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Strategies to limit (minimize) nitrogen leaching on dairy farms driven by seasonal climate forecasts

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Abstract

Dairy farmers in Florida are required to limit nitrogen leaching into the ground water below 10 mg L^{-1}. Literature shows that nitrogen leaching on a dairy farm varies greatly with forage systems, amount of manure N applied, seasonal rainfall amounts, and soil characteristics. The purpose of this study was to devise dairy-specific strategies for forage crops and manure effluent application rates conditioned to the El Niño Southern Oscillation (ENSO) phenomenon that determines El Niño, La Niña, or neutral years, each of which is associated with temperature and rainfall patterns, to reduce N leaching on a typical North Florida dairy farm. The Decision Support System for Agrotechnology Transfer (DSSAT) was used to simulate N leaching and biomass accumulation using 43 years of daily weather data and eleven forage systems supplied with four levels of manure N (20–160 kg N ha^{-1} mo^{-1}), and ten soil types where dairies are found. Higher N leaching and lower biomass accumulation occurred in El Niño years than in neutral and La Niña years. N leaching in all ENSO phases was high in winter, particularly in January and February compared to other times in a year. Overall, forage systems with the best potential to limit N leaching were: in the spring (March–May) those that combine bahiagrass or bermudagrass in El Niño years and corn in neutral and La Niña years; in the summer (June–August) those with bahiagrass or bermudagrass in El Niño, bahiagrass, bermudagrass, or corn in neutral, and corn in La Niña years; and in the winter (December–March) those with intercropping of ryegrass, rye, oats, and wheat. This study demonstrates that recommendations for least N leaching can be developed using ENSO phase forecasts.

Keywords: ENSO forecast; N leaching; Dairy; Forage; Environment; Water pollution

1. Introduction

The presence of high N levels in water of the Suwannee River Basin has become a concern in recent years because of associated environmental and human health hazards (Cabrera et al., 2005, 2006a). Due to suspicion that high N amounts applied through dairy manure to forage fields may be an important factor contributing to this problem, dairy farmers are now required to comply with new environmental regulations either through permits or voluntary incentive-based N-management programs (Cabrera et al., 2006b). The main strategy farmers have to manage their total N loads is through utilizing N to produce forage crops (Cabrera, 2004). Dairy farmers in North Florida have to dispose off their liquid and dry manure on their own fields. When the farms are land locked as is the case of North Florida, the ratio of manure applied per land area increases together with the increase in milk production. Consequently, forages in the fields are important in up-taking nutrients applied as the manure.

Several studies have documented that a great portion of N applied through manure leaches beyond the root zone. On

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dairy farms in Georgia, Hubbard et al. (1987) found five times greater concentrations of NO_3–N below the root zone than the 10 mg L^{-1} maximum acceptable level permitted in the U.S.A. with 1080 kg N ha^{-1} yr^{-1}. Vellidis et al. (1993) also measured 1.5–2 times more NO_3–N leaving the soil than the maximum acceptable level permitted in the U.S.A. in a bermudagrass (*Cynodon* spp.)-rye (*Secale cereale* L.) double crop supplied with 400 and 800 kg of manure N ha^{-1} yr^{-1}, respectively. In Georgia, Johnson et al. (1991) found that about 38% of N manure applied was leached from a triple crop consisting of bermudagrass, rye, and corn (*Zea mays* L.) when 1000 kg N ha^{-1} of manure N was applied. Newton et al. (1995) measured 20% N leaching with manure N applications of 400 kg ha^{-1} yr^{-1} and 42% with applications of 800 kg ha^{-1} yr^{-1}.

Nitrogen leaching is also a major problem on sandy North Florida soils, which receive even more rainfall (1600 mm yr^{-1}) than in Georgia. For example, French et al. (1995) found that almost 32% of N was lost from a crop sequence of corn and rye when 360 kg of manure N ha^{-1} yr^{-1} was applied, which increased to 55% at a higher rate of 670 kg of manure N ha^{-1} yr^{-1}. In a 4-year study, Woodard et al. (2002) studied the effect of different combinations of forage systems and N rates on N leaching. The amount of N uptake (kg) was: 429 for bermudagrass, 155 for corn, 114 for sorghum (*Sorghum bicolor* L.), and 70 for rye when supplied with 910 kg N ha^{-1} year. For each kg biomass produced, N uptake in kg was: 0.021 for bermudagrass, 0.012 for corn, 0.012 for sorghum, and 0.018 for rye. They also found seasonality in N losses when compared across forage systems. For example, in the bermudagrass–rye system, the rate of N leaching was 29% but NO_3–N levels never exceeded 10 mg L^{-1} during the time bermudagrass was growing (April–November), but NO_3–N levels went above 30 mg L^{-1} during the time of the rye (December–March). For the corn–sorghum–rye system, the rate of N leaching was 52% and NO_3–N levels reached 20–40 mg L^{-1} during corn growth (April–July), 20–60 mg L^{-1} during sorghum growth (August–November), and 30–60 mg L^{-1} during rye growth (December–March).

Earlier field studies suggest that N leaching in dairy fields is a function of forage combination, soil type, seasonal climate variation, and agronomic management (Newton et al., 1995; French et al., 1995; Woodard et al., 2002). They have provided 2–4 years of measurements of N leaching for specific locations and several forage crops, but there is no adequate long-time series of field data to characterize the role of year-to-year climate variability on N leaching across locations where dairy farms are found.

This study investigated the use of El Niño Southern Oscillation (ENSO) forecast that determines El Niño, La Niña, or neutral years, each of which is associated with temperature and rainfall patterns, to devise management strategies that dairy farmers in North Florida could adopt to attain ecologically safe N leaching levels. The ENSO phase is forecasted in early fall (August–September, www.AgClimate.org) and it runs from October 1st of one year to September 30th of the next year. Consequently, farmers could use an ENSO prediction to plan winter of this year, and spring and summer crops of next year. It was hypothesized that climate variability associated with ENSO phase and seasonality could be used to develop a sequence of forages to reduce N leaching in North Florida dairy farms. This hypothesis was tested by simulating ENSO impacts on N leaching from various forage systems under intensive application of dairy manure effluent in North Florida dairy farms.

2. Materials and methods

Prior to this study, a base-line inventory of forages grown on existing dairy farms in North Florida was made. In addition to this inventory, long-term daily weather data as well as data on soils of dairy farms was collected as needed for DSSAT crop simulation model evaluations and calibration. Crop simulations were performed on existing forage crops for all soils and with all weather data, which were then analyzed to determine their suitability to limit N leaching.

2.1. Characteristics of dairy farms in the study area

The study area covered 64 dairies located in North Florida (Cabrera, 2004). The dairies were spread across the Suwannee River Water Management District (21.30–30.37°N, and 82.43–83.35°W) across five counties: Suwannee (19), Lafayette (25), Gilchrist (7), Levy (7), and Alachua (6). According to a survey of 21 dairy farmers in the study area, Cabrera (2004) inventoried the most popular forages grown by farmers during different parts of the year. Accordingly, the most popular forages (in percentage of land area) grown on farms in North Florida dairy farms during spring–fall were relayed crops of bermudagrass–bermudagrass (35%, i.e. 35% of the area was devoted to bermudagrass followed by bermudagrass), corn–sorghum (29%), bahiagrass (*Paspalum notatum*)–bahiagrass (16%), corn–millet (*Pennisetum glaucum*) (13%), bahiagrass–millet (4%), and corn–corn (3%). In winter, most common forages were ryegrass (*Lolium multiflorum*) (43%), rye (26%), oats (*Avena sativa*) (26%), and wheat (*Triticum aestivum*) (5%). Forage combinations varied during the spring–summer and summer–fall seasons, but not during the fall–winter season as winter forage is always intercropped ryegrass, rye, oats, and wheat in various combinations. Table 1 presents all the sequences of crops dairy farmers are already using in North Florida. Even when perennials such as bermudagrass and bahiagrass are already installed in the fields, farmers sod-plant them; consequently, all sequences presented in Table 1 are possible to strategize.

Dairy farm fields received a highly variable amount of manure N effluent depending on herd size, land available,

Table 1
Forage system sequences currently prevalent amongst dairy farms in North Florida as a function of planting time[a] (e.g., the field sawn for corn in spring–summer is replanted with bahiagrass in summer–fall, and replanted again with ryegrass, rye, oats, and wheat in fall–winter)

Spring–Summer (March–July)	Summer–Fall (July–November)
Bahiagrass	Bahiagrass
Bermudagrass	Bermudagrass
Corn	Sorghum
Corn	Bermudagrass
Corn	Bahiagrass
Corn	Millet
Corn	Corn
Millet[b]	Sorghum
Millet[b]	Corn
Sorghum	Millet
Sorghum	Corn

Source: Adapted from Cabrera (2004, Figs. 6–7).

[a] Fall–winter forage is always the same: a combination of ryegrass, rye, oats, and wheat.

[b] Not found in interviews, but they are possible.

and waste management system. Monthly rates of manure N effluent applied to fields were estimated by Cabrera (2004) by simulating dynamic cow flows in Markov-chains integrating data from seasonality, culling rates, reproduction rates, milk production of North Florida dairies, and a 40% rate of volatilization after application on sandy soils of North Florida (Cabrera et al., 2006b). The estimated manure N effluent incorporated into the soil varied between 20 and 160 kg ha^{-1} mo^{-1} in two applications per month.

The detailed soil analysis for 10 soil types where dairy farms were situated were extracted from the soil series maps of the Soil Survey Geographic Database (SSURGO), Natural Resource Conservation Service (2002). These data were converted into variables and the format needed by the Decision Support System for Agrotechnology Transfer, DSSAT v4.0 system (Jones et al., 2003), using SBuild software (Uryasev et al., 2003), where the soil water holding limits were estimated using the Saxton et al. (1986) method. The soil types identified by county are detailed in Table 2.

Rainfall varies over the region of study. However, long weather records and specific data on solar radiation needed to conduct a simulation study were only available for the Levy station (29.42 N, 82.82 W). Levy is situated in the lower central part of the study area and daily weather data from 1956 to 1998 were available from Mavromatis et al. (2002). Each of these 43-years were classified as belonging to an ENSO year, which begins in October and runs through September of the next calendar year, according to the Japan Meteorological Index (JMA, 1991). El Niño is the name for the unusual warming of the Pacific Ocean's surface (exceeding 0.4 °C above normal temperatures for six or more months), whereas La Niña occurs when colder than normal temperatures occur in the same area of the Pacific Ocean (Trenberth, 1997). These 43-years thus consisted of 11 El Niño years, 10 La Niña years and the remaining 22 neutral years.

2.2. Forage crop simulations

Forage crops found on North Florida dairy farms were simulated using adapted crop models in DSSAT v4.0 (Jones et al., 2003). These dynamic crop models simulate crop growth and yield in response to management, climate, and soil conditions. The soil C and N components were simulated using a widely tested and accepted model, the CENTURY (Parton et al., 1987) as implemented in DSSAT by Gijsman et al. (2002). The CENTURY model simulates soil N balances that include soil and surface organic matter, inorganic N, additions and removals of N, and all processes of the N cycle in the soil such as decomposition, denitrification, immobilization, mineralization, and N leaching (Wegehenkel and Mirschel, 2006; Corbeels et al., 2005; Liu et al., 2005).

Table 2
Soil types, some characteristics, and their sources of information used for the study

Series/orders	County	Depth (cm)	Drainage[a] rate	Available water cm/cm soil	CEC[b] meq 100 g^{-1}	Survey
Arredondo–Gainesville–Millhopper ults/ents	Alachua	166	0.75	0.11	6.0	Thomas et al. (1985)
Arredondo–Jonesville–Lake ults/alfs/ents	Alachua	148	0.65	0.09	5.0	Thomas et al. (1985)
Bonneau–Blanton–Eunola Thermic Siliceous Fine-loamy	Gilchrist	164	0.80	0.12	6.6	Weatherspoon et al. (1992)
Penney–Otela alfs/ents	Gilchrist, Lafayette	149	0.80	0.08	3.6	Weatherspoon et al. (1992)
Penney–Kershaw ents	Gilchrist	128	0.75	0.05	3.2	Weatherspoon et al. (1992)
Millhopper–Bonneau ults	Levy	175	0.85	0.09	7.0	Slabaugh et al. (1996)
Otela–Jonesville–Seaboard alfs/ents	Levy	135	0.75	0.10	5.5	Slabaugh et al. (1996)
Blanton(high)–Lakeland ults	Suwannee	158	0.60	0.09	2.7	Houston et al. (1965)
Blanton (low) ults	Suwannee	196	0.80	0.12	7.4	Houston et al. (1965)
Blanton–Ortega–Penny ults/ents	Lafayette	140	0.75	0.07	5.1	Weatherspoon et al. (1998)

Note: Drainage, CEC, and pH are only for the first soil layer.

[a] 0.60 (well), 0.75 (somewhat excessive), 0.85 (excessive).

[b] Cation exchange capacity < 3.0 (extremely low), 3.1–5.0 (very low), 5.1–7.0 (low), 7.1–10.0 (medium).

2.2.1. Calibration of DSSAT crop models

The crop models used in this study included that of CROPGRO-bahiagrass, CROPGRO-bermudagrass (Rymph et al., 2004), CERES-maize (Ritchie et al., 1989), CERES-sorghum (Alagarswamy and Ritchie, 1991), CERES-millet (Singh et al., 1991), CERES-wheat, ryegrass, rye, and oats (Godwin et al., 1989). Tsuji et al. (1998) have cited at least 38 field validation studies involving these models throughout the world and results indicated that the models performed well after initial calibration. For example: Jagtap and Abamu (2003), Jagtap et al. (1999), Jagtap and Adeleye (1999a,b) reported high R^2 between simulated and observed corn yields when they adapted the CERES-maize model in West Africa; Macrobert and Savage (1998) found an $R^2 = 0.83$ between simulated and predicted wheat yields; Thornton et al. (1997) concluded that the CERES-millet model from DSSAT was adequate after calibration to predict yield abnormalities of millet; and see Folliard et al. (2004) for validation of the CERES-sorghum model. Rymph et al. (2004) have calibrated and validated CROPGRO-bahiagrass and bermudagrass for Florida conditions. From all these studies, we concluded that the crop simulation models used in this study have been successfully calibrated in earlier efforts, under a variety of circumstances, which give us confidence in our calibration procedures.

Simulation models have to be tested against field data, and if need be, calibrated to assure their validity. The DSSAT models were calibrated for forage crops used in this study using published field data. Cultivar coefficients were manipulated to match field data of biomass production without distinguishing between grain and forage. Specifically, the thermal time for emergence, the critical photoperiod to maximum development rate, the relative leaf size, the partitioning, and the phylochron interval were manipulated for corn, sorghum, and millet; and vernalization in addition for wheat (for more details see Cabrera, 2004). The calibration was similar for sorghum, corn, and winter forages using data from Woodard et al. (2002). For brevity, only the calibration for forage sorghum is described here. In Woodard et al. (2002) forage sorghum raised between early August and early November produced between 7 and 10 Mg ha^{-1} of dry matter and absorbed between 99 and 150 kg N ha^{-1}, under large N applications of manure effluents.

For corn forage, maize was utilized; for forage sorghum, grain sorghum; for pearl millet, grain millet; and for small grain winter forage, wheat. Since the main objective was to assess potential N leaching and there are no studies that deal with calibration or validation of DSSAT models on N leaching, biomass accumulation (which determines N uptake and N leaching) was used as the variable in the calibration process. Parameters of the CENTURY model used in the soil component cannot be manipulated in the DSSAT system as it is commonly done with the crop genetic parameters. Previous studies have demonstrated the validity of this assumption. Bowen et al. (1993) performed a study with maize under application of large amounts of N of green manures. They concluded that the N submodel of CERES-Maize realistically simulated N availability to succeeding maize. Consequently, N remaining in the soil and N leached can be estimated as function of N uptake by the crop. Saseendran et al. (2004) found, through a long-term simulation study, that N leaching and residual soil N can be measured as function of yield and N uptake in winter wheat crops. Gijsman et al. (2002) incorporated the CENTURY module to the DSSAT models and evaluated it with several crops using 40-year data. They concluded that the models simulated well the simultaneous processes occurring in the soil and in the crops; consequently, N leaching is a function of N residual in the soil, which depends on N uptake by the crop and its biomass accumulation. Previous studies such as Bowen et al., 1993; Saseendran et al., 2004; Gijsman et al., 2002 support the use of biomass N content of crops as a valid indicative of N leaching.

Irrigated fodder sorghum received two manure effluent applications every month containing 21, 29, or 38 kg N ha^{-1} each, for a total of 500, 690, and 910 kg N ha^{-1} yr^{-1} as detailed in the Woodard et al. (2002) study. The sorghum crop received 6 applications with a total of 132, 174, and 228 kg N ha^{-1}, respectively. A new cultivar called forage sorghum was created following the process of calibration.

Fig. 1 presents a comparison between simulated calibration and observed data for sorghum, corn, winter forage (Woodard et al., 2002), and millet (Fontaneli et al., 2001) indicating an acceptable verification based on the root mean square error (RMSE) of the simulated and observed data for each. In all the cases, the RMSE was lower than the SD of the observed data. Hunt and Boote (1998) indicate that good predictability of crop models occurs when the intercept is close to 0, the R^2 is high, and the slope is close to 1. Fig. 1 presents R^2 and slopes for all the evaluated crops calculated when the intercept was fixed to 0. All the R^2 were high and all slopes were very close to 1. Based on the graphs and data in Fig. 1, we concluded that crop models were appropriately simulating crop biomass, N uptake, and consequently N leaching. We recognize that predictions outside our calibration range may result into higher errors.

2.3. Simulation study

Forage systems were arranged in three growing seasons: spring–summer, summer–fall, and fall–winter as is common in North Florida dairy farm systems (Table 1). Eleven forage crops, four manure N incorporation ranges (10, 20, 40, and 80 kg ha^{-1} application^{-1}), and ten types of soils were simulated for 43 years of daily weather data (1956–1998). Residual organic matter from one crop to the next was accounted for as well as other management choices that are common in these systems such as extra irrigation and harvest events.

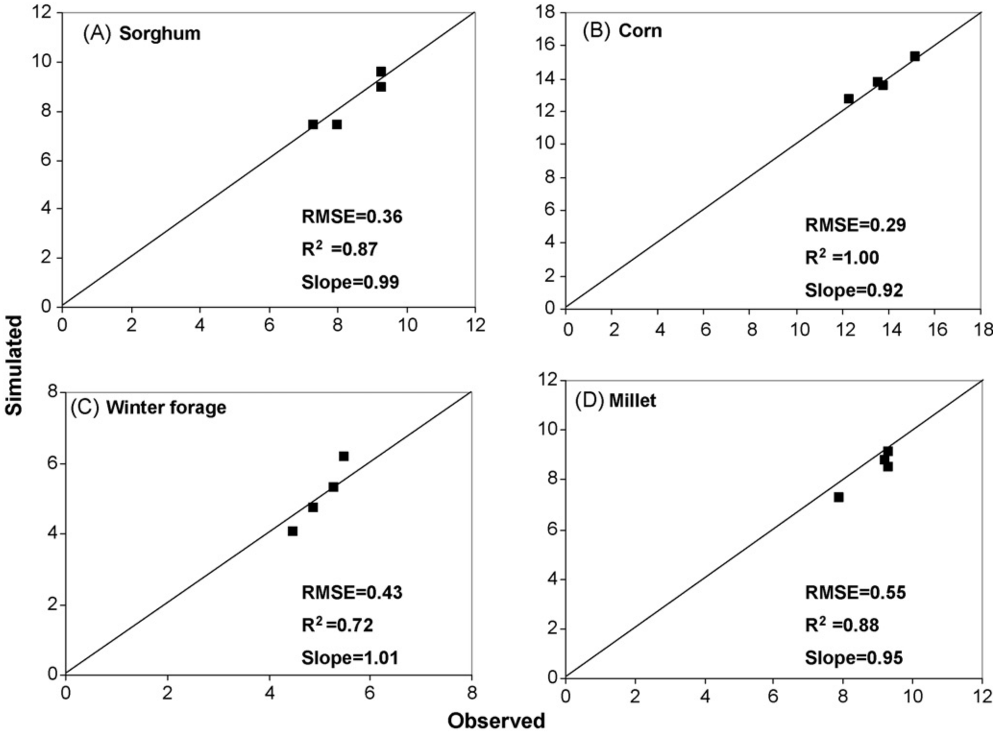

Fig. 1. Observed vs. simulated biomass for different forages. Bell, Gilchrist, Florida, 1996–1998: (A) Sorghum; (B) Corn; (C) Winter forage. And Gainesville, Florida, 1996–1997; (D) Millet. RMSE is overall root mean square errors.

3. Results

3.1. N leaching and forage system

Forage systems showed considerable variability in their ability to limit N leaching (Fig. 2). Changes in N leaching by ENSO phase and forage systems were not monotonic. For example, the corn–millet system had a greater N leaching range than millet–corn system when comparing El Niño with neutral years. However universally, there was a significantly greater likelihood of N leaching during an El Niño year than during a neutral and a La Niña year ($P < 0.01$).

Extreme amounts of N leached when 960 kg ha^{-1} yr^{-1} (80 kg ha^{-1} mo^{-1}) was applied. It ranged from a maximum

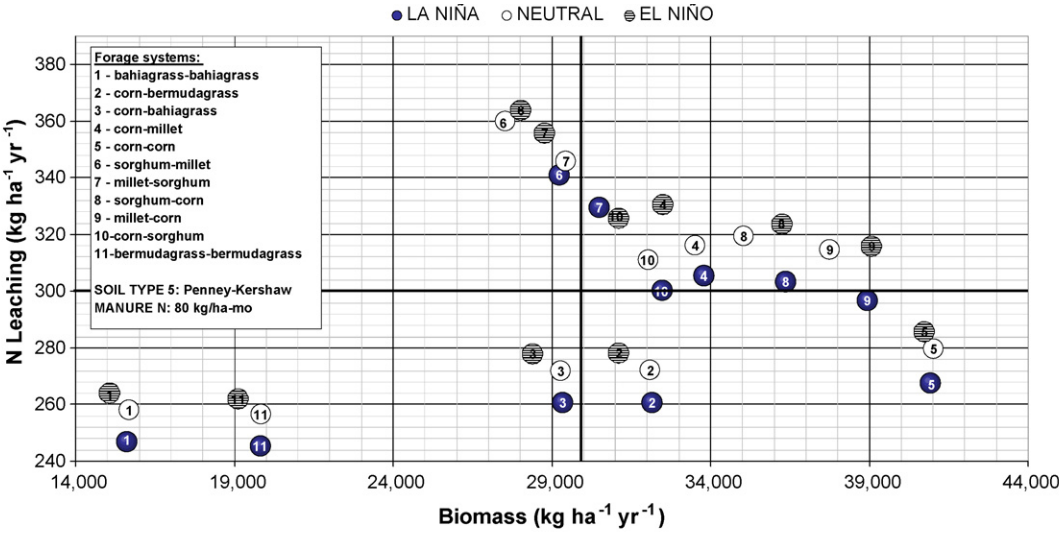

Fig. 2. Yearly N leaching and biomass accumulation for different ENSO phases (La Niña, neutral, and El Niño) when 80 kg ha^{-1} mo^{-1} is applied on different crops on soil type Penney-Kershaw. *Note*: Bold lines divide figure into four panels with respect to N leaching and biomass (kg ha^{-1} yr^{-1}) at: 300 N leaching and 30,000 biomass accumulated.

of 365 kg ha^{-1} yr^{-1} or 38% for an El Niño phase and sorghum–millet crop system to a minimum of 246 kg ha^{-1} yr^{-1} or 26% for a La Niña phase and full-season bermudagrass. Generally, cereal–cereal forage systems involving combinations of bahiagrass and bermudagrass were the most efficient, while crop–crop combinations were least efficient in reducing N leaching. The grass based systems (bermudagrass and bahiagrass) had the highest ratios of N uptake/biomass and the lowest percentage of N leached, while millet–corn, millet–sorghum, and sorghum–millet had the highest N leaching percentages. Higher N leaching occurred for El Niño phases and higher ratios of N uptake/biomass occurred in La Niña or neutral years.

3.2. N leaching and soil type

Nitrate leaching from a given forage system varied considerably depending on predominant soil type on dairy farms (Fig. 3). Variability in N leaching due to soil series differences was greater than the variability among the forage systems, indicating that the choice of a field for manure application is more important than forage crops. Nitrogen leaching (kg ha^{-1} yr^{-1}) from the corn–sorghum double crop ranged from 518 or 54% (El Niño phase, soils Millhopper–Bonneau) to 255 or 27% (La Niña phase, soils Arredondo–Jonesville-Lake). Differences between El Niño and La Niña phases varied from 65 (kg ha^{-1} yr^{-1}) on Otela–Jonesville–Seaboard soils to 23 (kg ha^{-1} yr^{-1}) on a Bonneau–Blanton–Eunola soils. Among soil series, forage combination of corn followed by sorghum in a field with the Millhopper–Bonneau soil is likely to leach the most and on Arredondo–Jonesville–Lake soil leach the least. However, there was interaction between soil type and ENSO phase regarding N leaching.

3.3. N leaching and seasonality

Excessive soil moisture content associated with seasonally high rainfall played an important role in N transport beyond the root zone leading to leaching as shown in Fig. 4. Fig. 4 also shows (A) mean monthly rainfall over 1956–1998 categorized by ENSO phase; (B) the simulated monthly biomass; and (C) the simulated monthly N leaching by ENSO phase from a corn–bahiagrass double crop. On a month by month basis, the amount of N leached was strongly related with the relative amount of rainfall and its variability by ENSO phase (e.g., in January higher N leaching and higher rainfall occurred in El Niño phases) except in February, when the highest N leaching was predicted for La Niña phases with the lowest rainfall amounts.

The highest predicted N leaching, however, did not coincide with the overall highest rainfall season. By comparing Graphs A and C, it can be noted that the rainy season (June through September) did not coincide with the highest N leaching amounts. This rainy season coincided with highest biomass accumulation (Graphs A and B). During December through February when higher amounts of N leaching and lower biomass accumulation occurred, the rainfall was rather low.

Monthly N leaching predictions indicated great variation among ENSO phases throughout the year and identified the critical period between December and February. The critical single month was January when N leaching was substantially higher than any other month ($P < 0.01$) representing 47% of the total in a year.

3.4. Combined analysis

Respecting the current forage system sequences in the study area (Table 1), the best options that leached the least N

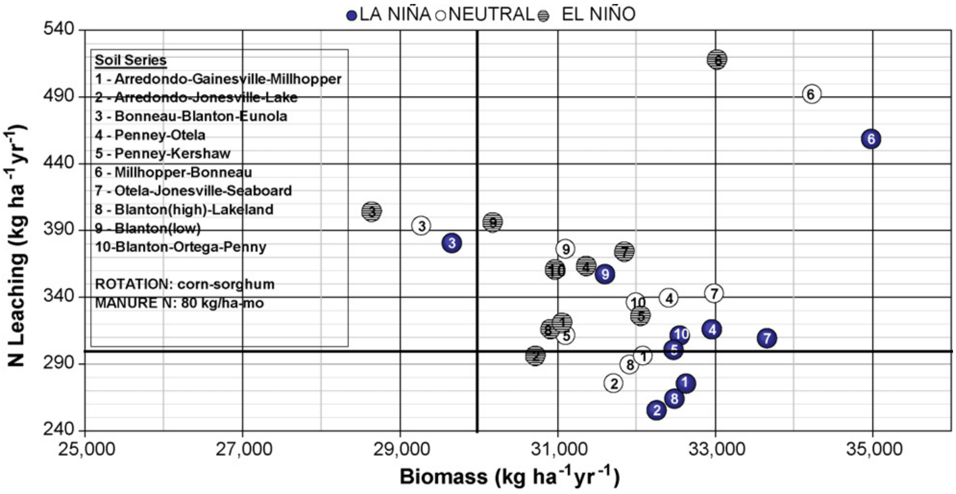

Fig. 3. Yearly N leaching and biomass accumulation for different ENSO phases (La Niña, neutral, El Niño) when 80 kg ha^{-1} mo^{-1} are applied for different soil types with corn–sorghum double crop. *Note*: Bold lines divide figure in four panels with respect to N leaching and biomass (kg ha^{-1} yr^{-1}) at: 300 N leaching and 30,000 biomass accumulated.

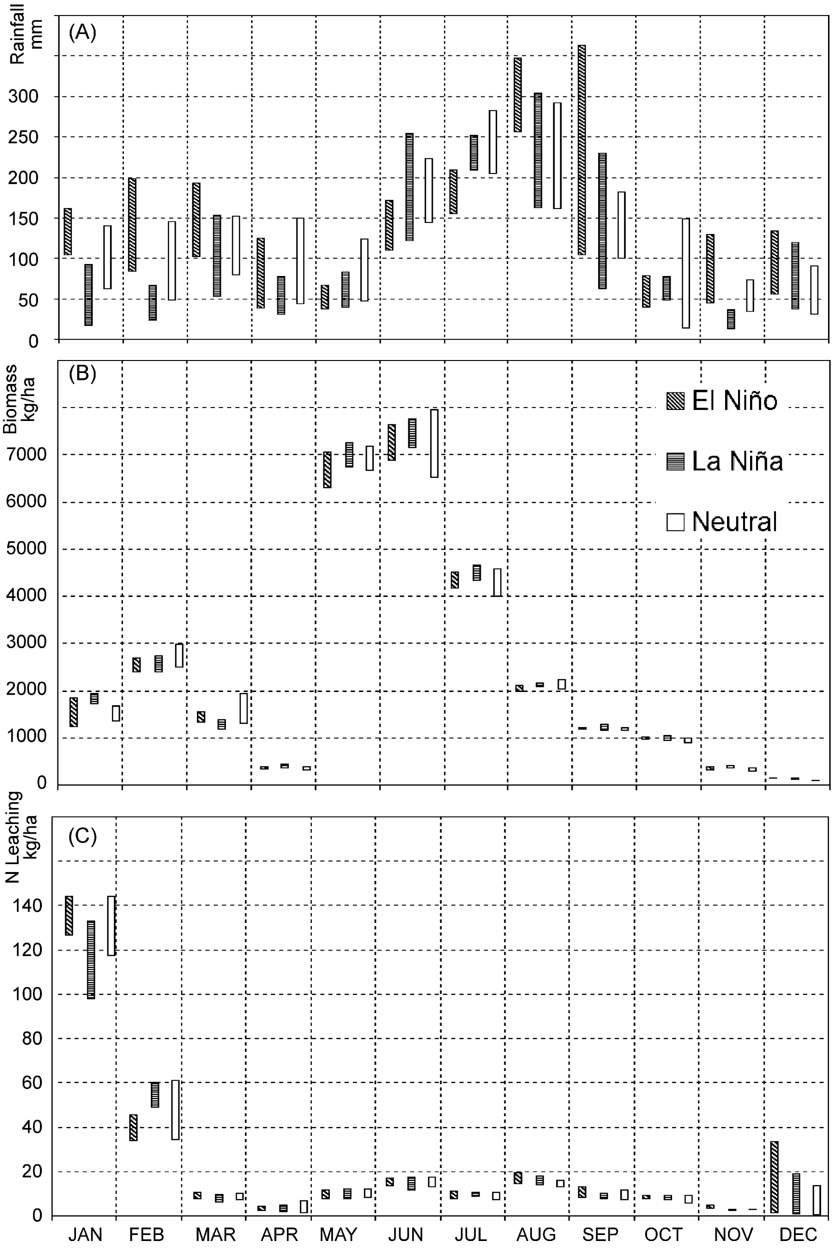

Fig. 4. (A) Monthly rainfall (mm) by ENSO phases in Levy Station (29.42N, 82.82W) for the period 1956–1998. *Source*: prepared with data from Mavromatis et al. (2002). (B) Monthly biomass accumulation (kg ha^{-1}) and (C) Monthly N leaching (kg ha^{-1}) by ENSO phases for a double crop consisting of corn–bahiagrass in soil type 5: Penney-Kershaw when applied 80 kg ha^{-1} mo^{-1} of manure N effluent. Range between 75 and 25 percentile in each distribution.

according to ENSO phase were selected. Analysis from all combinations of simulations involving ENSO phases, forage systems, soil types, and seasons were combined in Table 3 to identify the best forage systems that leach the least amount of N according to ENSO phase and soil type. Overall, the best forage systems to minimize N leaching were those that had in the spring (March–May) bermudagrass and in the summer (June–August) bermudagrass in El Niño years or full-season bermudagrass or bahiagrass in neutral or La Niña years. Table 3 also shows the expected N leaching and biomass yield for each tactical adjustment based on ENSO phase and soil type. Knowing the ENSO phase in early fall of one year (forecast that holds for a full year), farmers are able to make decisions on forages to be grown the next year in spring–summer and summer–fall, with the fall–winter crop always fixed to intercropping of ryegrass, rye, oats, and wheat. By using the tailored managements it is feasible to reduce N leaching to the target level of 10 mg L^{-1} or lower in four soil types in La Niña years and in three soil types in El Niño and neutral years; however, the exception was soil type Millhopper–Bunneau that always presented substantially higher N leaching levels. Even in this case, the recommended strategies would bring the N leaching levels below 15 mg L^{-1}, which is very close to the 10 mg L^{-1} target. Table 3 shows in addition the estimated N leaching with a sequence consisting of corn–sorghum (considered the

Table 3
Forage management strategy that produced the least N leaching (April–November) by ENSO phase and soil type (80 kg ha^{-1} mo^{-1} application) compared with common corn–sorghum

Soil Type	El Niño			Neutral			La Niña		
	Forage	N Leach	Biomass	Forage	N Leach	Biomass	Forage	N Leach	Biomass
Arredondo Gainesville Millhopper	Full-season bermudagrass	9.80, 22.02, −12.22	12,697, 24,399, −11,702	Full-season bermudagrass	8.22, 20.97, −12.75	12,420, 23,733, −11,313	Full-season bermudagrass	9.25, 19.80, −10.55	12,697, 24,399, −11,702
Arredondo Jonesville Lake	Full-season bermudagrass	8.01, 21.56, −13.55	12,611, 24,038, −11,427	Full-season bermudagrass	8.22, 20.45, −12.23	12,340, 23,378, −11,038	Full-season bermudagrass	7.60, 19.31, −11.71	12,165, 23, 12,142
Bonneau Blanton Eunola	Full-season bermudagrass	12.52, 32.57, −20.05	12,133, 22,008, −9,875	Full-season bermudagrass	10.44, 24.74, −14.30	12,883, 24,261, −11,378	Full-season bermudagrass	12.04, 28.24, −16.20	11,726, 21,048, −9,322
Penney Otela	Full-season bermudagrass	10.20, 26.05, −15.85	13,163, 24,935, −11,772	Full-season bermudagrass	10.44, 24.74, −14.30	12,883, 24,261, −11,378	Full-season bermudagrass	9.64, 23.33, −13.69	12,704, 23,906, −11,202
Penney Kershaw	Full-season bermudagrass	10.49, 25.45, −14.96	12,360, 23,712, −11,352	Full-season bermudagrass	11.06, 24.05, −12.99	10.1011, 23,055, −10,954	Full-season bermudagrass	10.10, 22.57, −12.47	11,936, 22,711, −10,775
Millhopper Bonneau	Full-season bermudagrass	22.26, 45.00, −22.74	14,211, 26,767, −12,556	Full-season bermudagrass	22.60, 43.90, −21.30	13,916, 26,066, −12,150	Full-season bermudagrass	20.96, 44.50, −23.54	13,270, 25,964, −12,694
Otela Jonesville Seaboard	Full-season bermudagrass	13.58, 26.99, −13.41	13,607, 25,631, −12,024	Full-season bermudagrass	13,6071, 26.06, −12.35	13,1, 24,947, −11,626	Full-season bermudagrass	12.77, 26.38, −13.61	13,133, 24,587, −11,454
Blanton (high) Lakeland	Full-season bermudagrass	8.30, 21.04, −12.74	12,791, 24,255, −11,464	Full-season bahiagrass	8.36, 19.86, −11.50	12,521, 23,591, −11,070	Full-season bahiagrass	7.80, 18.93, −11.13	12,349, 23,243, −10,894
Blanton (high) Lakeland	Full-season bermudagrass	8.30, 21.04, −12.74	12,791, 24,255, −11,464	Full-season bermudagrass	8.36, 19.86, −11.50	12,521, 23,591, −11,070	Full-season bermudagrass	7.80, 18.93, −11.13	12,349, 23,243, −10,894
Blanton (low)	Full-season bermudagrass	13.86, 30.45, −16.59	12,560, 23,298, −10,738	Full-season bahiagrass	14.36, 29.37, −15.01	7,843, 22,649, −14,806	Full-season bahiagrass	12.80, 28.01, −15.21	7,693, 22,309, −14,616
Blanton Ortega Penny	Full-season bermudagrass	14.12, 26.71, −12.59	12,963, 24,340, −11,377	Full-season bahiagrass	14.30, 25.90, −11.60	8,124, 23,675, −15,551	Full-season bahiagrass	12.86, 25.48, −12.62	7,970, 23,326, −15,356

Key:

Forage	N Leach	Biomass
Recommended Forage	1	4
	2	5
	3	6

1 = mg/L N leach by strategic forage
2 = mg/L N leach by corn-sorghum
3 = mg/L prevented to be leached
4 = kg yield by strategic forage
5 = kg yield corn-sorghum
6 = kg yield difference

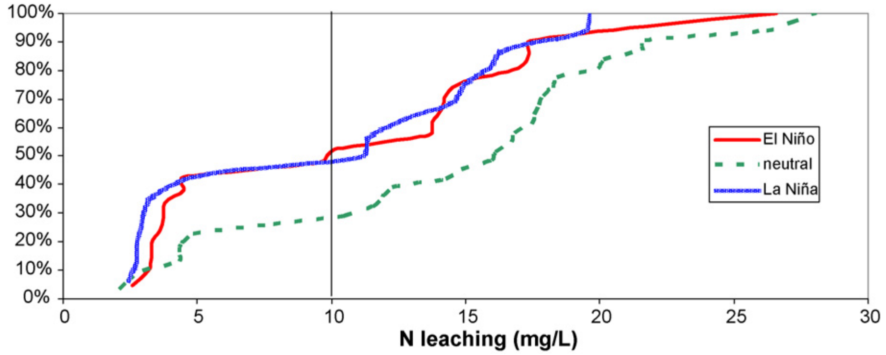

Fig. 5. Probability of N leaching to reach below 10 mg L^{-1} by ENSO phase with full-season bermudagrass (April–November) aggregated for all soil types and with an application of 80 kg N^{-1} ha^{-1}.

default or control forage sequence) against which we compare the tradeoffs of N leaching and biomass with any selected sequence. As seen in Table 3, N leaching is substantially reduced (in all cases by more than 10 mg L^{-1}) by using the recommended options, even though there would be a tradeoff of decreasing biomass production.

Knowing beforehand the potential consequences of manure N applications according to ENSO phase may help producers to plan ahead for extra caution as for example increasing the area farmed or collecting extra solids from the liquid manure during El Niño years when more N leaching is expected, even though the crop strategies would not change.

We also analyzed the probability to reach levels below the target of 10 mg L^{-1} of full-season bermudagrass, the crop that more efficiently controls N leaching across soil types. Fig. 5 indicates that such probability would be very similar for El Niño and La Niña years (close to 50%), whereas it would only be 29% for neutral years.

4. Discussion

Simulated patterns of both N leaching, their intra and inter annual variability, and biomass accumulation from this study are highly consistent with field studies performed in the same region by Woodard et al. (2003, Tables 5 and 6); Woodard et al. (2002, Figs. 5 and 6); and Macoon et al. (2002, Table 2). A high level of agreement exists between the simulations and the field experiments regarding: (a) amounts of dry matter accumulation of individual and yearly multiple crops; (b) seasonality of substantially higher amounts of N in the soil solution during winter; and (c) higher N removal and consequently less N leaching with grasses (bermudagrass and bahiagrass). Full-season bermudagrass had substantially higher ratios of kg N uptake/kg biomass than corn and sorghum, and the predicted percentage of N leached was substantially lower with full-season bermudagrass than with corn–sorghum.

Earlier field studies did not last more than a few years and based on them it is not possible to infer N leaching differences or strategies to reduce N leaching among ENSO phases. Having access to 43 years of weather data allowed us to simulate the effect of ENSO phases on the distribution of N leaching. By studying the outcomes of the simulations it is possible to infer management strategies that demonstrate the trade-off between N leaching and biomass production. Figs. 2 and 3 show four panels formed by arbitrary levels of N leaching and biomass at 300 and 3000 kg ha^{-1} yr^{-1}, respectively. A dairy farmer could use these to target a level of N leaching and based on it, know the corresponding forage yield

Currently popular full-season bahiagrass or full-season bermudagrass were also found to be the best systems for El Niño years for reducing N leaching. However, they would not be the best for neutral and La Niña years. Also, the corn–corn double crop currently used on a small proportion of land was found to be good for reducing N leaching for neutral and La Niña years, but not for El Niño years. Other important current double crops of corn–millet and bahiagrass–millet were found not to be good systems for N leaching reduction.

N leaching could be reduced greatly by selecting the right crops for a set of given conditions including seasonal climate forecasts. This analysis should be performed on an individual farm-by-farm basis.

Fig. 4C describes a common N cycle in North Florida dairy farm fields under constant high pressure of manure effluent applications. This common cycle would have some variants depending on crop and climate variations. A build-up of N in the soil starts in the winter (December–March) because effluent applied to the surface during the cooler months, convert to nitrate (anion) at slow rates, continues in the spring (March–April), when a new crop season begins. During the spring, dominant low precipitation conditions with medium temperature (Fig. 4A), a new crop with a high requirement of N, and a depletion of N during the previous winter create conditions for low N leaching. In summer, rapid plant growth (Fig. 4B) uses large amounts of N which decreases N leaching (Fig. 4C). In fall, there is less N uptake and a higher N build-up in the soil. In winter, low crop growth, low N uptake, and high amounts of N in the soil increase the amounts of N leaching. This soil N cycle is also impacted by inter annual climate variability represented by ENSO phases. In this study, sequential carryover of N from year-to-year was not considered, assuming that the dynamics of the soil have reached a steady state. We reinitialized the soil component for each year of simulation because we wanted to isolate the ENSO impact on N leaching and be able to draw recommendations based on yearly ENSO forecasts. It would be interesting to study the N cycle in the soil for a series of years, using continuous simulation, because that would be more in tune with the way dairy farms operate. Nitrogen in the soil does not disappear at the end of the year and it is carried to the next crop season. Consequently, N in the soil in a given year is affected from the previous year and affects the next year. Using sequential simulation for several years would give a good picture of N accumulation and leaching throughout continuous manure effluent applications, but it would diminish knowledge of the impact of ENSO on N leaching.

Another reason why higher N leaching is predicted for El Niño years is because during these phases there are fewer but heavier rainfall events than in neutral and La Niña years, which have softer more frequent rainfalls. In addition, temperature, that is lower for El Niño years, may increase N leaching because it promotes lower plant growth and consequently lower N uptake. An attempt to relate N leaching with the Japan Meteorological Index (JMA, 1991), sea surface measurements used to predict the El Niño Southern Oscillation phases, showed little or no correlation. This attempt was performed not only relating the same month JMA and N leaching, but testing different potential lag times (one to six months) of the N leaching with respect to the JMA.

Water holding capacity and depth of soils are believed to hold most of the causes for the differences observed. Shallow soils with very high permeability favor N leaching.

5. Conclusions

The use of crop simulations and classifying years according to ENSO phase was a viable approach in recognizing trends, interactions, and identifying absolute values of N leaching and biomass accumulation under different conditions of seasonal climate variation, manure N application, soil type, and forages grown. It would be impossible to design and conduct a field experiment of this magnitude.

Higher amounts of N leaching are expected during El Niño years and lower amounts during La Niña years. During winter, specifically between December and February more than 50% of annual N leaching occurs.

There is considerable interaction between soil types and N leaching. Soils that leach the most are those with characteristics of Millhopper, Bonneau, Eunola, Blanton and soils that leach the least are those with characteristics of Arredondo, Jonesville, Lake, and Lakeland.

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