices to estimate daily biomass accumulation and N leaching for specific crop sequences that are common in North Florida dairy farm systems. These forage systems are user-defined.

Forage crop simulations were pre-run using and adapting crop models contained in the DSSAT v4.0. 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), where the drained upper limit values were corrected using Saxton et al. (1986) (Fig. 3D).

Forage crops were calibrated and validated for North Florida dairy farm conditions and all potential forage combinations were run for all N effluent ranges, ten types of soil found in the study area (Fig. 3E), and for 43 years of daily weather data (1956–1998). Daily cumulative N leached (kg ha^{-1}) and biomass (kg ha^{-1}) outputs from the simulations were compiled in monthly rates for the span of the study period (1956–1998). All months were classified according to ENSO phases and results were summarized by the factors incorporated in the simulations: 12 months × 3 ENSO phases × 4 manure N applications × 10 soil types × 11 forage combinations. A database containing this information was integrated into the main model, so that real results from crop model simulations can be reproduced for any situation required. For the case of the manure N application, an interpolation function was used to cover points that were not used in the original crop model runs. For the pasture fields, a correction was performed based on the fact that these fields receive direct deposits of manure and they are not irrigated.

The forage system control allows the user to input data in up to 10 fields. These define field size, the type of field (spray field or pasture), and the sequence of forage crops. Through the “soil tab,” the user locates the farm geographically, which determines the type of soils in which the forage crops will be grown. Additionally the crop models use climatic information according to the selection of climatic years, which is discussed in following section.

The driver control assures that the crop models communicate with the waste management module to estimate N leaching and biomass accumulation based on amounts of manure N either directly deposited to pasture fields or sprayed after treatment in the manure waste system.

2.3.6. The climatic module

The climatic component allows the user to select the starting year of the simulation and run the model for a selected number of years. The climatic module assembles the forecast climatic conditions under which the forage systems will grow. It is a user choice based on a classification of climatic years based on ENSO in El Niño, La Niña, and neutral year events between 1956 and 1998. Also an average of all 43 years can be selected. After selecting the run timeline, the user can select the forecast climatic years (Fig. 3F). ENSO phase forecast are now becoming more identifiable for North Florida conditions several months in advance (O’Brien et al., 1999; www.coaps.fsu.edu).

The objective is to devise management options that might be more desirable (decreasing N leaching) according to forecast ENSO phases. It also allows the user to compare the outcomes among different ENSO phases and average years.

2.3.7. The economic module

The economic module requires current farm economic data. Profitability is estimated every month and is sensitive to the manure N recycled on-farm and the amount of biomass produced as feed inside the farm gate. The estimated manure N recycled is converted to chemical fertilizer in order to estimate its monetary value. As a guide for the user the economic module shows an average for Florida farms by default published by the DBAP, www.animal.ufl.edu/dbap/ (de Vries et al., 2000). The user can personalize prices and costs by entering them directly on the menu (Fig. 3G). This module reassembles a monthly balance of revenues less expenses. Revenues on a dairy farm come from sale of milk, sale of cows, sale of calf and heifers, gain on purchased livestock, sale of crops, and other revenues. Expenses are divided onto feed purchase, personnel, milk marketing, crop expenses, and other expenses.

The value of milk is the product of the milk produced and its market price. More than 90% of the revenue on North Florida dairy farms comes from milk (de Vries et al., 2000); therefore, the model is highly sensitive to this factor.

2.3.8. The optimization module

Another function incorporated in the DyNoFlo Dairy model is the optimization that is triggered by a button called "optimize" located in a tab with the same name (Fig. 3H). The optimization module sets up and automatically solves a linear programming matrix.

The optimization module is a dual linear programming model that maximizes profit (Π) or minimizes N leaching (N_L) of multiple scenario simulation runs s under restrictions of at most average $\overline{N}_L$ or at least average $\overline{\prod}$, respectively, as defined in Eqs. (3) and (4).

$$\max \prod = \sum_{s=1}^{S}\sum_{m=1}^{12}\prod\nolimits_{ms} \cdot X_{ms} \text{ subject to } \sum_{m=1}^{12} X_{ms} \cdot N_L \leq \overline{N}_L \text{ and } X_{ms} \geq 0 \tag{3}$$

$$\min N_L = \sum_{s=1}^{S}\sum_{m=1}^{12} N_L \cdot X_{ms} \text{ subject to } \sum_{m=1}^{12} X_{ms} \cdot \prod\nolimits_{ms} \geq \overline{\prod} \text{ and } X_{ms} \geq 0 \tag{4}$$

X_{ms} is the variable defined as the relative fraction of a chosen scenario s in a month m. A scenario is a set of management practices (i.e., "high" crude protein in diet, corn–sorghum–winter forage rotation in sprayfields, bahiagrass in pasture fields, and 80% of confined time). Scenarios in an optimization are formed by combining levels of selected management practices. Previous livestock, waste, forage, climate, and economic modules estimate monthly N leaching and profit that are the technical coefficients in the optimization matrix. $\overline{N}_L$ and $\overline{\prod}$ are average N leaching and average profit for all scenarios selected in an optimization. Optimization is repeated independently for each ENSO phase; therefore, management strategies are a function of predicted seasonal climate conditions.

3. Model results

3.1. Validation of the DyNoFlo Dairy model and its components

Given the limited number of dairies in the study area (45), statistical validation of the whole farm DyNoFlo Dairy model was not feasible. Nor it was feasible to validate N leaching because measurements are not available. However, the crop models, the main component for estimating N leaching and crop biomass, have been amply validated by previous studies (Rymph et al., 2004; Jones and Kiniry, 1986; Hunt and Boote, 1998). They were further calibrated for North Florida conditions using experimental data from Woodard et al. (2002).

The dynamic livestock and manure handling components were calibrated and validated with lengthy and detailed interviews with 21 dairy owners. Additionally, these components were calibrated and validated with three focus groups with extension agents, USDA technical staff, Florida Department of Environment Personnel, private consultants, and other members of the Suwannee River Partnership.

Finally, the complete DyNoFlo Dairy model was validated with three diverse dairy farms (large, medium, and small) in the study area and one focus group with the Suwannee River Partnership members. In all four of these sessions, additional components of optimization and feasible adjustments were incorporated and deemed to be satisfactory.

Table 1
Characteristics of a synthesized North Florida dairy farm

Characteristic	Unit	Value
TAC	Head	400
Bulls	Head	16
Heifers	%	100
RHA	kg year^{-1}	7700
TNL	%	29
N volatilized sprayfields	%	30
N volatilized pasture	%	40
Sprayfields	ha	28
Pasture	ha	32
Net income	US$ Mg milk^{-1}	19.60

Note: TAC, total adult cows; RHA, rolling herd average; TNL, total N lost through the waste management system.

3.2. Analysis of a synthesized Dairy in North Florida

A synthesized farm was created using field data for analyses purposes. Because of the sensitivity of the N leaching, a "synthesized" farm was ideal for combining many real characteristics of dairies in the study area without identifying any specific farm for which the DyNoFlo Dairy model could be run to perform relevant analyses. The synthesized farm was studied using the simulation and optimization tools of the DyNoFlo Dairy model for graphical, statistical, and optimization analyses.

The synthesized farm had 400 adult cows, 16 bulls, and raised 100% of its heifers. The rolling herd average was 7700 kg year^{-1}, and the amount of crude protein in the diet was "high." The milking cows spent 80% of their time confined. The total N lost through the waste management system was 29% (Van Horn et al., 1998) and it was estimated that there was an extra 30% N volatilized from the soil when applied (Van Horn et al., 2001); the volatilization by direct deposition in soils was estimated at 40% (Van Horn et al., 2001) (Table 1). This dairy farm had 28 ha of sprayfields and 32 ha of pasture fields with diverse forage system rotations as indicated in Table 2.

Table 2
Area, type of fields, and forage rotations in synthesized 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

3.3. Results of the synthesized North Florida dairy farm

The DyNoFlo Dairy simulation model was run to simulate this synthesized farm, using the average soil type and the overall net income at US$ 19.6 per Mg of milk produced. The simulation started in October 2004 and followed three consecutive years, assuming 2004/2005 to be a La Niña year, 2005/2006 a neutral year, and 2006/2007 an El Niño year.

Nitrogen leaching and profit varied on a yearly basis for different ENSO phases. Overall N leaching was always lower in La Niña years (6124 kg farm^{-1} or 101 kg ha^{-1}) than in neutral years (6% lower) or in El Niño years (13% lower). Profitability was inversely related to N leaching, La Niña years have the highest profitability and El Niño years the lowest (Fig. 6).

On a monthly basis (Fig. 4), N leaching varied from 68 kg in April for La Niña years to 2700 kg in January for El Niño years. January and February were the months with the highest leaching rates (Fig. 4A). January alone was the critical month that accounted between 30% (La Niña years) and 40% (El Niño years) of overall yearly N leaching. Accumulated biomass (plant growth) increased, as expected, towards the summer months (Fig. 4B) when higher temperatures and rainfall determined greater plant growth. Profitability was highest between the months of April and July (maximum in May for La Niña years) because of higher N recycled or higher biomass accumulation.

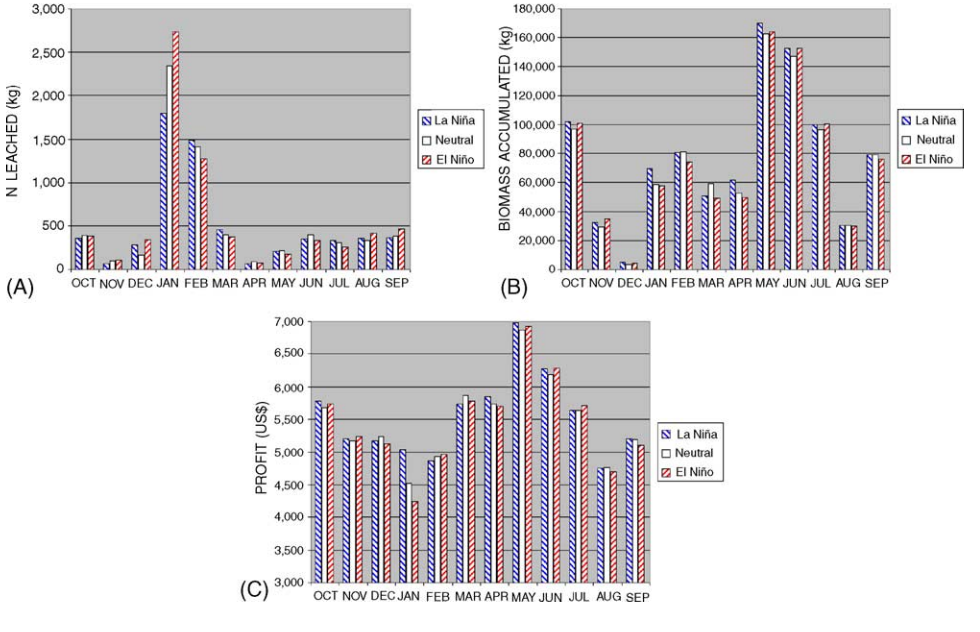


Fig. 4. Monthly estimations for synthesized small North Florida dairy farm: (A) N leaching; (B) biomass accumulation; (C) profit.

Table 3
Combination of environment characteristics and management strategies simulated by the DyNoFlo Dairy model for the sensitivity analysis

Environment/Management	Code	Value
Soil types	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)
	10	Blanton–ortega–penny
ENSO phases	1	La Niña
	2	Neutral
	3	El Niño
Confined time (CT)	1	80%
Forages pasture (pasture)	1	Bahiagrass–bahiagrass–winter forage
	2	Bermudagrass–bermudagrass–winter forage
Forages sprayfields (fields)	1	Bahiagrass–bahiagrass–winter forage
	2	Corn–bermudagrass–winter forage
	3	Corn–bahiagrass–winter forage
	4	Corn–millet–winter forage
	5	Corn–corn–winter forage
	6	Millet–sorghum–winter forage
	7	Sorghum–corn–winter forage
	8	Millet–corn–winter forage
	9	Corn–sorghum–winter forage
	10	Bermudagrass–bermudagrass–winter forage
Crude protein (CP)	1	Low
	2	High

3.4. Sensitivity analysis

The DyNoFlo Dairy model was run for the synthesized farm and various potential environmental and managerial options as scenarios that could impact N leaching and profitability. Scenarios were created by combinations of the 10 North Florida dairy farm soil types, three ENSO phases (La Niña, Neutral, and El Niño climatic years), two levels of confined time (CT, 80 and 60%), two combinations of forage sequences in pasture, 10 combinations of forage sequences in sprayfields, and two levels of protein in the diet (“low” and “high”) (Table 3).

Fig. 5 compares the yearly N leaching and profitability of selected factors. Circles in Fig. 5 represent managerial or environmental conditions represented by the numbers inside them.

Nitrogen leaching was higher and profit was lower consistently for El Niño years and the opposite for La Niña years (Fig. 5). Fig. 5A illustrates N leaching and profitability for the 10

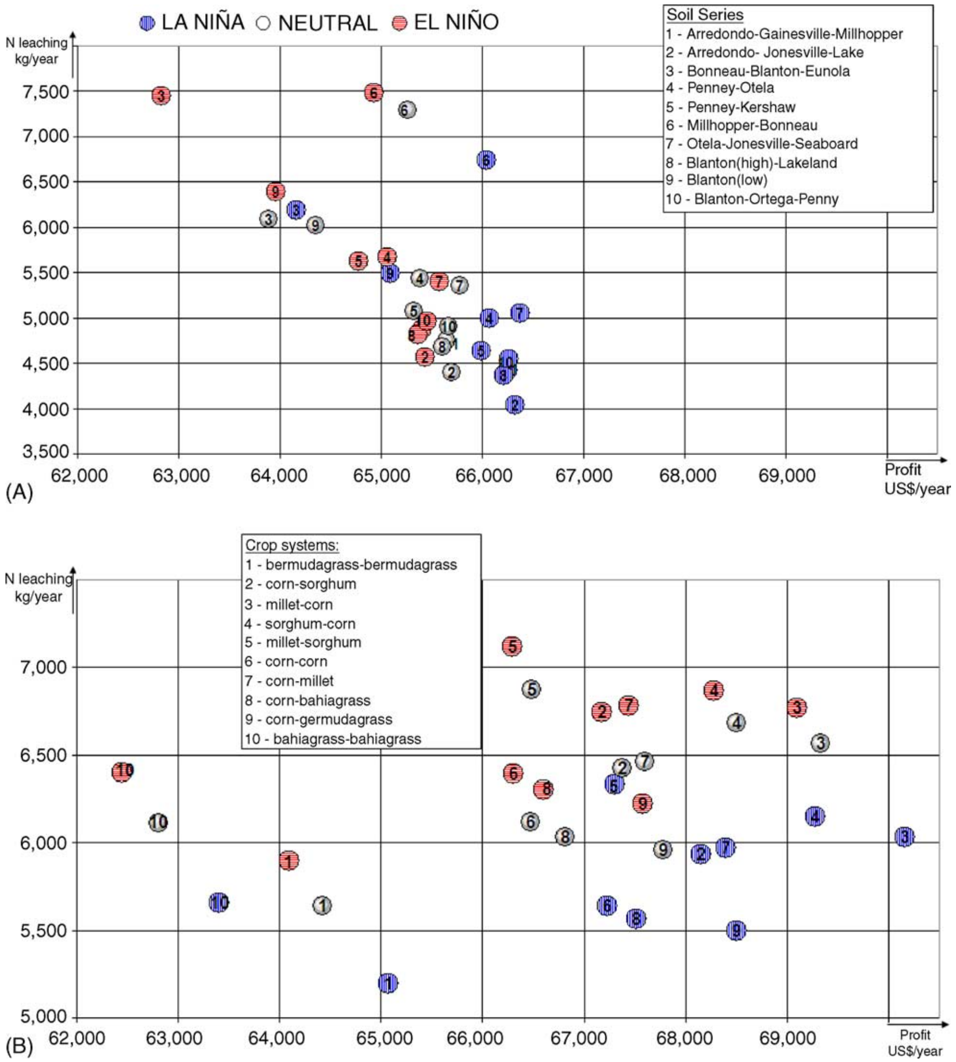


Fig. 5. Overall farm N leaching and profit when confined time is 80% and crude protein in diet is “high.” (A) Soil series of the study area when the pasture and sprayfields are planted with bermudagrass. (B) Crop systems in sprayfield during spring and summer when soil is type 4 (Penney–Otella) and pasture is bahiagrass.

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.

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

Fig. 5B displays the relationships among 10 different crop systems for spring–summer to summer–fall in the sprayfields. Rotation consisting of bermudagrass–bermudagrass outperformed the others with the least N leaching and medium–low profitability. It is followed by system of corn–bermudagrass, which had medium-to-high profitability. Rotation consisting of bahiagrass–bahiagrass had low–medium N leaching, but the lowest profitability of all. The most profitable crop system was rotation millet–corn, but with a medium to high level of N leaching.

A decrease in the amounts of N leaching was observed when the crude protein in the diet changed from “high” to “low” in the order of 10% with a negligible increase in profit (figures not shown). Similarly, N leaching decreased in the order of 7% with a negligible increase in profit when the confined time of the milking cows on the synthesized was changed from 80 to 60%. Impacts in changes in crude protein and confined time vary depending upon other specific farm conditions such as the area of sprayfields and pastures, the manure handling system specifications, and the number of cows.

3.5. Optimization of the synthesized farm

The linear programming optimizer of the DyNoFlo Dairy model included combinations of the following management options: confined time (CT), crude protein (CP), pasture forage rotations, and sprayfield forage sequences in the synthesized farm. The optimizer found a set of management practices with better characteristics of lower N leaching and higher profit when compared with the baseline situation of the farm. The selected management options are summarized in Table 4 and results compared with the original situation are presented in Fig. 6.

The management strategies selected by the optimizer were a “low” CP level; a variable level of CT, 60% of CT for cows that will use 59% of the pasture and 80% of CT for cows that use 41% of the pasture; a bermudagrass–bermudagrass–winter forage sequence for all

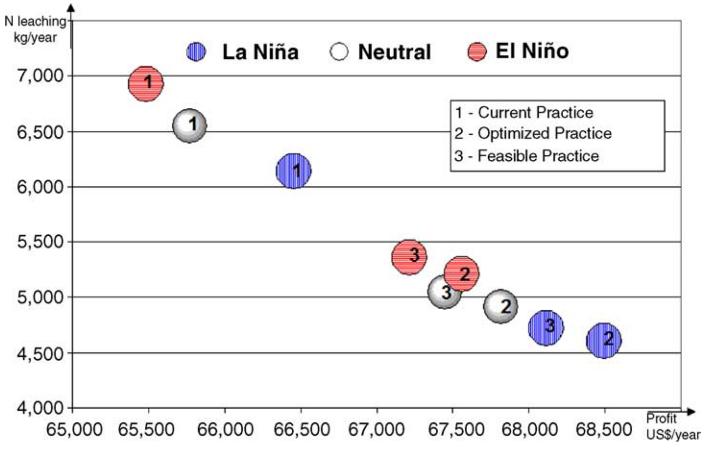


Fig. 6. Comparison of N leaching and profit of current, optimized and feasible practices of the synthesized North Florida dairy farm for different ENSO phases.

Table 4
Management strategies selected by the optimizer

Management	Selected level		
CP	Low		
CT	60%	59% of the pasture	
	80%	41% of the pasture	
Pasture	Bermudagrass–bermudagrass–winter forage		
Sprayfields		ha	
	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

Note: CP, crude protein; CT, confined time.

pasture land and variable areas of forages for sprayfields for different ENSO phases, as seen in Table 4.

With these combinations, the optimizer estimated that N leaching would vary from 4603 kg year^{-1} for a La Niña year to 5215 kg year^{-1} for an El Niño year. An intermediate figure of 4916 kg year^{-1} was the outcome for a neutral year.

Comparing these values with the previous results of the farm "as is," substantial variations were noticed. N leaching could be decreased up to 25% and profit could still be increased by approximately 3.15%, in all ENSO phases.

3.6. Feasible practices for the synthesized farm

In reality, farmers cannot change all practices proposed by the optimizer. For instance, slight changes in area of sprayfields may not be feasible. However, dairy farmers usually would be able to change some of the proposed practices. The optimization results serve as guidelines for making such changes, taking into account that these optimization results would present better environmental outputs. By cross-referencing results achieved by the optimizer with the farmer-proposed practices, changes that are "feasible" for farmers can be determined.

The optimization proposed a decrease in CP in the diet from "high" to "low." This is a feasible change for a dairy farmer to make. Next, the optimization proposed to switch the

Table 5
Feasible crop systems in synthesized dairy farm

Field	Area (ha)	Type	Spring	Summer	Winter
1	9.31	Sprayfield	Corn	Corn	Rye
2	6.07	Sprayfield	Bermudagrass	Bermudagrass	Ryegrass
3	5.67	Sprayfield	Corn	Bermudagrass	Wheat
4	7.69	Sprayfield	Corn	Corn	Oats
5	32.37	Pasture	Bermudagrass	Bermudagrass	Oats

CT between 80 and 60% for different groups of cows. If the farmer found it difficult to implement this specific change, CT levels would remain at 80%. Finally, the optimization proposed a series of crops for different ENSO phases. The farmer may prefer similar, though not identical crop changes suggested by the optimization. Feasible crop systems for the farm are shown in Table 5. This implemented bermudagrass instead of bahiagrass in pastures and sprayfields, and includes more in corn than sorghum and millet in sprayfields. Feasibility of management adjustments were determined through interaction with dairy farmers and other stakeholders.

With these “feasible” combinations the DyNoFlo Dairy simulation was rerun. Results estimated that the N leaching would vary from 4722 kg year^{-1} for a La Niña year to 5361 kg year^{-1} for an El Niño year. A neutral year would result in N leaching of 5048 kg year^{-1}. Comparing these N leaching values with the original, farm “as is” N leaching could be reduced by approximately 23% in all ENSO phases, and the profit could still increase by 2.5% (Fig. 6).

4. Conclusions

Although many simulation models in different parts of the world dealing with the issue of N leaching on dairy farms already exist (Topp and McGechan, 2003; Rotz et al., 2002; Kuipers and Mandersloot, 1999; Berentsen and Giesen, 1994) the DyNoFlo Dairy model adds novel aspects with the combined interaction of Markov-chain flow of cows, climatic differentiation of ENSO phases, profitability linked to N leaching and N utilization, and dual optimization of N leaching and profitability.

For established dairies attempting to reduce N leaching and maintain an adequate profit level, a large number of cows exist in a fixed area, so only relatively small changes in number of animals are possible. Given that land area and soil type are fixed, and confined time is not very flexible, the most critical factor for reducing N leaching without impacting profit is selection of crop rotations on sprayfields and pastures. The best pasture is bermudagrass. Sprayfields should be planted to bermudagrass as well, and then strip planted in the sod with corn. In the winter, both sprayfields and pastures should be planted with a very dense over seeding of mixed winter forages (oats, wheat, rye, ryegrass). Changing from the “high” to the “low” crude protein in diet can substantially decrease the N flows mostly to the sprayfields. In addition to these longer term adjustments, when El Niño years are forecast, the most feasible seasonal adjustments are: (1) a heavier voluntary culling rate to reduce the number of cows; (2) export manure; and/or (3) rent additional pasture land and decrease confined time.

The DyNoFlo Dairy model has even greater potential to reduce N leaching when designing new dairies rather than making adjustments to existing dairies.

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