The National Pilot Program Integrated Modeling System: Environmental Baseline Assumptions and Results for the APEX Model

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Philip W. Gassman

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Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070

Philip Gassman is an associate scientist, Resource and Environmental Policy Division, Center for Agricultural and Rural Development.

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ABSTRACT

This paper presents the underlying assumptions and results for the Agricultural Policy/Environmental eXtender (APEX) model, which was applied within an integrated modeling system for the National Policy Program (NPP) environmental baseline simulations for the Upper North Bosque River Watershed (UNBRW), located in Erath County, Texas. The integrated modeling system consists of an economic model that is linked to an environmental component comprising the field-scale APEX and watershed-scale Soil Water Assessment Tool (SWAT) models. The environmental baseline simulations test and calibrate the complete environmental component, using monitoring data obtained during 1993-94 in the UNBRW. The economic model was not executed for the environmental baseline, although underlying assumptions built into the economic model were used. The results are edge-of-field environmental indicators obtained from the APEX model.

THE NATIONAL PILOT PROGRAM INTEGRATED MODELING SYSTEM: ENVIRONMENTAL BASELINE ASSUMPTIONS AND RESULTS FOR THE APEX MODEL

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The "Livestock and the Environment: A National Pilot Project" (NPP) was initiated in the Upper North Bosque River Watershed (UNBRW) in Erath County, Texas, to help provide solutions to real and perceived environmental problems associated with the local dairy industry. The key environmental problems in the UNBRW have been identified as runoff of nitrogen (N) and phosphorous (P) from manure application fields and odor from feedlots, waste storage ponds, or during application of manure. The nutrient runoff is primarily from nonpoint source pollution while the odor tends to emanate more from point sources. The focus of the NPP is to develop strategies to help mitigate the nonpoint source pollution problems that can arise from application of dairy manure to waste disposal fields.

A major component of the NPP was the development of the Comprehensive Economic and Environmental Optimization Tool-Livestock Poultry (CEEOT-LP), that consists of a representative dairy farm economic model (economic model) linked to an environmental component comprising the Agricultural Policy/Environmental eXtender (APEX) model (Williams et al. 1995) and the Soil Water Assessment Tool (SWAT) model (Arnold et al. 1994). The system is designed to assess the economic and environmental impacts of proposed policies for the dairy industry in the UNBRW. Both edge-of-field and in-stream N and P environmental indicators can be evaluated with the environmental component.

The goal of the environmental baseline is to determine how well the environmental component performed in comparison with in-stream water quality monitoring data. Direct comparison with measured data was only possible for the SWAT model within the environmental baseline; no edge-of-field measurements were available for the fields simulated in APEX. However, the SWAT results are a function of the nutrient loadings from APEX, so the accuracy of SWAT in comparison with in-stream monitoring data is also an indirect indication of APEX accuracy. Also, comparisons of APEX output with measured data were previously performed by Flowers (1996) for eight test plots in or near the UNBRW. To the extent possible, the APEX assumptions and parameter modifications that were a product of these test runs were incorporated into the environmental baseline simulations.

The economic model was not directly linked to the environmental component for the environmental baseline, although underlying assumptions used in the economic model were incorporated in the analysis. The environmental models were configured to reflect as much as possible the actual cropping practices and total manure production during the time that the in-stream monitoring data were available (September 1993 to December 1994).[1] This report is limited to the assumptions and results pertaining to the APEX environmental baseline simulations.

The Integrated Modeling System

Figure 1 is a schematic of CEEOT-LP as configured for the NPP. The integrated system is initiated by describing a set of policy scenarios that cover a range of economic instruments and best management practices that could potentially be applied to the dairy industry in the UNBRW. Once the set of policy scenarios has been defined, the scenarios are executed individually within the economic model. The economic model is run in a static, short-term (one year) mode for three classes of dairies: (1) small, 0-249 head; (2) medium, 250-599 head; and (3) large 600+ head. Representative herd sizes of 225, 400, and 1,200 head are assumed for each of these three size classes in the economic model. Output from the economic model includes production costs, net returns, technology choice, cropping rotation, and the amount of N and P produced in the manure. A more detailed explanation of the economic model can be found in Osei et al. (1995).

The linkage between the economic model and the environmental component is accomplished by passing data generated for each policy scenario in the economic model directly to APEX. These data are the total N and P estimated to be produced per cow in the manure, the selected cropping system, and nutrient fractions that define the amount of organic and mineral N and P in the manure. The APEX field-level simulations are then performed using run_apex, an automatic input file builder and execution program that reads in soil layer, daily weather, management, and other data, creates the required input files, and executes APEX for selected waste application fields for each dairy. Two types of output files are generated for each APEX simulation: (1) the standard output file and (2) swatout.out files that contain flow, sediment, and nutrient loading output required to link APEX to SWAT. Selected indicators, such as annual amounts and long-term averages, are scanned from the standard output files providing information to evaluate the tradeoff between the edge-of-field environmental performance and the economic performance for the representative dairy farms. Similarly, the swatout.out files allow SWAT to estimate the long-term trends and averages regarding the in-stream water quality impacts of N and P loadings to the stream system for both the environmental baseline and subsequent policy analyses. They were also designed so that the in-stream N and P indicators could be simulated in SWAT for 1993-94 for the environmental baseline, allowing direct comparison with the monitoring data collected during that period.

The input layers to the SWAT model were constructed with an interface program that is executed within the GRASS (Geographic Resources Analysis Support System) Geographic Information System (GIS). These data include soil layer and map, land use, topography (digital elevation map), stream system, subsurface geology, reservoir and pond, and weather. Once the data layers were developed, the watershed was subdivided into a total of 150 smaller subbasins or micro-watersheds. The output from specific APEX runs representing all fields receiving liquid or solid dairy waste within a given micro-watershed were then aggregated into one swatout.out file and input at the outlet of that micro-watershed in SWAT. The N and P in solution and sediment-bound phases were then routed through the stream system in SWAT. Assessment of downstream impacts can be made at the outlet of the entire UNBRW located near Hico. Alternatively, analyses of in-stream water quality can be made at the outlet of any micro-watershed. The linkages between APEX and SWAT are discussed in more detail in Gassman and Hauck (1996).

Philosophy of APEX Applications for the NPP

The APEX model is designed to operate as a whole farm or farm watershed model. In this context, the model routes flow, sediment, and nutrients (and pesticides) in both the solution and sediment phases between fields on a farm and eventually to the mouth(s) of the farm watershed. Alternatively, nutrient routing can be performed in APEX for a small watershed that may transcend farm boundaries. For the NPP applications, APEX was run as a single-field rather than a whole-farm model for two reasons: (1) roughly 50 percent of the dairy manure application fields in the study area do not drain into adjacent fields and (2) the required effort to generate the information on how the remaining 50 percent of the fields drain to each other would have been prohibitive, given that very limited additional modeling accuracy would be expected. The multifield capabilities of APEX were used only for filter strip policy scenarios, where nutrient runoff (in water and on sediment) is simulated from a dairy manure application field across a filter strip.

Assumptions Unique to the Environmental Baseline

The majority of the assumptions used for the APEX simulations are also valid for the policy scenarios. However, there were three key assumptions that were unique to the environmental baseline: (1) the use of actual dairy herd sizes rather than permitted herd sizes; (2) the simulation of the actual crops that are stated in the permits or water quality management plans (for nonpermitted dairies), instead of the crops selected in the economic model; and (3) the length and structure of the daily historical temperature and precipitation data used to drive the APEX simulations.

The assumed total of manure produced in the watershed for the environmental baseline is calculated using actual herd sizes of the dairies whereas permitted herd sizes are used for the policy scenarios. Table 1 presents a distribution of actual and permitted herd sizes across the three dairy size classes in the watershed. The actual herd sizes shown in Table 1 are based both on a survey of the dairies that is described in Nelson et al. (1992) and on more recent surveys performed by the Texas Natural Resource Conservation Commission (TNRCC). Some of the actual herd sizes could not be obtained from these surveys so they were estimated from a typical ratio of actual milking herd size to permitted herd size. Also, some changes in ownership and operation have occurred on the dairies since the survey by Nelson et al. (1992) was taken. Most notable was the closure of a 6,000-head calf operation (equivalent to approximately 620 dairy cows) in mid-1995. To reflect this fact, the number of dairies was reduced from 95 to 94 in the permitted category. This allowed the calf operation manure loadings to be incorporated into the environmental baseline but prevented an overestimation of manure production for the policy scenarios that are designed to estimate future impacts.

The cropping systems that are simulated in the environmental baseline include coastal bermuda, coastal bermuda overseeded with winter wheat, winter wheat, sorghum hay, and sorghum hay-winter wheat rotation. These environmental baseline cropping systems cover most of the permitted fields in the watershed. However, some fields had to be recategorized into the five simulated cropping systems for the environmental baseline, as shown in Table 2. In most cases these fields were recategorized by similar crop types; representing alfalfa by coastal bermuda and peanuts by sorghum are probably the weakest assumptions. However, only four fields are affected by these latter two assumptions.

The crops categorized as coastal bermuda were further classified into two subcategories on the basis of crop productivity. This delineation was made to reflect the ability of the more productive coastal fields to better resist soil erosion, as opposed to the native pasture and hay grazer fields listed in Table 2 that are usually less productive. This was directly accounted for in APEX through the crop parameter denoted the "minimum C factor," used internally in the model when calculating water erosion estimates. Values of 0.002 and 0.004 were assumed for the higher and lower productive coastal bermuda crops as described in Flowers (1996).

The environmental baseline was executed for a 10-year period (1985-94) rather than the 30-year simulation period (1965-94) used for subsequent policy scenarios.[2] The shorter simulation length was used for the environmental baseline runs to reflect the actual time period of the establishment of large dairies in the UNBRW. A further enhancement was made to the APEX weather input by accounting for variation in precipitation patterns that occurred in the UNBRW for the final 16 months (September 1993 to December 1994) of the environmental baseline.[3] This was accomplished by mapping specific waste application fields to one of 19 different rain gauges, depending on which micro-watershed the field was located in. The methodology of linking the fields to the specific rain gauge precipitation data was consistent with the methodology used in SWAT and is described in further detail in the Soil and Weather Data Inputs section. The use of the specific rain gauge data provides the most accurate N and P runoff loadings possible to SWAT for the final 16 months of the environmental baseline, for which SWAT output was compared with available in-stream monitoring data as discussed in Rosenthal et al. (1997).

Tillage and Manure Application Assumptions

Management assumptions required for APEX involve the configuration of planting, tillage, manure and commercial fertilizer application, and harvesting passes for each simulation run. Fixed dates are assumed for each operation as a function of cropping system for both the solid and liquid manure simulations (i.e., no attempt is made to vary the dates due to weather), except for the liquid manure applications that were driven by a lagoon submodel and vary according to rainfall patterns. Table 3 lists the tillage, planting, and harvesting operations and dates assumed for each cropping system and manure type. These systems represent conventional tillage; no evidence exists that reduced- or no-till is practiced by dairy producers.

The timing and rates of manure application are a function of the cropping system and the personal preferences of the producer. Because of a lack of knowledge of individual producer practices, it was difficult to assess how much manure is applied and at exactly what time for a given manure disposal field. Thus, the simulated dates of the solid manure applications were based on recommended practices for the different cropping systems, to the extent possible. Table 4 shows the assumptions regarding the percentage of the total annual solid manure applications that were applied in a given month for each cropping system. The applications to coastal Bermuda are designed to coincide with the time of establishment or reemergence from dormancy in early April, and at the three harvests that occur in mid-June, August, and October (there are only two harvests in the first year, as shown in Table 3). Only two applications are made to coastal bermuda when overseeded with winter wheat, because there is one less simulated harvest of coastal Bermuda for this cropping system. Applications to sorghum and winter wheat occur just before planting.

Technically, solid manure applications should be incorporated when applied to fields that will be planted to row crops. However, this is not required in the regulations developed by the Texas Natural Resource Conservation Commission (TNRCC) if there is a suitable "buffer zone" around the waste disposal field. The assumption was made that such buffer zones existed for all dairy waste application fields planted to row crops. Therefore, all simulated solid manure applications were surface-applied in the environmental baseline.

Manure Application Rates

The best guidance available in setting the simulated manure application rates in APEX was to follow the assumptions used in the TNRCC permitting process. The initial step in this process was to calculate the total amount of N and P produced in fresh manure. Following that, nutrient losses from the feedlot and lagoon system were determined. Based on assumptions given in Barkemeyer and Henson (1990), it was assumed there would be N losses of 50 percent from the solid manure on feedlots and 20 percent from the liquid manure in the lagoon system (Table 5). This results in equivalent annual levels of N and P per cow of 125 and 54.5 lb in solid manure and 17.8 and 8.6 lb in liquid manure that are ultimately field-applied.

After accounting for losses on the feedlot and from the lagoon, the key step employed by the TNRCC in the permitting process is to ensure that the manure be applied at a high enough rate so that enough N is available to meet the demand of the assumed uptake capacity of the crops (the agronomic rate) shown in Table 6. Important assumptions embedded in this step (Table 4) as taken from NRCS (1990) are: (1) only 50 and 80 percent of the remaining N in the solid and liquid manure, respectively, is plant-available, and (2) 20 percent of the N that is in either surface-applied solid or liquid manure will be lost due to ammonia volatilization (no volatilization losses are assumed for incorporated solid manure applications). These assumptions imply that only 64 percent of the N in the liquid manure and 40 percent of the N in the solid manure will be readily available to the plant. Thus, the actual application rates of N in solid and liquid manure that are required to satisfy the N agronomic rates are 1.56 and 2.5 times greater than the crop agronomic rates, as shown in Table 7. Because the relative proportion of N to P is assumed to be constant in the manure, the resulting P application rates shown in Table 7 are also much higher than the P agronomic rates listed in Table 6.

In reality, the volatilization rates and PAN proportions will be dynamic, changing over time as a function of climate and other factors. However, these rules are a guide for producers in establishing manure application rates, because it is not possible for them to track the dynamic aspects of manure nutrient availability. It is also important to note that the permitting process assumptions actually apply to the application of manure to a field for the first time. Ideally, credit would be taken in subsequent years for mineralization of residual organic N from previous applications, which would reduce the per acre N application rates in manure (and P rates also) until an equilibrium is reached after several years (USDA

1978). There is a provision in the TNRCC regulations to require a producer to adjust application rates based on the nutrient content of the soil, should the levels of N and/or P become excessive. However, anecdotal evidence observed by those working with local dairy operations indicates that soil testing results are not commonly used to adjust the manure application rates.

Thus, it was assumed that the manure N and P amounts were applied in APEX at the rates shown in Table 7 in every year of each 10-year simulation for the environmental baseline. However, the simulation of volatilization and other soil nutrient processes is in fact dynamic in APEX, varying daily as a function of weather and management. Thus, while the 20 percent volatilization rate assumption (Table 5) was built into the application rates, the actual volatilization rates simulated by APEX varied markedly from this (see the results section).

The application rates shown in Table 7 and the underlying assumptions have been reviewed by NRCS and TNRCC personnel. Stanford (1996) and Donham (1996) stated that the NRCS has been working with some local dairy producers in the UNBRW to reduce the amount of P applied per acre, by applying the manure based on a P agronomic rate rather than the N-based rates shown in Table 7, and then supplementing the manure applications with mineral N in commercial fertilizer. However, so far only a limited number of producers have switched to applying their manure based on P. Overall, it is their observation that there is a mixture of practices occurring in the watershed, with the majority of producers applying their manure at rates similar to those listed in Table 7. Chasteen (1996) has also verified that the application assumptions used for the NPP are consistent with what is allowed in TNRCC dairy permits.

Manure Nutrient Fractions

For the NPP, coefficients had to be developed for the APEX fertilizer file that defined the dairy manure in terms of five nutrient constituents. These constituents are mineral N, mineral P, organic N, and organic P that add to 1.0 or 100 percent on a nutrient basis, plus an ammonium (NH_4) value that represents the fraction of the mineral N that is in ammonium form. Table 8 shows the nutrient constituents assumed for the dairy manure on a "nutrient basis"; the application rates shown in Table 7 would be directly entered into APEX when the fertilizer file coefficients are configured on a nutrient basis. The N coefficients assumed for the APEX simulations are based on an extensive literature review by Osei et al. (1995) As shown in Table 8, the majority of the N is organic for the solid manure while the opposite holds true for the liquid manure. Nearly all of the mineral N in both manure types is assumed to be ammonia. Further literature review revealed that only limited data are available for estimating the amount of P in dairy cow manure that is in mineral form (Table 9). Based on the values listed in Table 9, the assumption was made that 65 percent of the total P was in mineral form, a standard given by American Society of Agricultural Engineers (ASAE 1995) that fell within the range of estimates provided by the other studies.

The nutrient coefficients in Table 8 were converted into "manure-based" coefficients (Table 10) for the APEX simulations. The manure-based coefficients represent the fraction of the total manure applied that was made up of mineral N, mineral P, organic N, and organic P (ammonium again representing the fraction of mineral N that is in the ammonium form). Thus, using the manure-based coefficients shown in Table 10 requires that the total manure load be simulated rather than just the equivalent nutrient application rates. For example, a total solid manure load of almost 32,000 lb/ac (dry weight basis) would have to be applied on an annual basis to coastal bermuda to achieve the N and P application rates of 750 and 326 lb/ac given in Table 7. Simulation of the application of the total manure load allows for the additional organic matter that is contributed from the manure to be added to in the soil profile. This resulting build-up of organic matter is consistent with soil measurements in the UNBRW, where higher than normal soil organic matter levels have been observed for fields that have been used for several continuous years for dairy waste application.

The conversion of the nutrient coefficients into manure-based coefficients was performed with the calculation

$$manure\_coef = nutrient\_coef((N_{cow} + P_{cow}) / manure_{cow}), \qquad (1)$$

where manure_coef is the respective manure-based coefficient, nutrient_coef is the corresponding nutrient-based coefficient, N_{cow} and P_{cow} are the total N and P contributed by each cow per year to the application fields, and $manure_{cow}$ is the assumed amount of total manure that each cow produces annually on a dry weight basis. The values assumed for N_{cow} and P_{cow} are 125 and 54.4 lb in solid manure and 17.4 and 8.6 in liquid manure, as mentioned previously. The $manure_{cow}$ amount was assumed to be 5,331 lb., based on (ASAE) recommendations cited in MPS (1987) for a 1,400-lb. dairy cow.

Assumptions and Description of the Lagoon Submodel

The timing of liquid manure applications is driven in APEX by a lagoon submodel.[4] These applications occur at irregular intervals, because they are a function of daily washwater input and runoff from rainfall. The configuration of the APEX lagoon routine for the NPP simulations was based on a standard design of single-stage lagoons in the UNBRW, with some simplifications as shown in Figure 2.

Typically, single-stage lagoons in the area consist of five separate volume components, as shown in Figure 2.a: (1) accumulated solids, (2) wastewater, (3) additional capacity, (4) runoff volume for a 25-year/24-hour storm event, and (5) freeboard. In APEX, a simplified lagoon configuration is assumed that ignores the volume of accumulated solids and freeboard (Figure 2.b).

The sludge accumulation volume is a relatively minor volume component that does not greatly affect the overall lagoon water balance calculations. The freeboard is intended to provide an additional factor of safety if the effluent level in the lagoon should rise higher than the spillway depth. Overtopping of the lagoon will occur only if the effluent level exceeds the additional freeboard space. The implication of ignoring the freeboard in APEX is that overtopping of the lagoon will occur once the effluent level reaches the maximum volume depth, as shown in Figure 2.b (analogous to the spillway depth depicted in Figure 2.a). However, APEX simulation results have shown that overtopping rarely occurs.

The lagoon submodel requires inputs of the number of cows in the confined feedlot (dairy milking herd size), lagoon drainage area (ha), normal and maximum volumes (mm),[4] daily volume of washwater per cow (m^3), and daily manure loading per cow (kg). Calculations used to estimate the lagoon normal and maximum volumes required for APEX are based on standard NRCS lagoon design procedures that are a function of the required wastewater storage volume needed for the given dairy herd size and the storm water runoff from the lagoon drainage area.

The wastewater volume is designed to hold the washwater from a given dairy herd for a 24-day period. An average washwater input of 0.15 m^3/cow/day was input for each dairy, regardless of herd size, which is the average measured by Sweeten and Wolfe (1993) for 11 dairies in Erath County. The wastewater volume was thus calculated as

$$WV = (0.15)(24)(herd\_size)(0.1), \tag{2}$$

where WV is the wastewater volume in ha-mm, herd_size is the total number of cows in the dairy herd, and 0.1 is a conversion from m^3 to ha-mm.

Calculations of surface runoff to a lagoon are based on assumed runoff levels for the different components of a lagoon drainage area. Typically, a lagoon drainage area in the UNBRW includes the surface area of the lagoon, feedlot area, and an "in-between area" that consists of grassed waterways, berms, diversions, and other land features. For the NPP simulations, representative lagoon surface areas of 0.25, 0.6, and 0.9 ha are assumed for dairies categorized as small, medium, and large for the NPP simulations. The feedlot area is based on the cow density for each feedlot that, according to Stanford (1995), can range anywhere from 58 m^2 (600 ft^2) to 167 m^2 (1800 ft^2) per cow and does not follow any distinct pattern among different dairy sizes in the UNBRW. Stanford suggested that the most reasonable norm for cow density is a range of 74 to 93 m^2 (800-1000 ft^2); the midpoint value of 84 m^2 (900 ft^2) from this range was used for the APEX lagoon calculations. There is currently no consideration of in-between areas in APEX. The ability to factor in an additional in-between area was incorporated into run_apex using a simplified methodology. However, this option was not used for the NPP.

The 25-year/24-hour storm event design runoff depth for the Erath County area is 190.5 mm (7.5 in). The assumed runoff depth for the feedlot area is 160.3 mm (6.3 in), using a runoff curve number of 90. The design runoff depth for the lagoon surface area is 190.5 mm, since all the precipitation that falls on the lagoon will be captured by it. Therefore, the surface runoff volume is determined as

$$RF = (FA_{final})(160.3) + (SA)(190.5) \tag{3}$$

where RF is the surface runoff volume for a 25-year/24-hour storm event in ha-mm, FA is the feedlot area in ha, and SA is the assumed lagoon surface area in ha for a small, medium, or large dairy.

Following this step, the volume of the additional capacity (AC) is then estimated as 25 percent of the sum of the wastewater and surface runoff volumes. The normal and maximum volumes are then calculated as

$$NV = (AC + WV) / FA_{final} \tag{4}$$

$$MV = (AC + WV + RF) / FA_{final}, \tag{5}$$

where NV is the normal volume in mm and MV is the maximum volume in mm. The NV and MV values were converted into units of mm by dividing by the feedlot area, to satisfy the APEX input requirements. The NV and MV values are subsequently converted into units of m^3 internally in APEX.

The effluent level in the APEX lagoon routine is calculated on a daily basis, using a hydrologic balance of runoff and washwater inputs minus the estimated evaporation losses. An irrigation event is triggered when the lagoon effluent exceeds the normal (operating) volume depth, as shown in Figure 2.b. The depth of the applied effluent is a fixed amount that is computed at the start of each APEX run. A lagoon overtopping is reported in the APEX output if the lagoon effluent rises above the MV depth (Figure 2.b).

The timing of each irrigation from the lagoon, and the correspondingly applied N and P in the lagoon effluent, is driven by the daily accumulation of washwater plus the variable precipitation events. Nutrient dynamics are not simulated in the APEX lagoon routine; instead, the nutrient applications in the lagoon effluent are simulated according to the daily manure load per cow. The daily manure load per cow is computed for each dairy on a dry-weight basis by summing the annual manure production numbers and then dividing by 365 days (equivalent to roughly 6.6 kg per cow per day). This daily mass input is then converted in APEX into variable N and P concentrations in the lagoon irrigation effluent by using the coefficients in the fertilizer file (Table 10) and numerical techniques, where the concentration is a function of how many daily loadings have occurred since the last irrigation event. This allows the model to apply approximately the same annual liquid N and P application rates shown in Table 6 in every year of simulation.

Selection of Application Fields

A question related to nutrient application rates was determining to which fields the simulated manure rates would be applied for each dairy. Table 11 lists the characteristics for permitted liquid and solid manure disposal fields for four of the dairies in the UNBRW. These four dairies are exemplary of the other dairies in the watershed, in that there is a wide variation in total fields and total acres of various crops included in the permits. They also represent the majority of dairies in that most of the permits contain more crop acreage than is required to dispose of the manure, based on the N application rates listed in Table 7.

Again, due to uncertainty over individual producer practices, it was impossible to know exactly which fields a given producer would favor regarding manure disposal. Thus, anecdotal information was relied upon to establish the following rules for the field selection process for the simulated manure applications: (1) manure was applied to available "cash crop" fields first, such as sorghum, sorghum followed by winter wheat, winter wheat, and coastal bermuda overseeded with winter wheat; (2) any remaining manure after rule 1 was satisfied was applied to available coastal bermuda fields; (3) the selection process began with the first field at the top of the permitted field list for each dairy and proceeded down the list following the conventions of rules 1 and 2; (4) the acres of the final simulated field were reduced to the area necessary to dispose of the N in the manure, in situations when the total permitted acres of the field exceeded the acreage required for disposal; (5) additional listed permitted fields, beyond those necessary to receive manure at the assumed application rates, were excluded from the APEX simulations; and (6) additional acres were created for those dairies that did not have enough acres in their permitted field list to dispose of the manure N. Conditions invoking rule 6 were encountered for only a few dairies for the environmental baseline; it is possible that these dairies have additional permitted acres in another location that were not included in the permit information accessible to NPP researchers. An example of the field selection process is given in Appendix A for dairy 10 in Table 11.

An additional factor that was that taken into account for the field selection process was that some of the dairies have parts or all of manure application fields outside the watershed boundaries. A breakdown of those dairies with at least part of one liquid manure (liquid acres) or solid manure application field (solid acres) outside of the watershed boundary is given in Table 12. During the field selection process, the total manure load that could be disposed of on these "outside" acres was accounted for, if these additional acres were needed by the given dairy (prior to the creation of any new fields). However, dairy waste applications to such fields were not simulated in APEX, because the fields are outside of the UNBRW.

Soil and Weather Data Inputs

Soil Data

Soil data for the APEX simulations were obtained from the Map Unit Use File (MUUF) interactive computer program, described by Baumer et al. (1994). The MUUF program consists of both the Soils-5 and MUUF soil databases. The Soils-5 database can be searched by state or Soils-5 name while the MUUF database can be searched by soil map unit (also referred to as the SURRGO unit). The soil layer data required for the NPP were selected from the MUUF soil database. This allowed for the soil layer data to be linked to the dairy waste application fields on the basis of soil map units. The soil layer data were generated in the MUUF program using the EPIC model format option, the same format required for APEX. The data were organized into a single soil layer data file in order to facilitate the construction and execution of input data sets within run_apex.

Some problems were encountered with the MUUF soil layer data. First, there were 23 soils for which bad textural data were generated for the lowest layer. These lower layers were subsequently deleted from the soil layer database. One implication of this step was the potential for overpredicting nutrient leaching, due to the shallower profiles used for these 23 soils. Second, some soil types are defined in MUUF as complex soils; that is, consisting of more than one soil. For example, a purves-dugout (Pd) soil is defined as 37 percent purves, 25 percent dugout, and 38 percent "other material" (other material being our terminology; no data or description are provided for the remaining 38 percent). It was assumed for the APEX simulations that the first soil encountered with a given map unit would represent all the components of a complex soil. For the Pd example, purves was the first soil selected because it was the first component listed in the soil layer data file. This selection methodology nearly always resulted in selecting the soil component that made up the greatest amount of each complex soil. However, a different strategy such as executing all components within APEX and then determining the average values across all the outputs would have produced different results.

Area-weighted average soil slopes and slope lengths were used in the APEX simulations for all acres of each soil type that exist in the known manure application fields in the UNBRW (Table 13). The area-weighted average values were obtained with tools available in the GRASS GIS package. The slope values were used in both the computing of runoff and water erosion in APEX while the slope lengths were only used for estimating water erosion. Water erosion estimates were made with the MUSS or small watershed MUSLE (modified USLE) option in APEX.

Weather Data

Daily weather inputs to APEX include precipitation (mm), maximum and minimum temperature (°C), wind speed (m/s), and solar radiation (langleys or MJ/m^2). These weather inputs can be read either from historical data or generated internally in the model, or a combination of both. Even if historical data are available for all six weather inputs, a weather generator file is still required because of various stochastic processes that are simulated in the model.

Two different types of historical daily weather data sets were constructed for the NPP APEX simulations. First, a 30-year historical data file of daily precipitation and maximum and minimum temperatures was constructed for the APEX policy scenario simulations. This file consists of data from Dublin, Texas, for 1965-90 followed by four years of data (1991-94) from Stephenville, Texas, both of which are located in the UNBRW. The majority of the data were obtained from Dublin records due to inconsistencies in the Stephenville data over the same period. However, Dublin data were not available past 1990 so the four years of Stephenville data were spliced on to the end of the Dublin record to ensure that historical precipitation and temperature data were input to APEX for the period during which surface water monitoring data were collected.

Second, 19 separate 10-year historical weather data sets were constructed for the environmental baseline simulation from the last 10 years of the 30-year file (1985-94). Identical precipitation data were inserted in these files, for December 1985 to August 1993, from the original 30-year weather record. Then, the specific precipitation data recorded at each of the 19 different rain gauges mentioned previously was inserted into the final 16 months of the corresponding 10-year weather file. The maximum and minimum temperature data from the last 10 years of the 30-year file was inserted in all 19 of the 10-year weather files.

A weather generator table was also constructed for the APEX simulations, as shown in Table 14. The temperature and precipitation variables in Table 14 were obtained by inputting 30 years of Dublin weather records (1961-90) into WXPARM, an auxiliary program to APEX that computes monthly weather statistics from long-term daily weather records for the APEX weather generator. Because monthly solar radiation and relative humidity values were not available for either Dublin or Stephenville, existing values were inserted from an APEX weather generator table developed for Waco, Texas, located approximately 80 miles to the southeast of Stephenville.

A wind array of monthly average wind speeds and directions is also required when executing APEX if wind erosion is simulated and/or the Penman-Monteith evapotranspiration option is used. For the environmental baseline and policy scenario simulations, a previously constructed wind array for Bosque County (located to the south of Erath County) was used in the absence of any available data for the immediate area (Table 15). These wind data inputs were used only for the Penman-Monteith evapotranspiration estimations, because wind erosion was not simulated for the environmental baseline or policy simulations.

Runoff Curve Numbers

Runoff volume is calculated in APEX by using a modified version of the SCS (Soil Conservation Service, now the Natural Resources Conservation Service or NRCS) runoff curve number method (Mockus 1971b). The curve number method partitions rainfall between surface runoff and infiltration into the soil profile with runoff curve numbers that are a function of soil hydrologic group, hydrologic condition (good, fair, or poor), and crop type. The curve numbers are initially assumed to represent a 5 percent slope in APEX, and then are further adjusted according to inputted slope information. Initial calibration of the APEX hydrologic routine, consisting mainly of adjusting the runoff curve numbers within acceptable ranges, was performed by Flowers (1996) for eight sites in or near the UNBRW. The calibrated curve numbers did not reflect any pattern across soil hydrologic groups and crop types. This lack of a clear trend led to the decision to use the standard curve numbers given in Mockus (1971a) for each crop category as listed in Table 16.

The APEX Edge-of-Field Environmental Baseline Results

The APEX edge-of-field results for the environmental baseline are presented in two parts. First, the time profiles of key environmental indicators representing the outcomes of each indicator over the 10-year period are described. Second, a statistical summary of various environmental indicators for alternative cropping and management systems are given.

management assumptions, and were also influenced by soil, landscape, and cropping pattern distributions across the waste application fields.

Losses of N via surface runoff, subsurface flow and percolation, and crop uptake of N, are assumed to be in the mineral N form of nitrate (NO_3) in APEX. It is also assumed that NO_3 is directly produced via N mineralization from organic N and nitrification from ammonia (NH_3), ignoring any intermediary steps. Volatilization is simulated as atmospheric loss of NH_3 from the available NH_3 soil pool, while denitrification represents the conversion of NO_3 to N_2 gas. Crop uptake and surface runoff losses of P are in the labile form. Mineralization of P from organic P can result in additions to either the liable P pool or active mineral P pool.

Hydrologic Indicators

The trend of total average annual rainfall (mm) in the study area is shown in Figure 3 for the 1985-94 simulation period. The average annual rainfall for this period ranged from 930 to 949 mm, depending on the location of a given simulated field within the UNBRW. These precipitation levels are considerably higher than the 1965-94 average of 738 mm and the long-term historical average cited in McFarland and Hauck (1995) of 760 mm. This was especially true for the last five years that included the 1,300 mm that fell in 1991, the greatest amount of any year during the simulation period. These rainfall trends impact the results of several of the other APEX indicators, as revealed in the time profile plots.

Plots of surface runoff, percolation, subsurface flow, soil erosion (from water), and irrigation volume are shown in Figures 4 through 16. Upward trends toward the end of the simulated period are discernible for a majority of the plots, reflecting the higher precipitation amounts that fell in the last five years. Peak levels were predicted in 1991 for most of these indicators. Surface runoff was very similar between the liquid and solid fields (Figure 4), indicating that most of the irrigation water infiltrated the soil. This is confirmed by Figures 5 and 6, which show that the simulated percolation and subsurface flows were much higher for the liquid fields compared with the solid fields.

Crop Yield and Crop Nutrient Uptake

Estimated average annual crop yields and nutrient uptake rates are plotted in Figures 9 to 14 and 15 to 28. Increasing yields and crop nutrient uptake rates across the 10-year period are shown for most crops grown on the solid manure fields. These trends were a function of both higher rainfall in the last five years and increasing levels of mineral N (nitrate) availability, as shown in Figure 33. The predicted yields of the crops grown on the liquid manure fields held roughly constant or even declined over the simulated timeframe. Uptake of N and P by the liquid manure field crops showed similar trends.

Table 17 shows the total number of fields, 10-year APEX estimated yields, the corresponding "target yields," and the percentage differences between the predicted and the target yields. Of the 230 fields simulated, 80 percent were cropped with continuous coastal bermuda or coastal bermuda overseeded with winter wheat; relatively few fields were simulated as continuous sorghum or continuous wheat. The target yields given in Table 17 are the assumed yield levels in the economic model for the cropping systems simulated in the environmental baseline. These yields are not measured yields but rather typical or expected yields. The continuous cropping system target yields are based on yield goals for the agronomic rates listed in Table 6 (as described in NRCS 1991). The coastal bermuda and winter wheat target yields were assumed to be 25 percent lower when coastal bermuda was overseeded with winter wheat, which reflects typical observed yield impacts such as reported by Chasteen et al. (1994) and Sanderson and Jones (1996).

Of the 14 simulated cropping system average yields, 10 were within 20 percent or less of the corresponding target yield. The most extreme differences occurred for winter wheat within the continuous and sorghum-winter wheat cropping systems, where the estimated average winter wheat yields ranged from 24 to 53 percent below the target yields. The limited number of simulations performed for continuous winter wheat does not appear to be a factor in the lower predicted yields; execution of a larger simulation set for continuous winter wheat covering a broader range of soil types resulted in similar overall estimated average yields. The average winter wheat yields estimated for the coastal-winter wheat system probably benefited from the fact that true overseeding could not be simulated in APEX for this study; i.e., the coastal bermuda had to be killed when the winter wheat was planted and re-planted in the spring following winter wheat harvest. Thus, future simulations with enhanced versions of APEX may predict lower winter wheat yields for this system.[5] The sorghum and winter wheat yields simulated for the liquid manure fields were consistently higher than those estimated for the solid manure applications, regardless of cropping system, which conformed to expectations.

Equivalent target yields of 14.8 t/ha were assumed in the economic model for continuous coastal bermuda grown on both the solid and liquid manure fields. Similarly, the same target yield of 11.9 t/ha was assumed for coastal bermuda simulated under both manure types within the coastal bermuda-winter wheat cropping system. These target yields were based on an assumed N agronomic rate of 336 kg/ha, regardless of the applied manure type and crop rotation, following a review of UNBRW dairy waste management plans and input from local experts. This rate is normally assumed to be adequate for three cuttings of coastal bermuda, although coastal bermuda cuttings were not simulated in the economic model. Further discussion with local experts resulted in a consensus that an extra cutting can typically be obtained from irrigated coastal bermuda fields relative to coastal bermuda grown on solid manure waste disposal fields in the UNBRW.[6] Anecdotal information also suggests that higher annual yields are often obtained from the irrigated coastal bermuda yields as compared to the coastal bermuda harvested from the solid manure fields. Thus in APEX, four and three cuttings (following the first year) were simulated for continuous coastal bermuda grown on the liquid and solid manure fields, and three and two cuttings were simulated for coastal bermuda within the corresponding coastal bermuda-winter wheat cropping systems, for fixed dates representative of usual harvest periods (Table 3). The APEX nutrient application rates, however, were assumed to be the same rates as those used in the economic model, as listed in Table 7.

As shown in Table 17, the predicted yields for coastal bermuda grown on the solid manure fields were greater than the irrigated coastal bermuda yields for both cropping systems. This was especially true for continuous coastal bermuda, for which the predicted average annual irrigated yields were 1.6 t/ha less than the corresponding solid manure field coastal bermuda yields. The continuous coastal bermuda yields were several t/ha higher than counterpart yields estimated within the simulated coastal bermuda-winter wheat cropping systems, a result consistent with the assumed target yields for the coastal bermuda-winter wheat system.

The most probable explanation for the lower coastal bermuda yields predicted for the irrigated fields was a lack of adjustment in N application rates as a function of the number of cuttings. The standard N agronomic rate recommended for four cuttings of coastal bermuda is 448 kg/ha N per acre, 112 kg more than the 336 kg/ha N listed in Table 6 (for three cuttings). Likewise, the recommended agronomic rate for coastal bermuda-winter wheat is 403 kg/ha N when the coastal bermuda is cut twice, that is 112 kg/ha less than the corresponding rate listed in Table 6. These agronomic rates translate to total N applications of 700 kg/ha for irrigated continuous coastal bermuda and 1,008 kg/ha when coastal bermuda was overseeded by winter wheat for the solid manure fields, when the plant available N portions and N volatilization losses are accounted for (see Table 5), as compared to the actual simulated total N rates of 525 and 1,288 kg/ha listed for these two manure type-cropping system combinations in Table 7. Similar adjustments must also be made for the P rates.

Subsequent 10- and 30-year sensitivity runs of the environmental baseline were performed to determine the effect of the application rate adjustments upon the predicted coastal bermuda yields. Additional 10- and 30-year environmental baseline runs were also executed to assess the impact of variation in cutting date upon coastal bermuda yield, by using an APEX option called "heat unit scheduling". The heat unit scheduling option requires inputting a value between 0 and 1 for HUSC, which is defined in APEX as the fraction of the crop maturity that the harvest should be completed by. The fraction of the crop maturity on any given day is defined by Mitchell et al. (1996) as: "The number of heat units that have accumulated from planting until that day, divided by the total number of heat units required for crop maturity." The additional runs of the 10- and 30-year environmental baseline that incorporated heat unit scheduling were executed assuming an HUSC value of 0.5 for each cutting of coastal bermuda, allowing the model to adjust the individual coastal bermuda harvests according to the accumulated heat units rather than using the original fixed harvest dates.[7]

Seven additional environmental baseline simulations were performed by incorporating variation in simulation length, the previously described nutrient application rate adjustments, and/or adjustment of coastal bermuda harvest dates using heat unit scheduling (Table 18). The upward adjustment of applied N to the continuous irrigated coastal bermuda fields resulted in an annual average yield of 15.6 t/ha over 10 years, a 2 t/ha increase over the standard environmental baseline and a higher average yield than that predicted for the coastal bermuda grown under application of solid manure. Predicted solid manure field coastal bermuda and winter wheat yields decreased on average by 0.6 and 0.4 t/ha over 10 years in response to the downward adjustment of applied N for the coastal manure-winter wheat cropping system. Incorporation of heat unit scheduling resulted in coastal bermuda yield increases of 2.4 t/ha for irrigated continuous coastal bermuda and 4.7 t/ha when coastal bermuda was overseeded by winter wheat on the liquid manure fields. However, the predicted wheat yields declined within the irrigated coastal bermuda-winter wheat cropping system by 1.6 t/ha. Predicted yield impacts for the corresponding crops simulated on the solid manure fields were relatively small or nonexistent. The average annual liquid manure field continuous coastal bermuda yield was predicted to increase even more dramatically to 18.2 t/ha when the adjusted application rates were simulated in combination with heat unit scheduling. However, no additional yield impact was predicted when coastal bermuda was overseeded with winter wheat on the solid manure fields for this scenario.

Similar trends were predicted for the same scenarios when simulated for a 30-year time period. However, a key difference was that the continuous coastal bermuda grown on the solid manure fields was predicted on average to outyield counterpart irrigated yields, except when the adjusted nutrient application rates were simulated in tandem with heat unit scheduling. Virtually all of the estimated average annual yields were lower than those predicted for the 10-year timeframe, except for the solid manure continuous coastal bermuda fields, a reflection primarily of differences in precipitation inputs across the two time periods. The higher solid manure field continuous coastal bermuda yields reveal the effects of steadily increasing levels of plant available N in the soil profile, which mineralized from the large amounts of annually applied organic N.

The continuous coastal bermuda yields predicted for the solid manure field 30-year simulations exceed the Table 17 target levels on average by roughly 2 t/ha for each scenario. The target yield exceedance was even greater for both the 10- and 30-year irrigated continuous coastal bermuda scenarios, that included both the updated nutrient applications and heat unit scheduling. Wilkinson and Langdale (1974) developed a coastal bermuda yield response curve to fertilizer N inputs based on data reported from 12 separate studies performed mainly in the southeastern U.S. Yields responded linearly to N applications up to 672 kg/ha, reaching approximately 22 t/ha when 672 kg/ha N was applied. Maximum yields of roughly 30 t/ha were estimated in response to fertilizer N inputs of about 1,344 kg/ha. Annual coastal bermuda yields greater than 20 t/ha have been measured in the UNBRW (Chasteen et al. 1994); however, it is unclear whether yields exceeding standard target yields can be maintained long term. It is probable that APEX gave too much yield credit for high levels of plant available N in the soil profile, based on the yield estimates for the solid manure continuous coastal bermuda scenario scenarios shown in Tables 17 and 18. Test runs for a single irrigated continuous coastal bermuda scenario confirmed this trend, with predicted yields exceeding 28 t/ha in response to additional mineral N inputs of up to 600 kg/ha. This over-response to mineral N was verified by Williams (1997) and has since been corrected.

Changes in environmental impacts also occur when the updated rates and/or heat unit scheduling are incorporated within the 10-year environmental baseline. Table 19 lists 10-year average annual average edge-of-field levels predicted for five key APEX indicators, which are the nutrient loadings ultimately routed through SWAT. Incorporation of the updated application rates resulted in estimated reductions of 0.2 to 1.9 kg/ha for the coastal bermuda-winter wheat solid manure fields, depending on the indicator. Conversely, the higher N application rates simulated for the irrigated continuous coastal bermuda under the "updated rates" scenario led to increases of 0.1 to 2.1 kg/ha across the five indicators, offsetting at least in part the decreases predicted for the coastal bermuda-winter wheat solid manure fields. Additional predicted impacts on the five indicators were mostly minor when heat unit scheduling was simulated in conjunction with the updated application rates; the largest changes occurred for the predicted N loss in subsurface flow and P loss in sediment for the irrigated coastal bermuda-winter wheat.[8]

Overall, the incorporation of heat unit scheduling produced mixed results. Irrigated coastal bermuda yields increased to levels that were greater relative to the solid manure field coastal bermuda yields for both cropping systems, but this increase resulted in suppressed winter wheat yields when winter wheat was overseeded on coastal bermuda for the liquid manure fields. Inclusion of the updated nutrient application rates resulted in more realistic yield estimates; future analyses with APEX for the UNBRW should incorporate these updated rates. Shifts in environmental indicators also obviously occur when the updated rates and/or heat unit scheduling is simulated. However, the estimated yields given in Table 17 and the associated environmental impacts are satisfactory, especially within the context that the SWAT environmental baseline nutrient loading estimates are in reasonable agreement with in-stream monitoring levels as reported by Rosenthal et al. (1997). Further testing and refinement of the APEX crop growth submodule is recommended, however, especially for the continuous winter wheat yield estimates.

Nitrogen Indicators

Figures 29 to 37 compare liquid and solid fields for different N indicators. Estimated average annual organic N loss on sediment was higher from solid fields than liquid fields (Figure 29). However, average nitrate N losses in surface runoff were always predicted to be higher from the liquid fields (Figure 30). The highest annual losses for both indicators coincided generally with the highest erosion and runoff years, with the peak amount occurring for both indicators in the highest rainfall year of 1991. Average annual losses of N in subsurface flow and percolation (Figures 31 and 32) were higher from the liquid fields in almost every year, except for the predicted percolation amounts in 1993 and 1994. A trend of increasing N losses via subsurface flow is discernible for both the liquid and solid fields in Figure 31. The same is true for the simulated solid field N percolation losses shown in Figure 32. The predicted N percolation losses for the liquid fields reflect more of a response to yearly variation in rainfall and percolation rates rather than a trend in increasing losses.

Figure 33 contrasts the average annual mineralization trends between the liquid and solid fields. A roughly constant average mineralization rate of 200 kg/ha was predicted for the liquid manure disposal fields, as opposed to an increasing mineralization rate simulated for the solid fields that reached an average of 600 kg/ha by the end of the 10-year period. These differences underscore the fact that the majority of the N applied in the solid manure was in an organic form versus the mostly mineral composition of the applied N in liquid manure. Similar trends were also predicted for denitrification (Figure 34) and total nitrate in the soil profile (Figure 37). The loss of N to the atmosphere via denitrification (Figure 24) steadily increased over time for the solid fields, reaching an average maximum of almost 100 kg/ha at the end of the simulations. The predicted average annual denitrification rate was more constant, averaging roughly 40 kg/ha for the majority of time period. Following a sharp decline in the first year, the average soil N was predicted to steadily increase for the solid fields up to approximately 50 kg/ha by 1994 (Figure 37). In contrast, soil profile nitrate held constant for the liquid fields around an average of 20 kg/ha, following the first year. Both the denitrification and soil profile nitrate trends reveal the effects of mineral N becoming more available over time to the solid manure field cropping systems versus the liquid manure scenarios.

Dramatic differences were predicted for the average annual nitrification and volatilization rates, with the liquid field rates exceeding the solid field rates by nearly a factor of 10 (Figures 35 and 36). Ammonia volatilization was by far the major N loss pathway for the liquid manure fields, exceeding on average 250 kg/ha per year. The volatilized NH_3 amount was consistently predicted by APEX to be in a range of 45 to 53 percent of the applied NH_4 across all cropping system-manure type combinations[11]. This range compares favorably with many of the ammonia volatilization studies available in the literature (Table 20). However, the percentage of total applied N that was predicted to volatilize as NH_3 was approximately 40 percent for liquid manure versus only about 3 percent for solid manure. This radical difference highlights the N composition assumptions made for dairy cow manure (Tables 8 and 10). Nearly 100 percent of the mineral N is assumed to be NH_4 for both manure types, but only 7 percent of total applied N is assumed to be in mineral form for the solid manure as opposed to nearly 85 percent for the liquid manure. Most of the studies referenced in Table 20 were based on cattle or dairy cattle manure slurry with NH_4 contents ranging from 23 to 70 percent of the total N, values that fall between the levels assumed for the two manure types simulated in this study. Thus the levels of volatilized NH_3 simulated by APEX tend to bracket the reported levels in Table 20, as a percentage of the total applied N.

According to Williams (1996), the ammonia volatilization routine is a relatively untested component of the current version of APEX. Thus, the wide range predicted in volatilization rates between liquid and solid manure could be extreme. The simplified mineralization and nitrification steps simulated in APEX ignore several intermediary steps, described by Pierzynki et al. (1994) and Juergens-Gschwind (1989) as : (1) transformation of the organic N to NH_3, (2) mineralization of the NH_3 to NH_4, and (3) conversion of the NH_4 to nitrite and finally NO_3 via nitrification. Nitrification is represented in APEX as a direct conversion from NH_3 to nitrate, but this step is not included in the mineralization calculation. Instead, mineralization is assumed to occur directly in APEX from the fresh and stable organic nitrogen pools to nitrate. Pierzynki et al. state that nitrification is a rapid process in most soils, so this assumption may be reasonable for many conditions. Furthermore, Williams (1997) cites discussions with other researchers that support the assumption that conversion of organic N to NH_3 also takes place relatively quickly. Thus, the exclusion of this step in APEX may again be reasonable. However, it is possible that APEX may be underpredicting the potential ammonia volatilization losses from solid manure applications by not considering the intermediate conversion of organic N to NH_3.

Either way, these volatilization estimates indicate that assuming a flat 20 percent volatilization rate from both surface-applied liquid and solid dairy cow manure (see Table 5) in the UNBRW may not be satisfactory. Meisenger and Randall (1991) provide general guidelines on short-term and long-term volatilization losses from total applied N in manure, based on summary data from the Midwest Planning Service (1985) and Bouldin et al. (1984). These respective short-term and long-term volatilization loss ranges are 15 to 30 percent and 25 to 45 percent for broadcast solid manure, and 15 to 35 percent and 20 to 40 percent for sprinkler irrigated manure. The 20 percent TNRCC volatilization rate assumption tends to fall at the lower end of these ranges, and also falls within the values reported for the different studies listed in Table 19. However, Meisenger and Randall stress that better estimates should be substituted for the ranges they present based on more exact knowledge of local conditions, including the nutrient content of the locally applied animal manure. Thus, an in-depth review of the current volatization assumption incorporated in the permitting process may be necessary.

Phosphorus Indicators

Comparisons of P indicators between liquid and solid fields are shown in Figures 38 through 41. Average P losses on sediment (Figure 38) and in the solution phase of runoff (Figure 39) were very similar in most years. The peaks predicted for P lost on sediment mirrored closely the trends predicted for organic N loss with sediment (Figure 29). The maximum annual P lost via both sediment and surface runoff was again in 1991, the year of highest rainfall. Average P mineralization (Figure 40) was predicted to steadily increase over time for both the liquid and solid fields, with higher rates estimated for the solid fields for second half of the 10-year period. Build-up of labile P in the soil profile (Figure 41) was dramatic for both the liquid and solid fields, with maximum levels of nearly 600 and 400 kg/ha projected by the end of the simulation period. The P build-up underscores the fact that P is being applied at rates several times higher than the plant uptake rates, as shown in Tables 6 and 7.

A multiagency soil sampling effort conducted on several Erath County dairies has confirmed that significant soil P build-up is occurring in the soil surface in dairy manure waste application fields (Hauck 1997). Soil test P values measured (STP) in the top 15 cm of soil commonly exceed 200 parts per million (ppm), and STP values greater than 400 ppm were occasionally found. This soil build-up implicates the potential for increasing P losses to surface water over time, when the dairy cow manure is applied at the N-based rates listed in Table 7. In-stream monitoring data collected for the UNBRW stream system document that relatively high P losses are occurring from waste application fields (McFarland and Hauck 1995). Visual trends for the simulated P losses on sediment and in surface runoff shown in Figures 38 and 39 also indicate relatively high losses of P from the waste application fields. Some increasing trends in P losses are shown over time, especially on sediment, although this may be more a function of increasing rainfall rather than soil P build-up. Notably, good agreement has been demonstrated by the SWAT in-stream P movement simulations and the corresponding measured data (Rosenthal et al. 1997), indicating that the simulated APEX edge-of-field P losses are reasonable.

Means of Environmental Indicators

Tables 21 to 23 present the means of various environmental baseline N, P, yield, and hydrologic indicators by manure type and cropping system. These values provide an assessment of the different indicators by cropping system, which could not be determined from the majority of the plots in figures 3-41. A superscript 'a,' 'b,' or 'c' on any pair of values for liquid (I or irrigated) and solid (M or manure) fields indicates that they are not significantly different at either the 1, 5, or 10 percent level of significance. All others are at least significant at the 1 percent level of significance.

Long-term average values for crop yields and hydrologic indicators, by cropping system, are reported in Table 21. The yields are the same levels as given in Table 17. The hydrologic indicators were always greater for the liquid manure fields relative to the solid manure fields, except for the continuous winter wheat erosion estimates. This was due primarily to the additional irrigation volume inputs simulated for the liquid waste application fields.

The long-term mean values for the N and P indicators are shown in Tables 22 and 23, respectively. As already implied in the discussion of Figures 3 through 41, these results were heavily influenced by the total N and P application rates as well as the overall hydrologic balance. Higher losses of N on organic sediment were predicted from the solid fields as compared to the liquid fields, while the opposite was predicted for P.

Coastal bermuda appears to have had a mitigating effect on losses of N and P on sediment from both the liquid and solid fields. Surface runoff losses of soluble N were greatest for the irrigated fields. Counterpart P values were usually higher for the solid manure fields, with the highest amounts estimated for continuous coastal bermuda. The highest subsurface flow losses of N occurred for fields cropped with coastal bermuda overseeded with winter wheat. A mixed response was predicted for N percolation, with average values of more than 20 kg/ha predicted for coastal bermuda-winter wheat and sorghum-winter wheat under liquid manure, and more than 16 kg/ha for the continuous winter wheat solid manure scenario.

The 30-year mean nitrification, N volatilization rates, soil profile labile P, and P mineralization values were essentially correlated with the applied N and P application amounts. The N mineralization rates also follow this trend, except for the continuous winter wheat rates that were markedly higher than the counterpart continuous sorghum levels, even though the application rates were the same. The predicted denitrification levels did not follow any obvious pattern.

The indicators for N and P in the crop yield represent the nutrient uptake of the five cropping systems, and can be referenced to the target agronomic rates listed in Table 6. The liquid field N uptake estimates were always higher than those predicted for the solid manure scenarios, regardless of cropping system. However, the opposite was predicted for the 30-year environmental baseline, revealing the impact of increasing N mineralization over time for the solid waste application fields. Higher average P uptake rates were always predicted for the liquid manure scenarios, regardless of simulation duration. The predicted liquid and solid field N uptake values were 12 to 34 and 23 to 43 percent lower than the assumed agronomic rates. However, the continuous coastal bermuda and winter wheat P uptake rates exceeded the targeted agronomic rates by 6 to 26 percent, while the irrigated coastal bermuda-winter wheat and continuous sorghum P uptake rates were essentially equal to the Table 6 rates. The other estimated P uptake rates for coastal bermuda-winter wheat, sorghum-winter wheat, and continuous sorghum ranged from 3 to 24 percent below the agronomic rates.

Summary

An integrated modeling system called the Comprehensive Economic and Environmental Optimization Tool – Livestock and Poultry (CEEOT-LP), has been developed to assess the potential economic and environmental outcomes of proposed policies for the dairy industry located in the UNBRW in Erath County, Texas. An environmental baseline has been performed that was designed to test and calibrate the complete CEEOT-LP environmental component with monitoring data obtained from the UNBRW stream system. The discussion in this paper was limited to the assumptions and results for the APEX model, which was used to simulate the application of dairy cow manure to waste disposal fields in the UNBRW. Previous comparisons between APEX and measured data were performed by Flowers, et al. (1996) for eight sites in or near the UNBRW. Direct comparisons with monitoring data were not possible for these APEX simulations, because the in-stream N and P concentration and mass outputs are simulated in the SWAT watershed model. However, the APEX results provide key insight into the overall fate of the nutrients that were applied in the dairy cow manure.

The APEX results were clearly sensitive to management practices, defined primarily in terms of manure type (liquid or solid), N and P application rates, and cropping system. The results were also impacted by rainfall trends, soil type, and other environmental conditions. The edge-of-field hydrologic indicators generated by APEX showed that the highest levels of runoff, subsurface flow, percolation, erosion, and evapotranspiration occurred for the liquid manure scenarios, except for the continuous winter wheat erosion estimates. This was a direct result of the additional irrigation volume inputs that were erosion, and evapotranspiration occurred for the liquid manure scenarios, except for the continuous winter wheat erosion estimates. This was a direct result of the additional irrigation volume inputs that were simulated for the liquid manure scenarios. However, the N and P losses per hectare were greater from the solid fields relative to the liquid fields for some indicators, a function of both the higher N and P application rates for the solid waste application fields and different in manure mineral composition assumed for the solid and liquid waste application scenarios.

The predicted organic N losses on sediment were higher from the solid waste application fields across all five cropping systems, due to the high levels of organic N in the solid manure. The opposite was true for P loss on sediment, except for continuous winter wheat. Estimated surface runoff losses of N were consistently greater for the liquid scenarios. However, higher soluble P losses in surface runoff were again predicted for the solid manure waste application fields, except for the coastal bermuda-winter wheat. Losses of N via subsurface flow and percolation were greatest from the liquid waste application fields for virtually every cropping system scenario. Peak annual losses of N and P on sediment and in surface runoff, and N in subsurface flow and percolation, tended to be correlated with high rainfall years. The greatest annual losses occurred in the highest rainfall year (1991) for each of these indicators, except for the average N percolation on solid fields , that was predicted to be slightly higher in 1984.

Several of the APEX indicators were predicted to increase with time, including crop yield and nutrient uptake, N in subsurface flow and percolation, N and P mineralization, denitrification, and build-up of NO_3 and labile P in the soil profile. This phenomenon was restricted primarily to the solid field simulations except for P mineralization and soil labile P, both of which also steadily increased across the 30-year period for the liquid field scenarios. The pattern of increasing yields, crop nutrient uptake, and N losses in subsurface flow and percolation for the solid fields is a function of both increasing rainfall and increasing availability of soil mineral N (NO_3). The influence of rainfall is more noticeable towards the end of the simulation period, especially for the coastal bermuda solid fields that showed a significant yield increase during this time. The N mineralization levels for the solid fields increased from an average initial level of 100 kg/ha to almost 600 kg/ha by the end of the 10-year simulation period, resulting in increasing levels of soil nitrate N availability. This contributed in turn to reduced crop N stress and thus higher yields and nutrient uptake, and also to higher N losses via subsurface flow, percolation, and denitrification.

The average ammonia emission from the liquid fields was estimated to be about 250 kg/ha, roughly a factor of 10 higher than the mean rate predicted for the solid fields. The ammonia volatilization rates for both the liquid and solid fields were virtually constant across the entire simulation period. The volatilization results reflect the fact that the NH_4 content was assumed to be about 85 percent of the total N in the liquid manure, versus only about 7 percent of the solid manure total N.

The P mineralization rates increased in a fashion similar to the of the N mineralization rates, but at much lower levels. However, the amount of labile P was predicted to reach an average of approximately 400 and 600 kg/ha for the liquid and solid fields by the end of the simulation period. This result implies that applying dairy cow manure at the rates assumed for this study can result in very high build-up of soil labile P and potentially high corresponding losses of P via surface runoff and erosion. In-stream monitoring results reported by McFarland and Hauck (1995) confirm that high P losses are occurring from dairy waste application fields.

Unless otherwise stated, the APEX assumptions described in this paper are also valid for the policy simulations. The trends and responses reported for the APEX results will also carry over to the policy simulations. Overall, the APEX results proved very responsive to variation in management, climatic, and soil inputs, and were satisfactory regarding the goals of the NPP. Calibration and testing of the SWAT model using the APEX edge-of-field loadings, against in-stream monitoring data, has also proved successful (Rosenthal et al. 1997). Additional testing and perhaps modification of APEX may prove beneficial in confirming and/or improving volatilization and yield predictions. Improvement of APEX remains an ongoing goal of the NPP project team that is applying and refining CEEOT-LP.

APPENDIX A

Example of Field Selection Process within run_apex

This example of the field selection process that has been built into run_apex is for solid manure disposal on the actual herd size and permitted solid manure fields listed for dairy 10 (Table 11). The disposal process is based on: (1) the assumption that each cow from the 500 head dairy herd will ultimately contribute 125.1 lb N in the applied solid manure per year, as discussed in the Environmental Baseline Assumptions section, (2) the list of rules that are given in the Selection of Application Fields section for determining exactly which fields the manure will be disposed on, and (3) the N application rates given for the various crop types that are listed in Table 7.

Step1: Calculate the total solid manure N load that will be contributed from the 500 cows

total N load = 500 cows * 125.1 lb N = 62,550 lb

Step 2: Determine the total amount of N that can be applied on the first appropriate field according to the field selection rules; this is the first field on the list that is defined as a 37 acre sorghum/w. wheat field

N applied to first field = 37 acres * 800 lb N/acre = 29,600 lb

Step 3: Determine the remaining amount of manure N that needs to still be disposed of

Amount of N remaining = 62,500 lb N - 29,600 lb N = 32,900 lb N

Step 4: Determine the amount of N that can be applied on the next appropriate field; this is the second field on the list that is defined as a 45 acre sorghum/ w. wheat field

Total N that could be applied = 45 acres * 800 lb/N acre = 36,000 lb

Step 5: The total N that could be applied exceeds the total N that needs to be disposed of. Thus, the total acres that are simulated for the second field are adjusted to meet the demand as determined in step 3

Acres needed for field 2 = (32,900/36,000) * 45 acres = 41 acres

This example underscores the fact that the many of the dairies have more permitted acres than are needed to dispose of both the liquid and solid manure using the N-based application rates that are given in Table 7. Only two of the eight permitted fields were run in APEX for the dairy 10 solid manure disposal scenario, and only 41 acres of the 45-acre second field were required. It is stressed again that the field selection process used in run_apex is anecdotal in nature. Thus, the choice of fields shown here in dairy 10 may be quite different from what was actually done in reality.

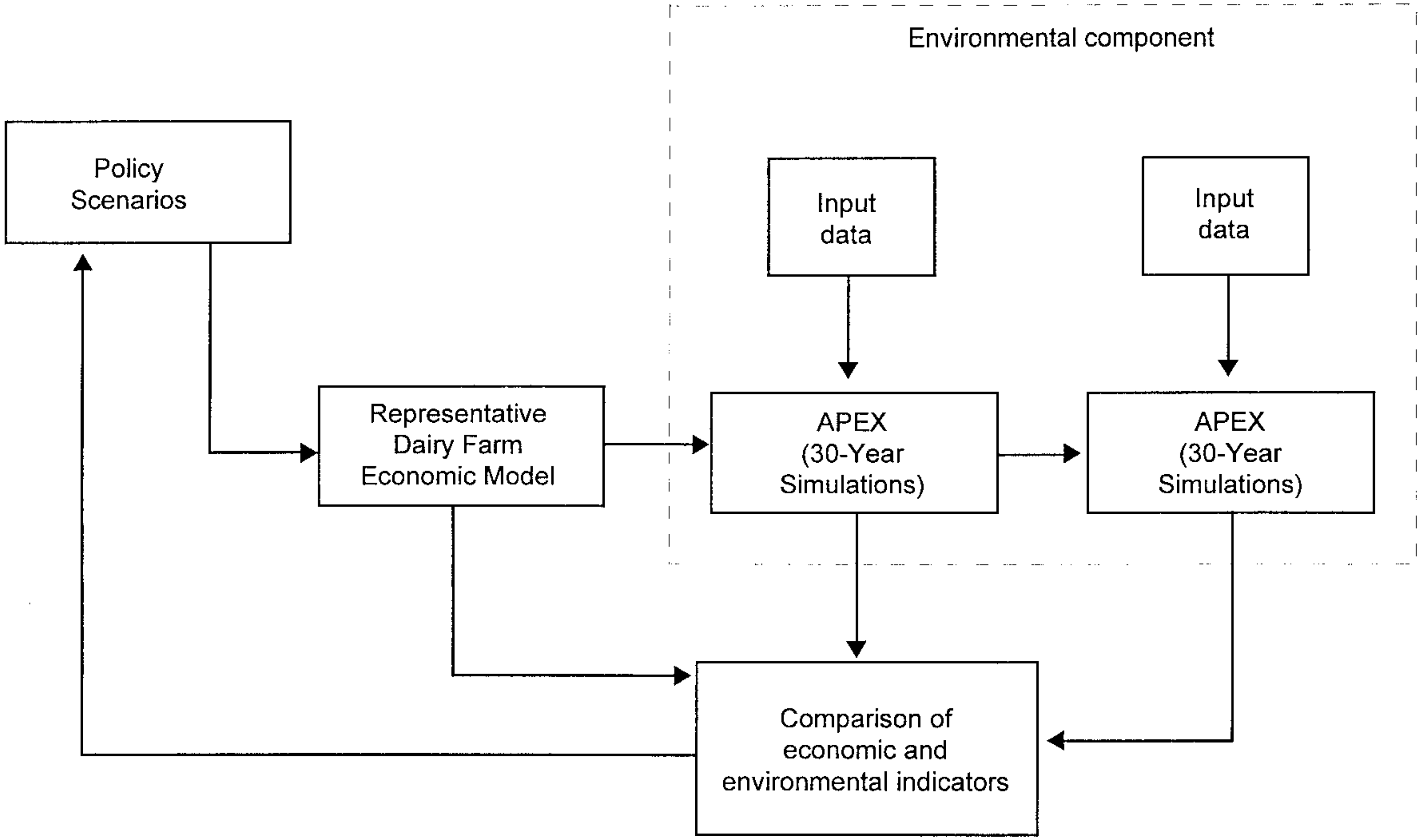

Figure 1. Schematic of the Comprehensive Economic and Environmental Optimization Tool-Livestock and Poultry (CEEOT-LP)

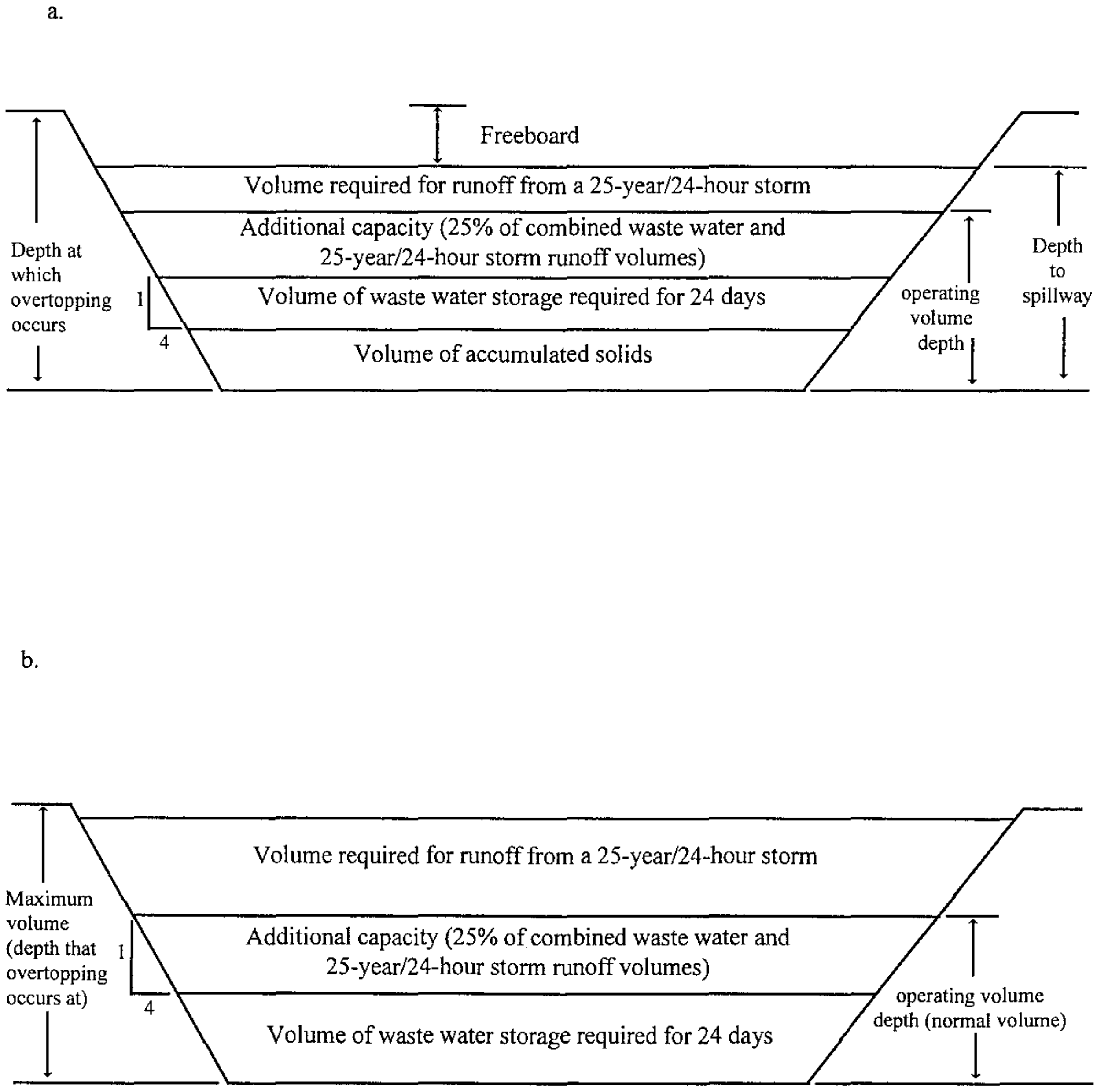

Figure 2. Configurations of a) standard lagoon design in the UNBRW and b) a simplified version that was used for the APEX simulations (note: drawings are not to scale).

Figure 3
Time Profile of Annual Rainfall in mm (Dublin, TX: 1965 90; Stephenville, TX: 1991-94)

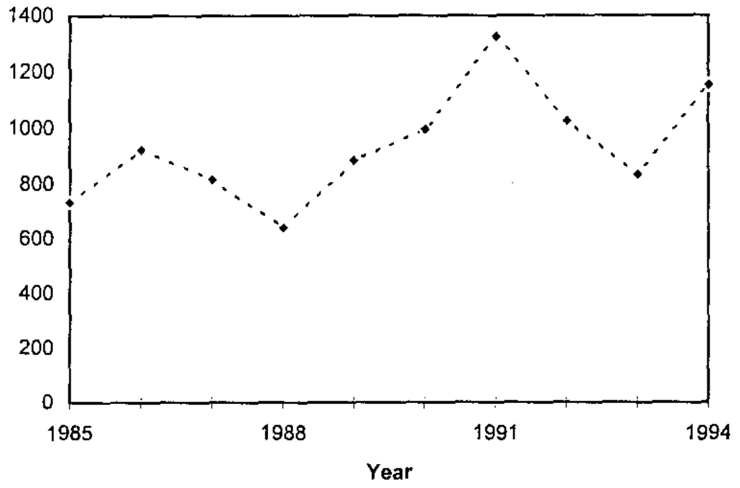

Figure 4
Runoff (mm): Liquid fields vs Solid fields

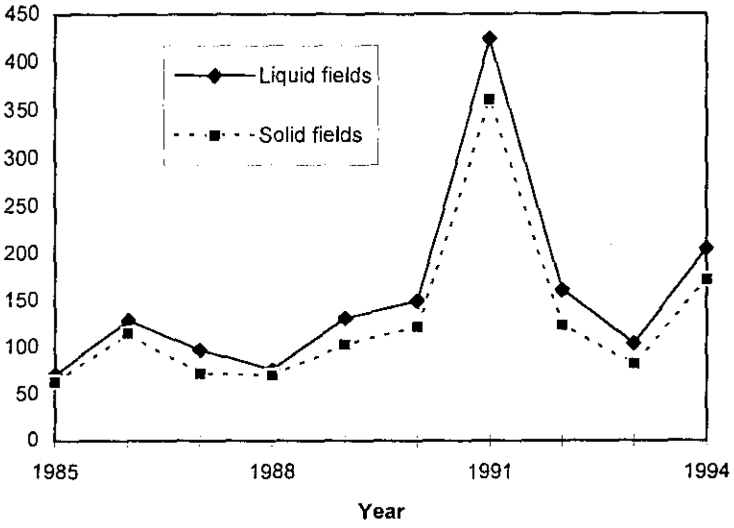

Figure 5
Depth of percolation (mm): Liquid fields vs Solid fields

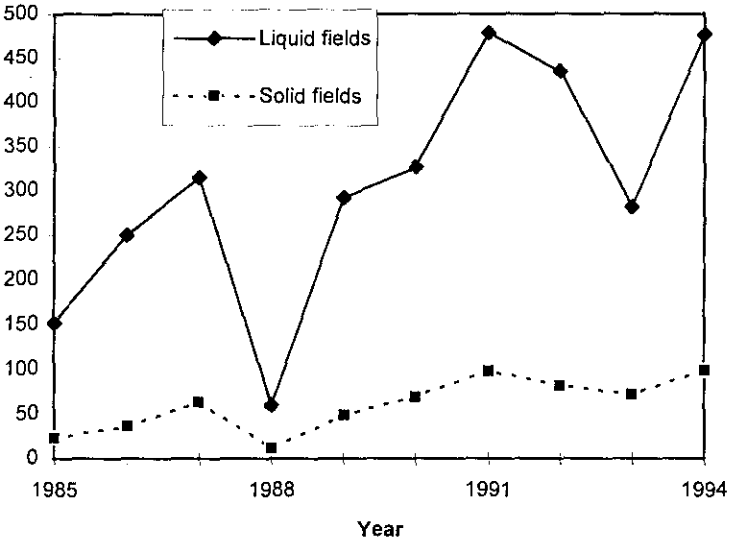

Figure 6
Subsurface flow (mm): Liquid fields vs Solid fields

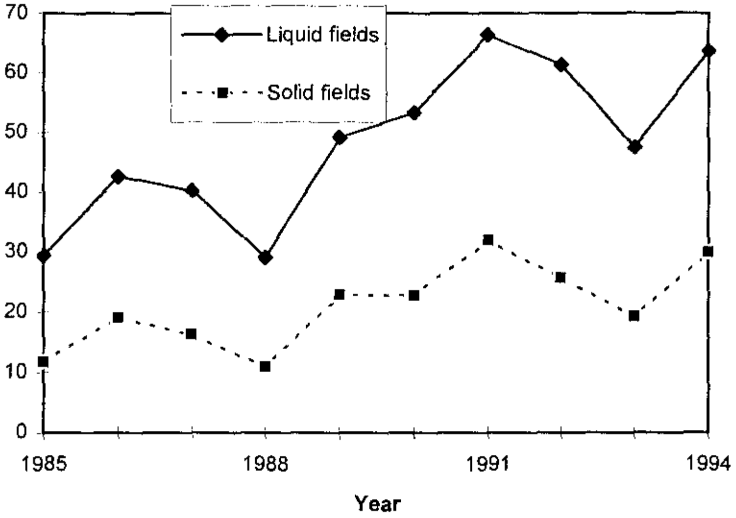

Figure 7
Soil erosion (kg/ha): Liquid fields vs Solid fields

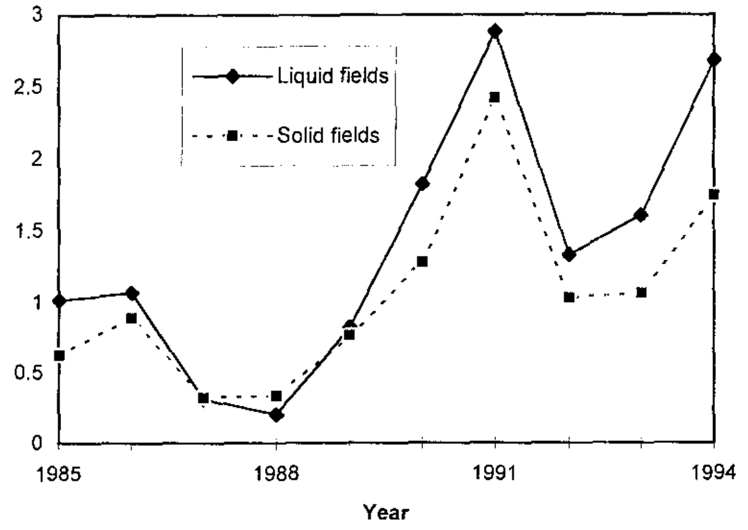

Figure 8
Bermuda yields on continuous bermuda rotation (tons/ha)

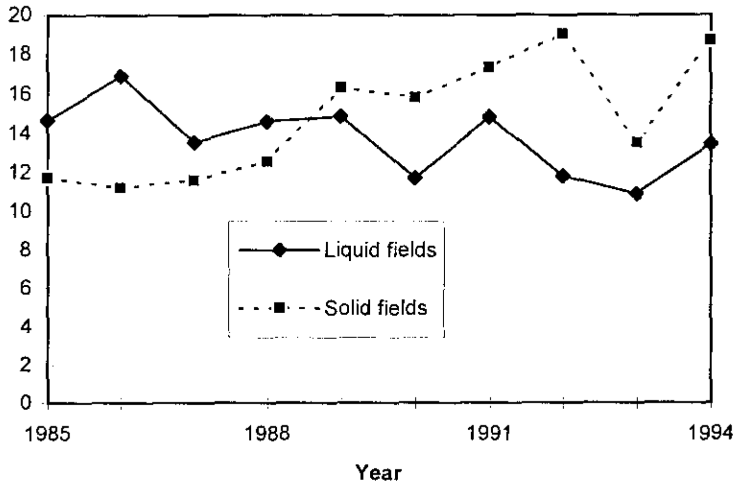

Figure 9
Bermuda yields on wheat-bermuda rotation (tons/ha)

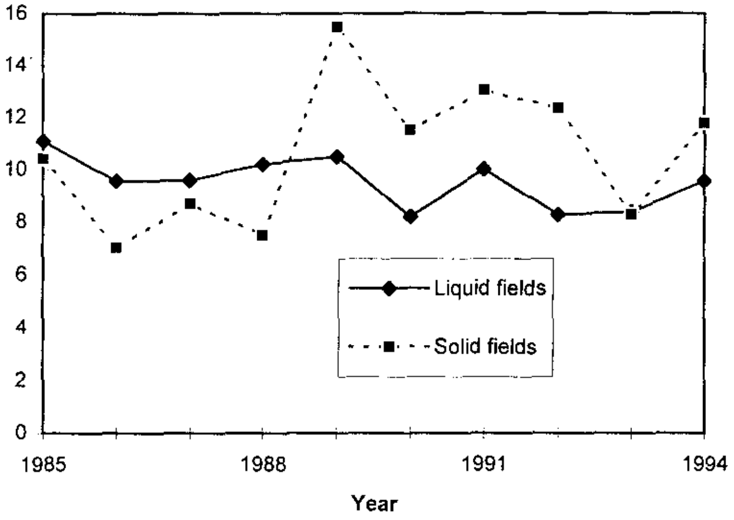

Figure 10
Sorghum yields on continuous sorghum rotation (tons/ha)

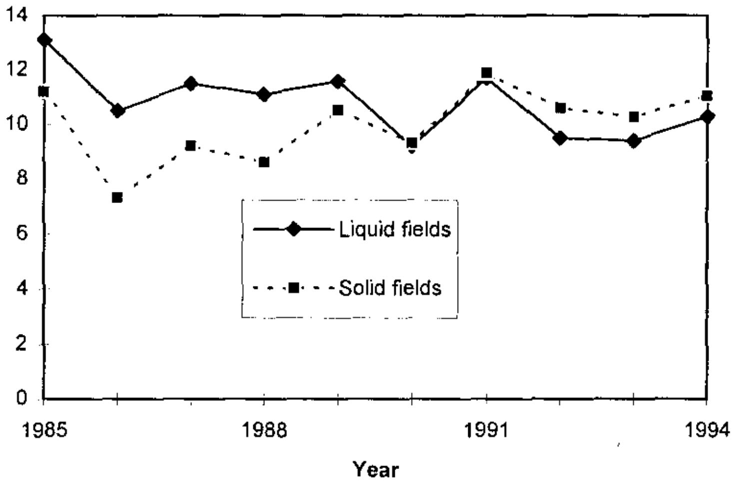

Figure 11

Sorghum yields on wheat-sorghum rotation (kg/ha)

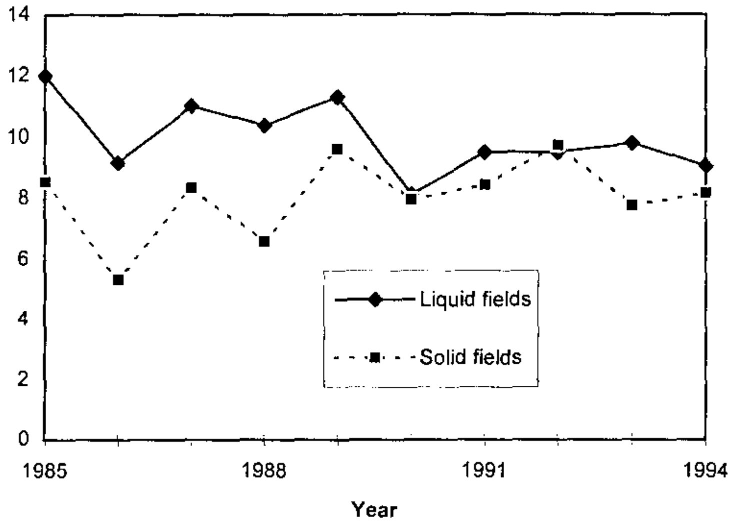

Figure 12

Wheat yields on continuous wheat rotation (tons/ha)

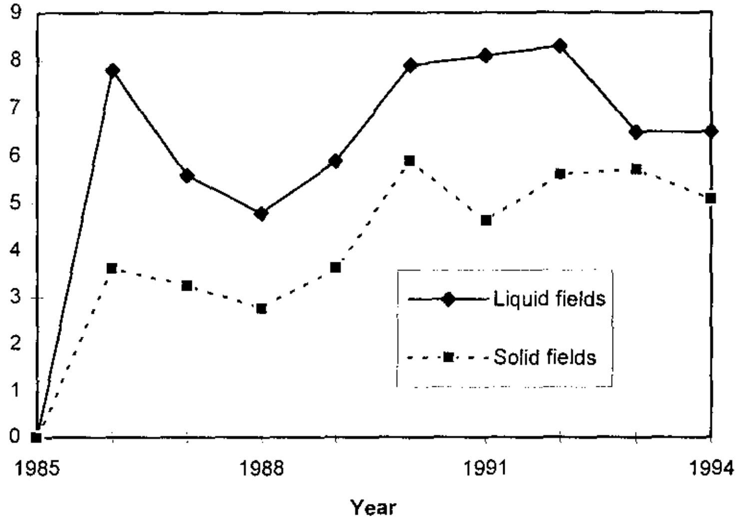

Figure 13

Wheat yields on wheat-bermuda rotation (tons/ha)

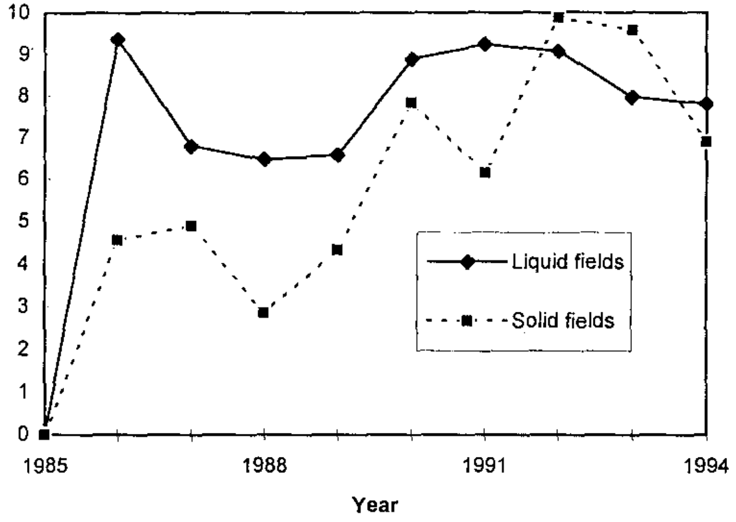

Figure 14

Wheat yields on wheat-sorghum rotation (tons/ha)

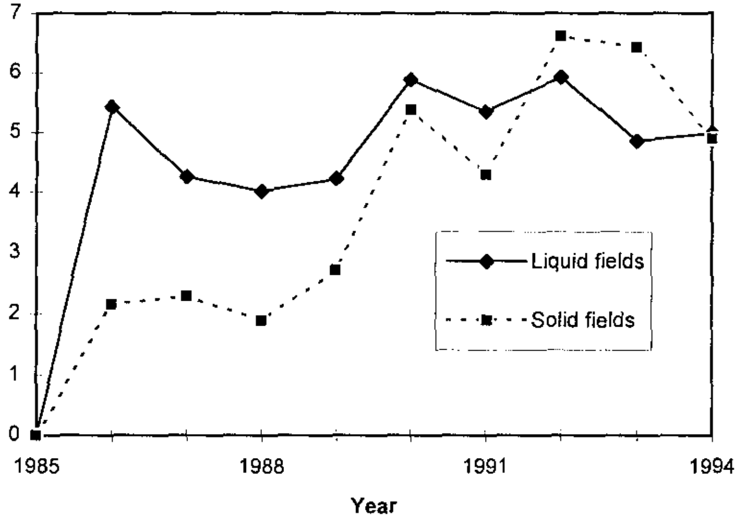

Figure 15
Uptake of nitrogen by coastal-winter wheat (kg/ha): Liquid fields

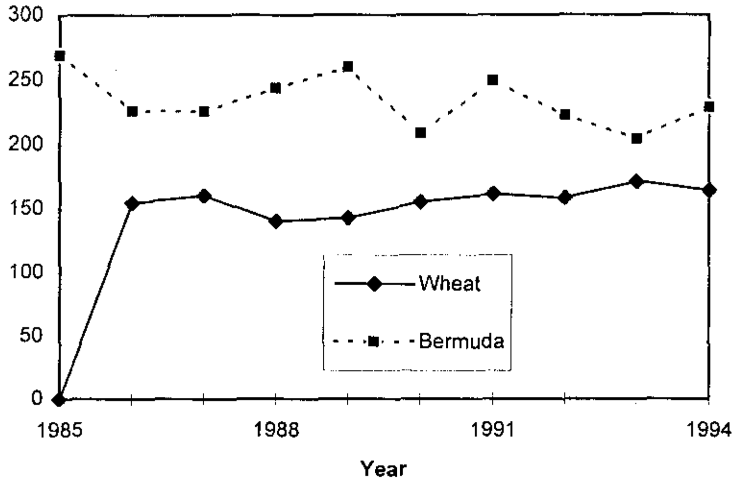

Figure 16
Uptake of nitrogen by coastal-winter wheat (kg/ha): Solid fields

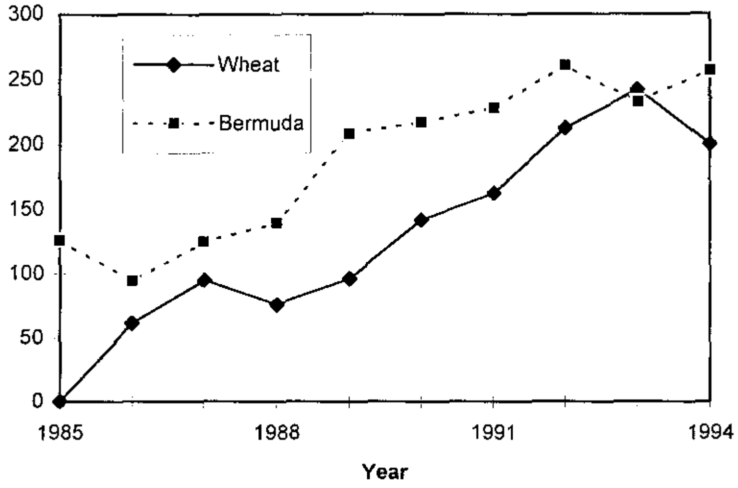

Figure 17
Uptake of phosphorus by coastal-winter wheat (kg/ha): Liquid fields

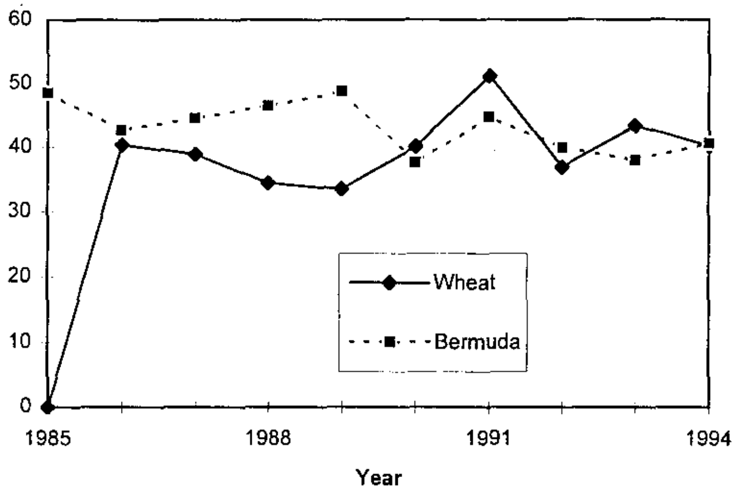

Figure 18
Uptake of phosphorus by coastal-winter wheat (kg/ha): Solid fields

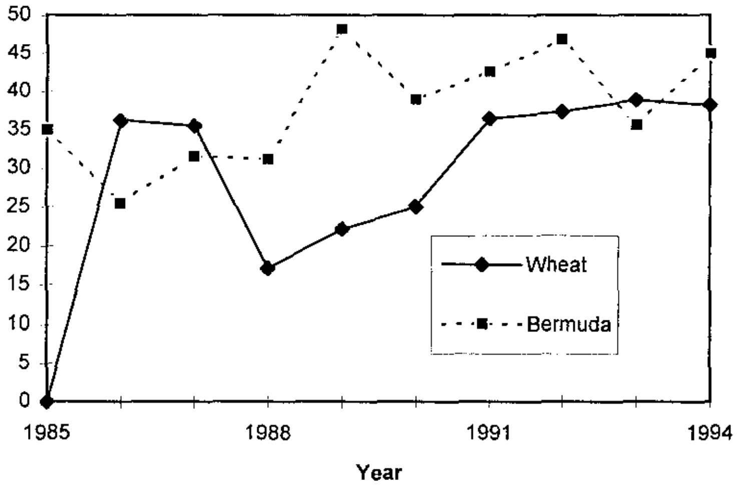

Figure 19
Uptake of nitrogen by sorghum-winter wheat (kg/ha): Liquid fields

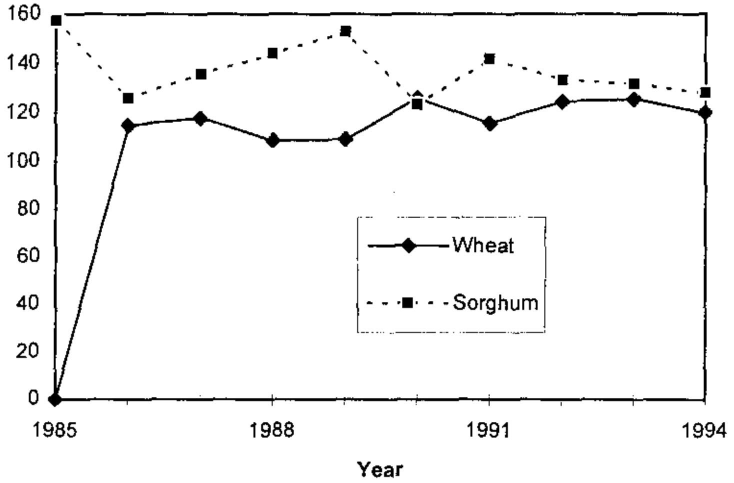

Figure 20
Uptake of nitrogen by sorghum-winter wheat (kg/ha): Solid fields

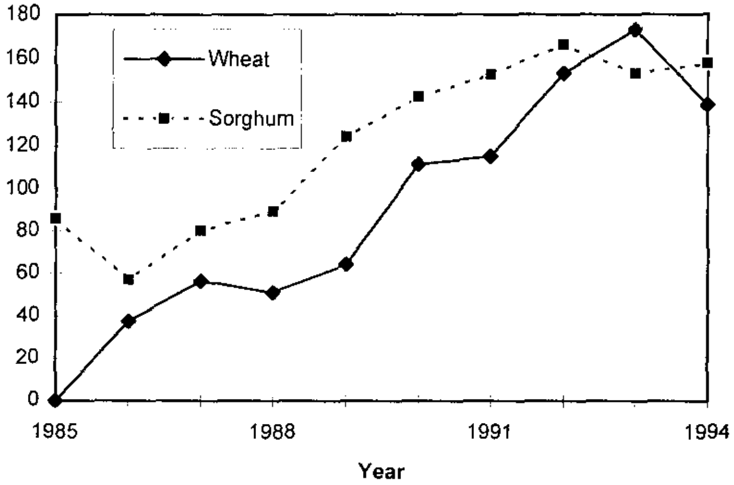

Figure 21
Uptake of phosphorus by sorghum-winter wheat (kg/ha): Liquid fields

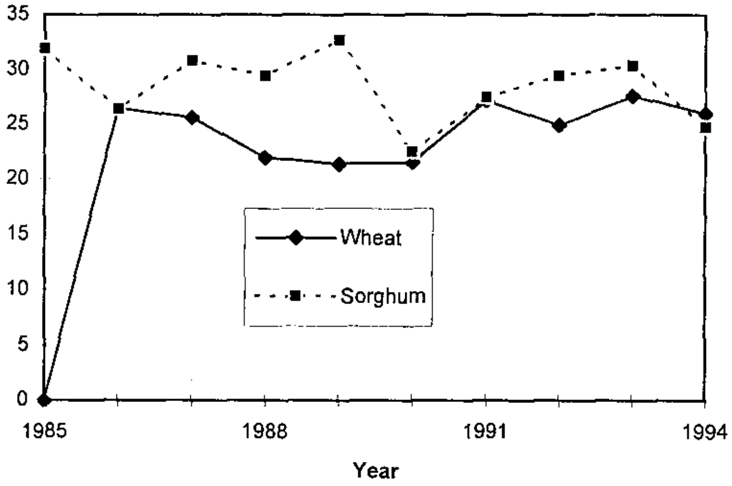

Figure 22
Uptake of phosphorus by sorghum-winter wheat (kg/ha): Solid fields

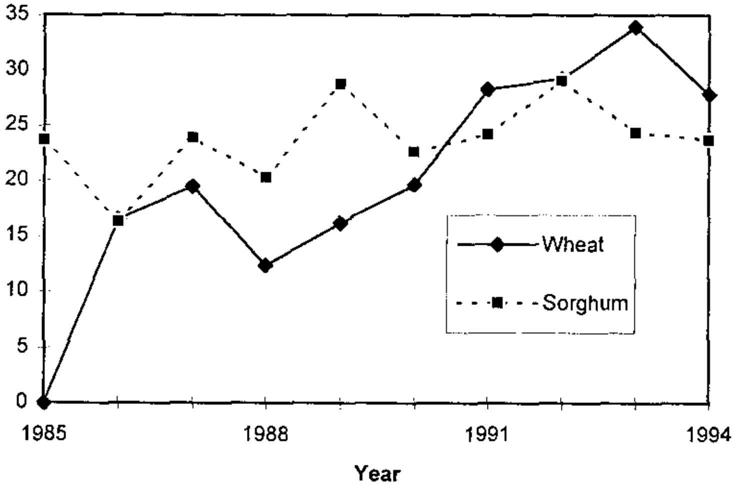

Figure 23
Uptake of nitrogen by coastal bermuda (kg/ha)

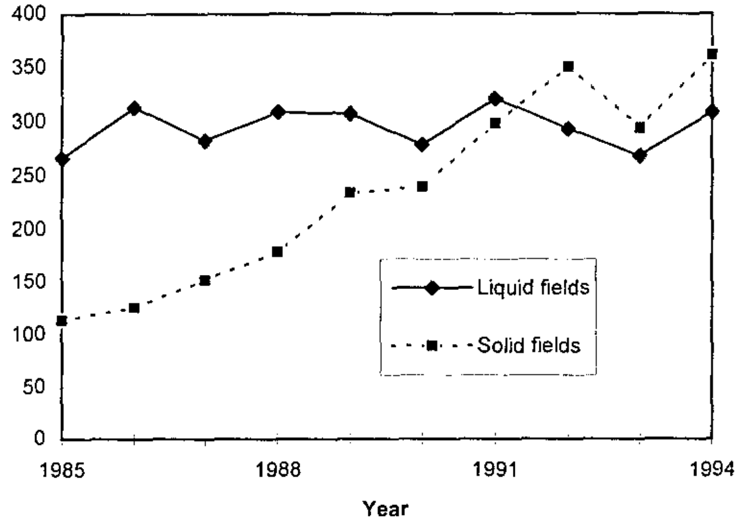

Figure 24
Uptake of phosphorus by coastal bermuda (kg/ha)

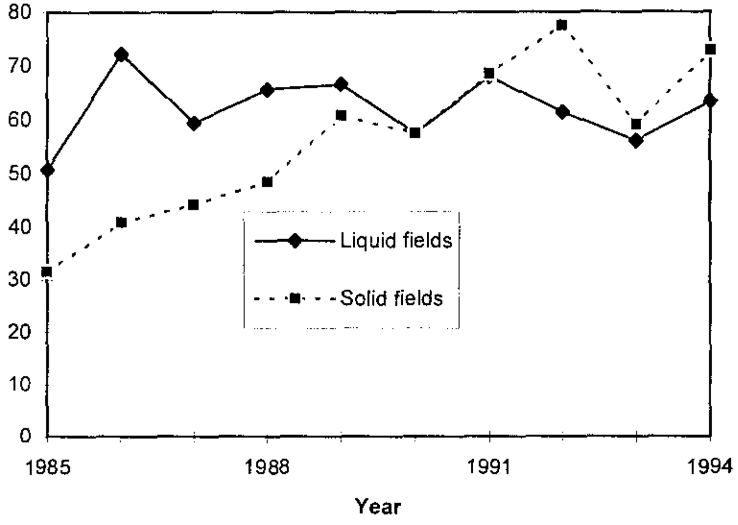

Figure 25
Uptake of nitrogen by winter wheat (kg/ha)

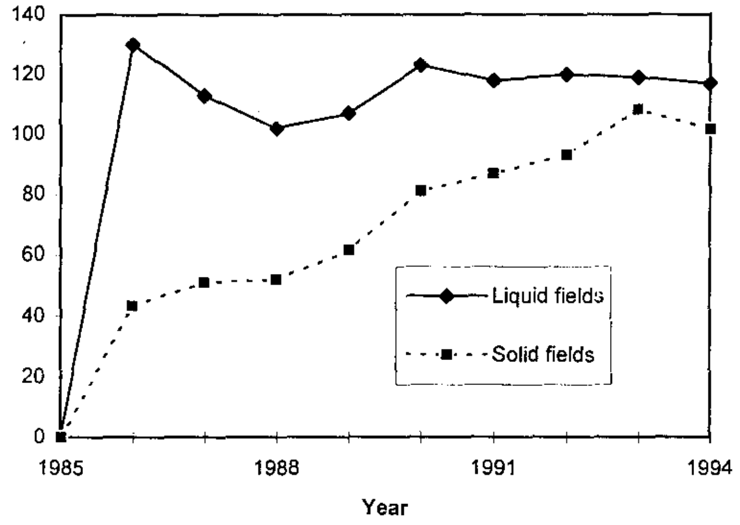

Figure 26
Uptake of phosphorus by winter wheat (kg/ha)

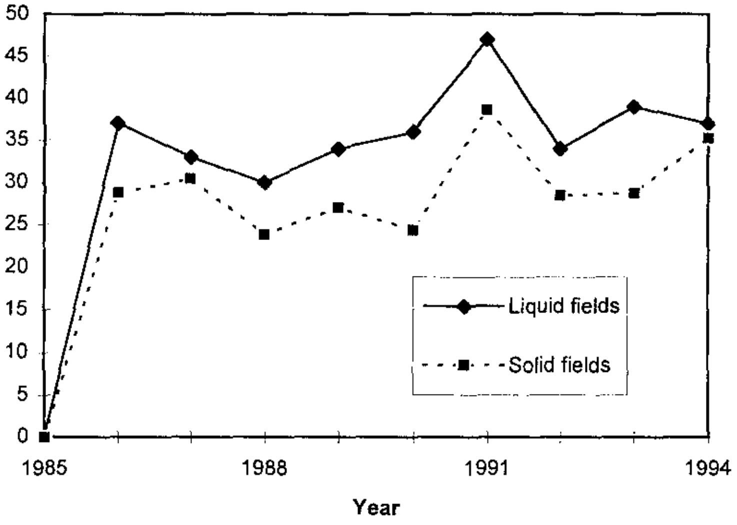

Figure 27
Uptake of nitrogen by sorghum (kg/ha)

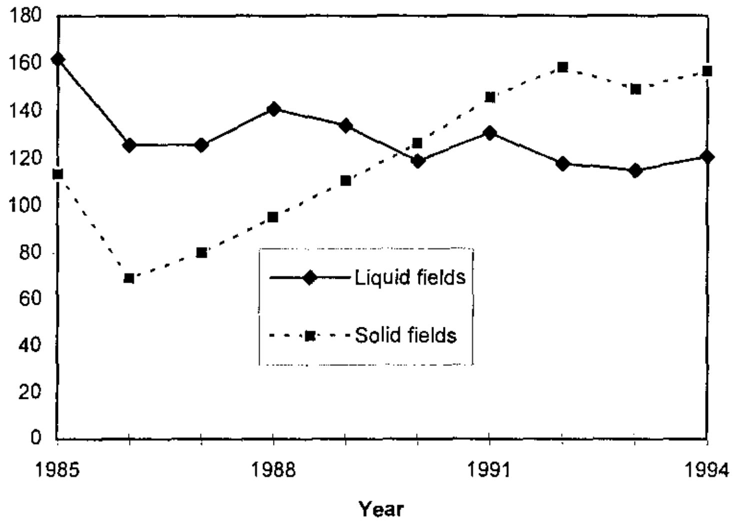

Figure 28
Uptake of phosphorus by sorghum (kg/ha)

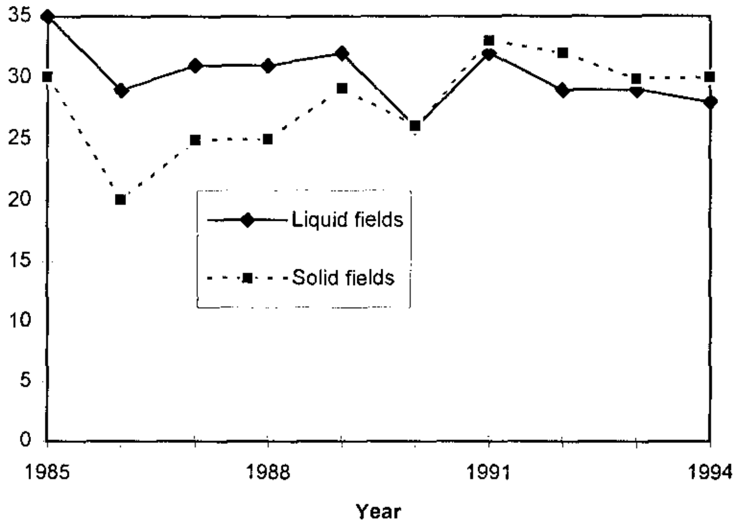

Figure 29
Organic nitrogen loss in sediment (kg/ha): Liquid fields vs Solid fields

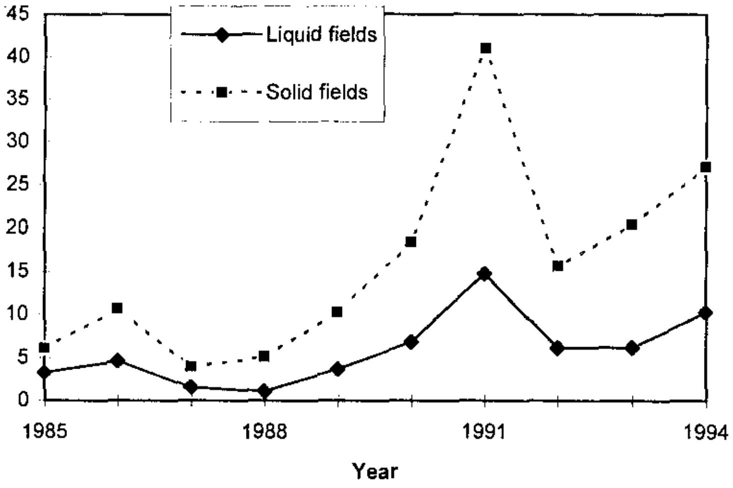

Figure 30
Nitrogen loss in runoff (kg/ha): Liquid fields vs Solid fields

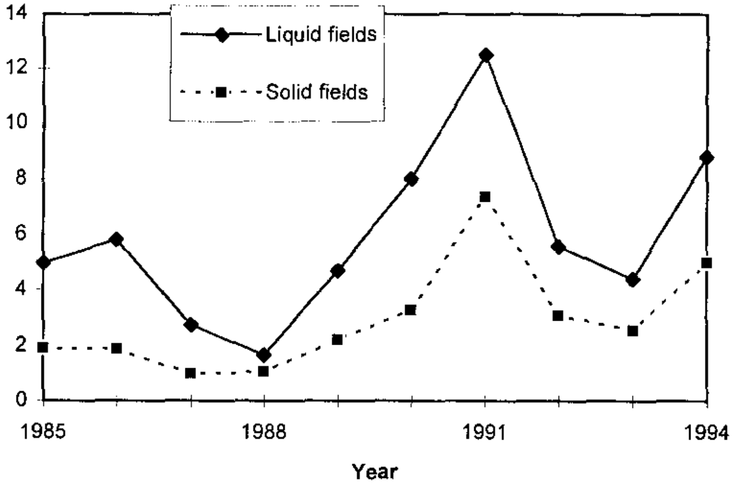

Figure 31
Nitrogen loss in subsurface flow (kg/ha): Liquid fields vs Solid fields

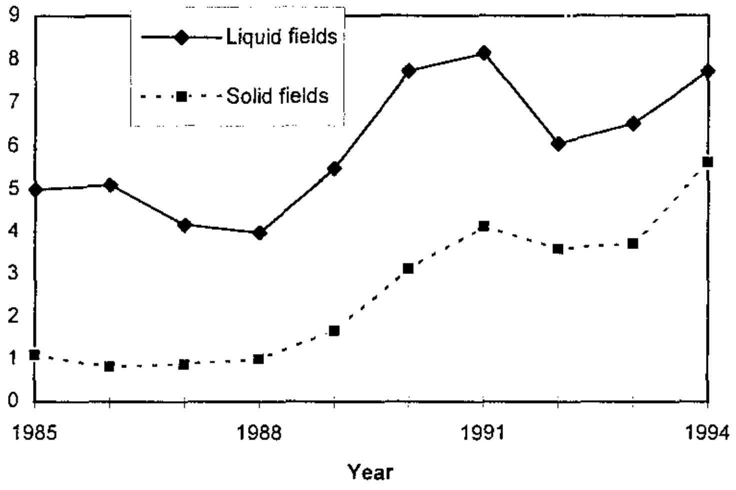

Figure 32
Nitrogen loss in percolates (kg/ha): Liquid fields vs Solid fields

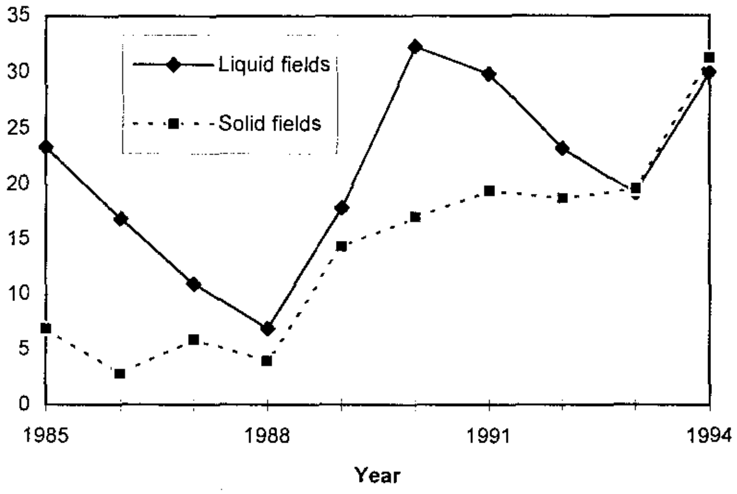

Figure 33
Mineralization of nitrogen (kg/ha): Liquid fields vs Solid fields

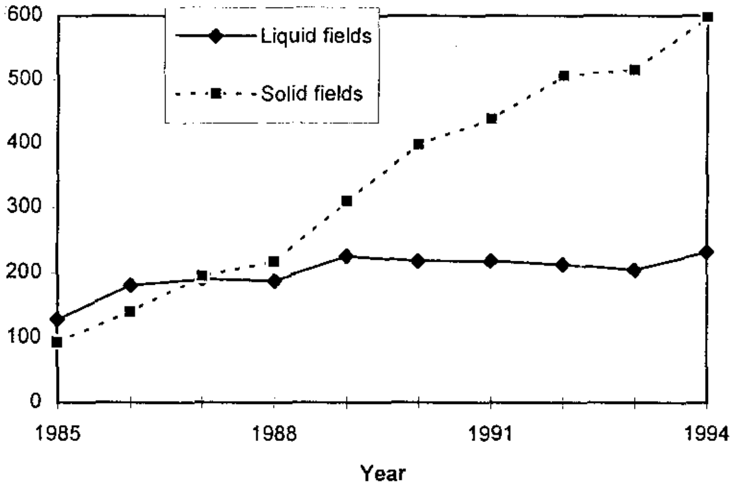

Figure 34
Rate of denitrification (kg/ha): Liquid fields vs Solid fields

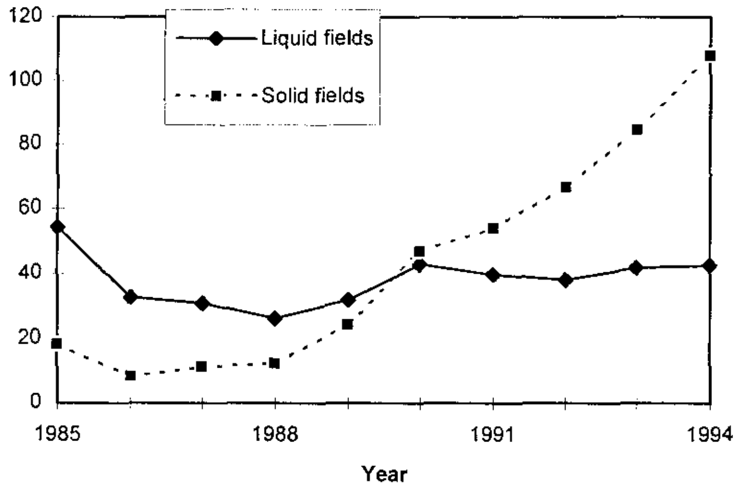

Figure 35
Nitrification (kg/ha): Liquid fields vs Solid fields

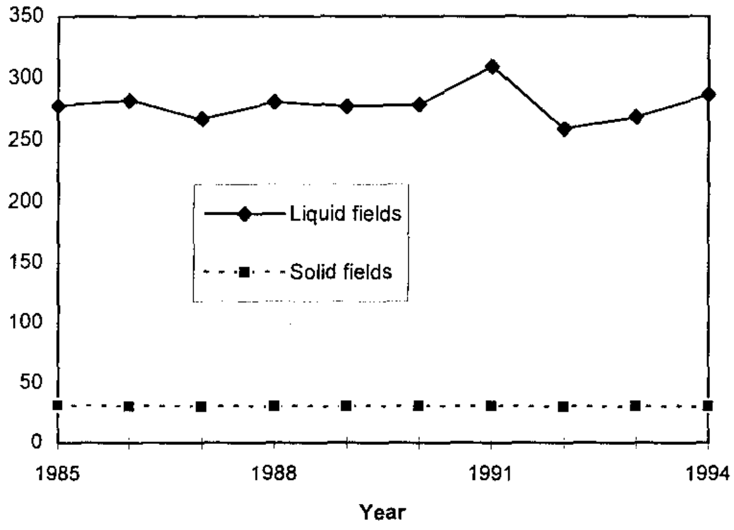

Figure 36
Rate of nitrogen volatilization (kg/ha): Liquid fields vs Solid fields

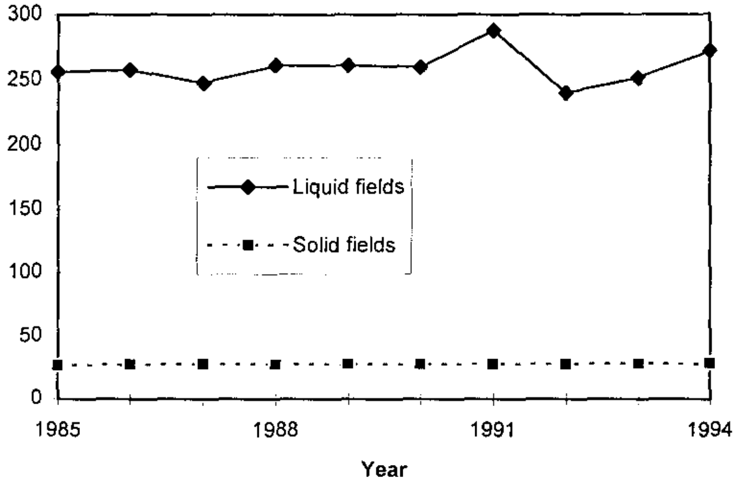

Figure 37
Total nitrate in soil profile (kg/ha): Liquid fields vs Solid fields

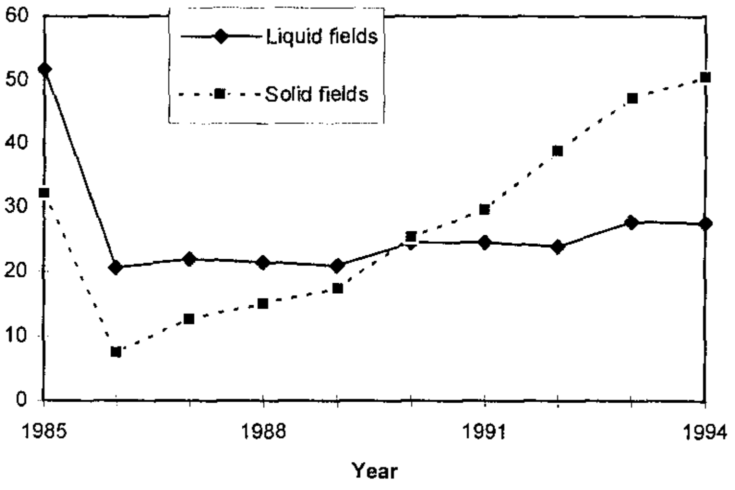

Figure 38
Phosphorus loss in sediment (kg/ha): Liquid fields vs Solid fields

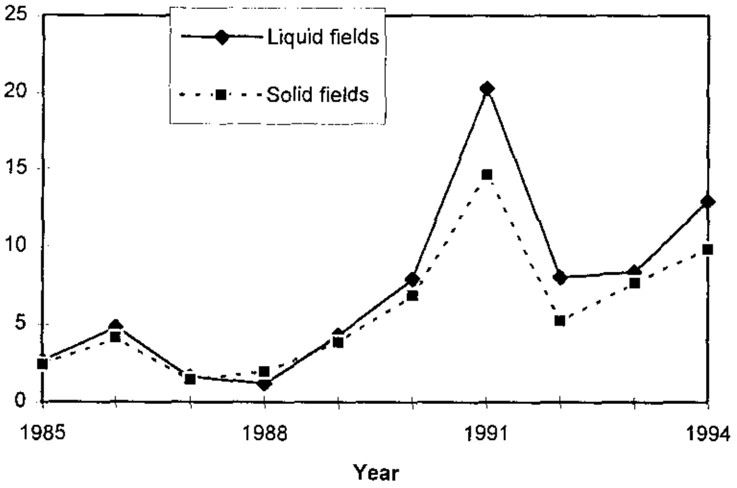

Figure 39

Phosphorus loss in runoff (kg/ha): Liquid fields vs Solid fields

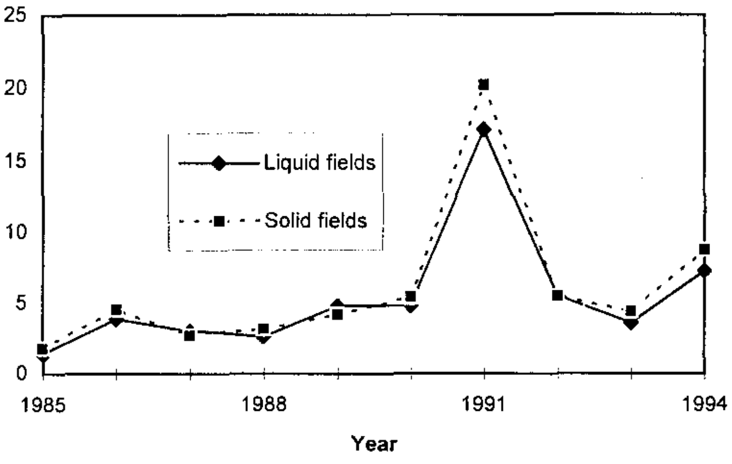

Figure 40

Mineralization of phosphorus (kg/ha): Liquid fields vs Solid fields

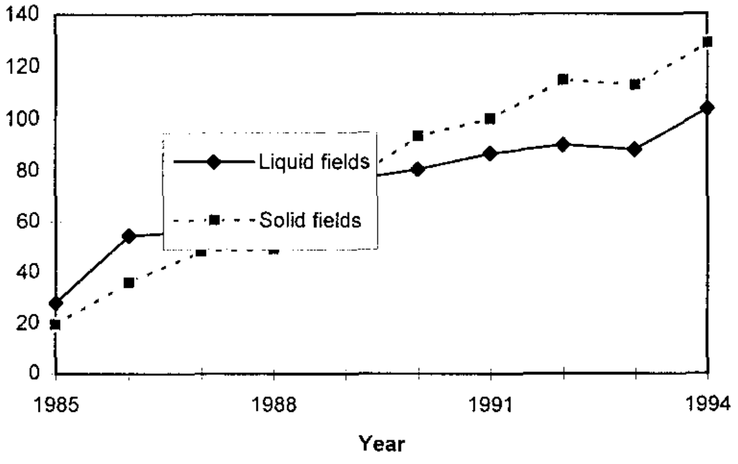

Figure 41

Amount of labile phosphorus (kg/ha): Liquid fields vs Solid fields

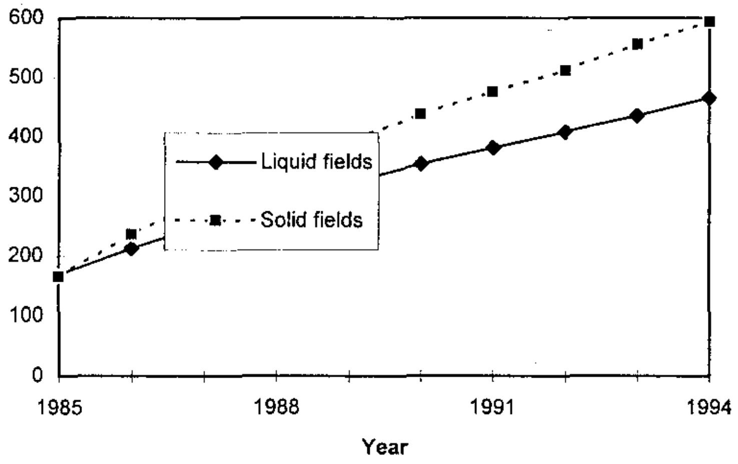

Table 1. Distribution of herd sizes by small, medium, and large dairies for actual and permitted dairy herds in the Upper North Bosque (UNB) river watershed

Dairy Class	Actual		Permitted	
	Dairies	Cows	Dairies	Cows
Small (0-249)	46	6,669	40	6,979
Medium (250-599)	34	14,309	20	8,740
Large (> 600)	15	13,567	34	29,975
Total[a]	95	34,545	94[b]	45,694

[a] The total simulated herd sizes are actually slightly lower than that shown here, in order to account for the dairies that can apply manure on acreage outside of the UNBRW.

[b] There is a one less "dairy" for the permitted herd sizes, reflecting the fact that one calf ranch ceased operations in the summer of 94 and thus is not incorporated in the policy scenarios.

Table 2. Permitted crops that were recategorized to the crops assumed in the APEX environmental baseline run

Original permitted crop(s)	Assumed crop(s)[a]	Total fields
Alfalfa	Coastal bermuda	2
Coastal/small grain	Coastal/w. wheat	16
Hay grazer	Coastal bermuda	3
Improved pasture	Coastal bermuda	2
Improved past. or coastal	Coastal bermuda	1
Kleingrass/w. wheat	Coastal/w. wheat	2
Native pasture	Coastal bermuda	6
Oats/sorghum	Sorghum/w. wheat	1
Peanuts/wheat	Sorghum/w wheat	2
Small grain	Winter wheat	3
Sorghum or small grain	Sorghum	1
Sorghum/small grain	Sorghum/w. wheat	3
Sudan	Sorghum	2
Sudan or sorghum	Sorghum	1
Sudan/w. wheat	Sorghum/w. wheat	20

[a] Coastal/w. wheat is coastal bermuda overseeded with winter wheat and sorghum/w. wheat is sorghum followed by winter wheat, as denoted in Table 3.

Table 3.Tillage planting and harvesting machinery and date assumptions for the APEX simulations

Cropping system	Manure type	Year(s)	Operation	Date
Coastal bermuda	irrigated	year 1	Tandem disk	April 14
			Drill planter	April 15
			Harvest (95%)	June 1
			Harvest (95%)	August 1
			Harvest (95%)	October 15
		remaining years	Harvest (95%)	June 1
			Harvest (95%)	July 15
			Harvest (95%)	September 1
			Harvest (95%)	October 15
Coastal bermuda	solid	year 1	Tandem disk	April 7
			Drill planter	April 15
			Harvest (95%)	August 1
			Harvest (95%)	October 15
		remaining years	Harvest (95)	June 15
			Harvest (95%)	August 15
			Harvest (95%)	October 15
Coastal bermuda/ w. wheat	irrigated	all years	Tandem disk	April 14
			Drill planter (coastal)	April 15
			Harvest (95%)	June 1
			Harvest (95%)	July 15
			Harvest (95%)	September 1
			Kill (coastal)	September 1
			Tandem disk	September 14
			Drill planter (wheat)	September 15
			Harvest (95)	April 1
			Kill (wheat)	April 7
Coastal bermuda/ w. wheat	solid	all years	Tandem disk	April 14
			Drill planter (coastal)	April 15
			Harvest (95%)	July 1
			Harvest (95%)	September 1
			Kill (coastal)	September 1
			Tandem disk	September 14
			Drill planter (wheat)	September 15
			Harvest (95%)	April 1
			Kill (wheat)	April 7

Table 3 (continued)

Cropping system	Manure type	Year(s)	Operation	Date
Corn silage	both	all years	Tandem disk	March 14
			Raw planter	March 15
			Harvest (95%)	July 4
			Kill	July 4
Sorghum hay	both	all years	Tandem disk	April 6
			Drill planter	April 7
			Harvest (95%)	July 5
			Harvest (95%)	August 20
			Kill	November 1
Sorghum hay/ w. wheat	both	all years	Tandem disk	April 6
			Drill planter (sorghum)	April 7
			Harvest (95%)	July 5
			Harvest (95%)	August 20
			Kill (sorghum)	September 7
			Tandem disk	September 14
			Drill planter (wheat)	September 15
			Harvest (95%)	March 30
			Kill (wheat)	March 31
Winter wheat	both	all years	Tandem disk	September 14
			Drill planter	September 15
			Harvest (95%)	April 1
			Kill	April 7

Table 4. Proportions of total annual solid manure that are applied during each month

Month	Coastal Bermuda	Coastal W Wheat	Sorghum W Wheat	Sorghum	Winter Wheat
January					
February					
March					
April	0.25	0.33	0.50	1.0	
May					
June	0.25				
July		0.33			
August	0.25				
September		0.34	0.50		1.0
October	0.25				
November					
December					

Table 5. Key assumptions used in the TNRCC permitting process that affect the simulated N application rates and acres in APEX

Assumption	Percent by manure type	
	Solid	Liquid
N feedlot losses	50	--
N lagoon system losses	--	20
N in remaining manure (after losses) that is plant available	50	80
Amount of surface applied N that is lost to volatilization[a]	20	20

Note: These assumptions also automatically affect the amount of P applied for each cropping system, due to a direct ratio of N to P assumed for the dairy manure (N:P ratio is aproximately 2.3:1).

[a] The volatilization loss assumption leads to an additional 20 percent of N being applied per acre; however, the actual amount volatilized in each simulation run is determined by APEX.

Table 6. Crop agronomic rates in lb/ac (kg/ha) for nitrogen (N) and phosphorus (P)[a]

	Crop				
Nutrient	Coastal Bermuda	Coastal-Winter Wheat	Sorghum Winter Wheat	Sorghum	Winter Wheat
N	300.0 (336)	460.0 (515)	320.0 (359)	160.0 (179)	160.0 (179)
P	44.0 (99)	70.0 (78)	53.0 (59)	26.0 (29)	26.0 (29)

[a] The agronomic rate is also referred to as the plant nutrient uptake rate.

Table 7. Total N and P applied in lb/ac (kg/ha) in solid and liquid manure after accounting for plant available nitrogen and surface application losses for the environmental and policy baselines[a]

	Crop				
Nutrient	Coastal Bermuda	Coastal Winter Wheat	Sorghum Winter Wheat	Sorghum	Winter Wheat
N solid	750 (840)	1150 (1288)	800 (896)	400 (440)	400 (448)
P solid	326 (365)	500 (560)	348 (390)	174 (195)	174 (195)
N liquid	469 (525)	719 (805)	500 (560)	250 (280)	250 (280)
P liquid	233 (261)	357 (400)	248 (278)	124 (139)	129 (139)

[a] These rates would be reduced by 20 percent for incorporated manure applications for which no surface losses due to ammonia volatilization would be assumed to occur.

Table 8. Dairy manure nutrient coefficients for APEX nutrient-based applications[a]

Manure Type	Nutrient Coefficients				
	Mineral N (NO_3)	Mineral P	Organic N	Organic P	Ammonium[b] (NH_4)
Solid	0.0490	0.1969	0.6481	0.1060	0.9716
Liquid	0.5662	0.2157	0.1020	0.1161	0.9871

[a] The mineral N, mineral P, organic N, and organic P factors add to 1.0 on a nutrient basis.

[b] The ammonia fraction represents the percent of the applied mineral N that is in the ammonia form.

Table 9. Estimates of the mineral (inorganic) P composition of dairy cow manure

% Mineral P	Comments	Reference
63		Barnett (1994)
65	Fresh dairy cow manure	ASAE (1995)
63	Dairy cattle feces and straw to be mixed with a sandy soil	van Fassen and van Dijk (1987)
74	Dairy cattle feces and straw to be mixed to a calcarbas sandy soil	van Fassen and van Dijk (1987)
77	Fresh dairy manure and waste scraped daily from gutters and alleys	Peperzak and Caldwell (1959)[a]
84	"	"
61	"	"
80	"	"
57	"	Staley et al. (1971)[a]
72	Dairy manure from loose housing that is bedded and cleaned periodically	Peperzak and Caldwell (1959)[a]
50	"	Ames and Gaither (1912)[a]

[a] As cited in Overcash et al. (1983).

Table 10. Dairy manure nutrient coefficients for APEX manure-based applications[a]

Manure Type	Nutrient Coefficients				
	Mineral N (NO_3)	Mineral P	Organic N	Organic P	Ammonia[b] (NH_4)
Solid	0.0017	0.0066	0.0218	0.0038	0.9716
Liquid	0.0028	0.0011	0.0005	0.0006	0.9871

[a] The mineral N, mineral P, organic N, and organic P fractions represent the percent of the applied manure that is in nutrient form.

[b] The ammonia fraction represents the percent of the applied mineral N that is in the ammonia form.

Table 11. Characteristics of the permitted waste application field for four example dairies in the UNBRW.

		Liquid manure (irrigation) fields				Solid manure fields			
Dairy	Herd size	Crop type	Soil type	Acres	Micro-watershed	Crop type	Soil type	Acres	Micro-watershed
6	400 (400)[a]	coastal bermuda	WoB2	30	24	coastal/wheat	WoB	91	24
						sorghum/wheat	DuC2	30	25
7	125 (100)	coastal/wheat	WoB	7	22	sorghum	DuC2	6	22
						coastal bermuda	WsC2	21	22
						coastal bermuda	DuC2	7	22
						coastal bermuda	DuC2	14	22
8	700 (250)	coastal bermuda	BdC	78	12	coastal bermuda	WoB2	360	12
10	600 (500)	coastal/wheat	WoB2	51	12	sorghum/wheat	WoB2	37	12
						sorghum/wheat	WoB2	45	12
						coastal bermuda	WoB2	53	12
						coastal bermuda	WoB2	128	12
						coastal bermuda	WoB2	34	12
						sorghum	WoB2	60	8
						coastal bermuda	WoB2	40	8
						sorghum	Pd	80	22

[a] Dairy herd sizes are for permitted and estimated actual (in parentheses).

Table 12. Dairies with acres outside of the UNBRW that are potentially available for manure disposal

Dairy	Liquid acres in	Liquid acres out	Solid acres in	Solid acres out
1	7	35	127	73
26	145	5	220	0
39	60	23	153	0
90	45	0	144	21
91	62	629	2	133
92	0	94	87	271
99	57	0	147	154
113	19	40	0	103

Table 13. Area weighted slopes and slope lengths by soil code for the UNBRW[a]

Soil Code	Slope (%)	Slope-length (m)
143AaD3	5.6	38.1
143AlD27.2	38.1	
143BaA	2.5	30.5
143BaB	3.6	121.9
143BaC3	4.2	76.2
143BcC2	3.8	61.0
143BdC	4.5	76.2
143Bo	2.7	30.5
143BrF	2.2	30.5
143Bt	10.4	30.5
143Bu	3.5	30.5
143By	3.1	30.5
143DeB	4.4	45.7
143DfA	3.5	30.5
143DfB	3.0	121.9
143DfC	4.9	91.4
143DlC	3.1	45.7
143DuC2	3.7	61.0
143DuD	6.6	38.1
143DuD3	4.6	38.1
143Fr	3.6	30.5
143Go	4.1	30.5
143Gu	4.4	30.5
143HeB	3.1	91.4
143Hn	3.8	45.7
143HoB	3.1	91.4
143LaB	3.8	121.9
143LaC	4.1	76.2
143LeB	3.8	121.9
143LeC	9.0	30.5
143LgC2	4.4	76.2
143LyB	2.6	121.9
143Ma	3.5	30.5
143MfA	3.8	22.9
143MfB	3.6	30.5
143NdC	3.0	45.7
143NpB	3.8	121.9
143NpD	3.8	121.9
143PcB	2.7	91.4
143PcC	3.9	121.9
143Pd	4.8	30.5
143Sa	6.2	30.5

Table 13 (continued)

Soil Code	Slope (%)	Slope-length (m)
143SdC	2.8	61.0
143SeC23.1	76.2	
143WaA 2.9	30.5	
143WaB	3.1	91.4
143WaB2	3.2	45.7
143WkA 2.9	45.7	
143WnC 3.2	91.4	
143WoB 3.5	91.4	
143WoB2	3.1	91.4
143WoC 4.4	76.2	
143WsC2	4.0	91.4
143WsD3	4.1	38.1
193ChB	9.5	30.5
193PdB	4.8	30.5
193DnB	0.9	30.5
193NuC	4.4	30.5
193ReD	3.1	30.5

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[a] Soil Codes that begin with 143 identify soils that are located in Erath County. Soil codes that begin 193 identify soils that are located in Hamilton County (the southern tip of the UNBRW is located in Hamilton County).

Table 14. Monthly weather generator table for Dublin, Texas that was used for the APEX simulations

EPIC variable	Definitions of variables	Units	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
OBMX	Average maximum air temperature	C	13.1	15.6	20.1	24.7	28.1	32.4	35.1	35.5	31.3	26.1	19.1	14.5
IBMN	Average minimum air temperature	C	-0.1	2.0	5.5	10.9	15.5	19.5	21.4	21.3	17.9	12.3	5.7	1.3
SDTMX	Standard deviation maximum daily air temperature	C	8.0	7.7	6.8	4.3	4.2	3.3	3.1	3.4	4.8	5.4	6.5	7.1
SDTMN	Standard deviation minimum daily air temperature	C	5.9	5.5	5.3	4.6	3.4	2.5	1.8	1.9	3.6	4.6	5.5	5.3
SMY	Average precipitation	mm	37.8	43.0	41.5	73.6	107.7	63.2	45.3	45.4	67.6	63.6	41.3	40.6
RST2	Standard deviation of daily precipitation	mm	8.32	8.63	9.16	14.58	16.97	13.40	12.60	13.66	15.27	13.60	9.70	8.56
RST3	Skew coefficient for daily precipitation	—	3.208	2.794	4.098	3.156	4.257	2.540	2.926	3.288	2.905	2.717	3.034	2.704
PRW1	Probability of wet day after dry day	—	.155	.164	.165	.172	.222	.136	.116	.115	.139	.143	.125	.130
PRW2	Probability of wet day after wet day	—	.436	.469	.392	.456	.450	.465	.412	.411	.494	.446	.448	.460
DAYP	Average number of rain days	d	6.7	6.7	6.6	7.2	8.9	6.1	5.1	5.1	6.5	6.4	5.6	6.0
WI	TP24 value b	mm	10.7	17.0	17.5	38.4	57.7	22.9	50.8	29.2	31.7	36.8	8.9	17.0
OBSL	Average daily solar radiation	MJm^{-2}	250.0	320.0	427.0	488.0	562.0	651.0	613.0	593.0	503.0	403.0	306.0	245.0
RH	Average relative humidity	%	.64	.63	.63	.62	.70	.64	.62	.60	.63	.64	.65	.65

Table 15. Monthly wind array for Bosque County, Texas that is used in the APEX simulations

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average wind speed (m/s)	5.81	5.81	6.26	6.26	5.81	5.81	4.92	4.92	4.47	4.47	4.92	5.36
Direction (% of time)												
N	10.0	9.0	8.0	7.0	5.0	2.0	2.0	2.0	4.0	7.0	6.0	7.0
NNE	6.0	7.0	6.0	7.0	3.0	3.0	2.0	3.0	6.0	5.0	9.0	3.0
NE	5.0	6.0	6.0	6.0	5.0	4.0	4.0	4.0	10.0	6.0	6.0	3.0
ENE	2.0	3.0	3.0	3.0	4.0	3.0	3.0	5.0	5.0	3.0	6.0	2.0
E	2.0	3.0	4.0	3.0	4.0	3.0	5.0	5.0	7.0	3.0	3.0	2.0
ESE	3.0	4.0	5.0	4.0	5.0	6.0	6.0	7.0	8.0	6.0	4.0	3.0
SE	8.0	10.0	9.0	12.0	13.0	16.0	16.0	17.0	16.0	17.0	3.0	8.0
SSE	12.0	11.0	13.0	17.0	17.0	23.0	18.0	21.0	15.0	12.0	8.0	13.0
S	13.0	11.0	12.0	16.0	18.0	21.0	21.0	18.0	14.0	12.0	12.0	12.0
SSW	5.0	4.0	5.0	5.0	6.0	7.0	8.0	6.0	4.0	4.0	15.0	6.0
SW	4.0	5.0	4.0	3.0	3.0	3.0	6.0	5.0	4.0	4.0	5.0	5.0
WSW	1.0	1.0	2.0	2.0	1.0	1.0	2.0	1.0	1.0	1.0	4.0	2.0
W	2.0	3.0	4.0	2.0	2.0	2.0	1.0	1.0	1.0	2.0	2.0	4.0
WNW	3.0	3.0	4.0	2.0	2.0	1.0	1.0	2.0	1.0	2.0	2.0	5.0
NW	8.0	9.0	6.0	4.0	2.0	1.0	1.0	1.0	2.0	5.0	6.0	9.0
NNW	10.0	9.0	8.0	5.0	3.0	1.0	1.0	1.0	1.0	5.0	3.0	8.0

Table 16. Runoff curve numbers assumed for the APEX UNBRW simulations

Crops	Hydrologic Condition	Hydrologic Group			
		A[a]	B	C	D
Costal Bermuda	Fair[b]	49	69	79	84
	Good[b]	39	61	74	80
Winter Wheat	good	63	75	83	87
Sorghum	good	67	78	85	89

[a] None of the waste application fields are classified as an A hydrologic group soil.

[b] The fair and good hydrologic conditions were used to differentiate between coastal bermuda in good condition and in fair condition (the latter consisting of native pasture and hay grazer fields).

Table 17. Number of fields, 10-year average yields, and target yields by crop for the cropping system - manure type combinations simulated in APEX for the environmental baseline.

Cropping System	Crop	Manure Type	Number of Fields	Average Yield (t/ha)	Target Yield (t/ha)[a]	% Difference[b]
Coastal b.	Coastal b.	liquid	31	13.7	14.8	-7
Coastal b.	Coastal b.	solid	69	15.3	14.8	3
Sorghum	Sorghum	liquid	1	10.8	9.9	9
Sorghum	Sorghum	solid	4	10.1	9.9	2
Coastal b./W. wheat	Coastal b.	liquid	43	9.5	11.9	-20
Coastal b./W. wheat	W. wheat	liquid	43	8.0	7.9	1
Coastal b./W. wheat	Coastal b.	solid	40	10.6	11.9	-11
Coastal b./W. wheat	W. wheat	solid	40	6.3	7.9	-20
W. wheat	W. wheat	liquid	1	6.8	9.9	-31
W. wheat	W. wheat	solid	5	5.8	9.9	-41
Sorghum/W. wheat	Sorghum	liquid	9	10.6	7.9	34
Sorghum/W. wheat	W. wheat	liquid	9	5.2	7.9	-34
Sorghum/W. wheat	Sorghum	solid	27	8.5	7.9	8
Sorghum/W. wheat	W. wheat	solid	27	4.2	7.9	-47

[a] The target yields are the yields that were assumed in the economic model, that are based on recommendations given in NRCS (1991). These are not measured yields, but rather yields that the agronomic rates listed in Table 6 are based on. A 25 percent yield reduction is assumed for coastal bermuda and winter wheat within a coastal bermuda overseeded with winter wheat system, that reflect typical observed yield suppressions for these crops when overseeded together.

[b] The % difference is based on the average yield relative to the target yield.

Table 18. Comparison of predicted average coastal bermuda and winter wheat yields (t/ha) in continuous coastal bermuda and coastal bermuda-winter wheat cropping systems for three different environmental baseline executions incorporating variation in simulation length, adjustment in nutrient application rates, and adjustment of coastal bermuda harvest dates using heat scheduling

Cropping System	Crop	Manure Type	Number of Fields	10-year; no HUs and original rates[a]	10-year; no HUs and updated rates[a]	10-year; with HUs and original rates[a]	10-year; with HUs and updated rates[a]	30-year; no HUs and original rates[a]	30-year; no HUs and updated rates[a]	30-year; with HUs and original rates[a]	30-year; with HUs and updated rates[a]
Coastal b.	Coastal b.	liquid	31	13.7	15.6	16.1	18.2	13.2	15.3	15.6	18.0
Coastal b.	Coastal b.	solid	69	15.3	15.3	15.7	15.7	16.7	16.7	16.9	16.9
Coastal b. /W. wheat	Coastal b.	liquid	43	9.4	9.4	14.1	14.1	9.2	9.2	13.5	13.5
Coastal b. /W. wheat	W. wheat	liquid	43	8.1	8.1	6.5	6.5	7.5	7.6	6.2	6.2
Coastal b. /W. wheat	Coastal b.	solid	40[b]	10.6	10.0	10.6	10.0	10.1	9.9	10.1	9.9
Coastal b. /W. wheat	W. wheat	solid	40[b]	6.3	5.9	6.3	5.9	5.5	5.5	5.5	5.5

[a] The 10-year and 30-year designations indicate length of simulation run; "no HU," indicates that the coastal bermuda harvests were simulated using fixed dates while "with HU," indicates that the coastal bermuda harvests were adjusted by APEX using heat unit scheduling; "original rates" indicates that no adjustments were made in nutrient application rates while "updated rates" indicates that nutrient application rates adjustments were incorporated for irrigated continuous coastal bermuda and coastal bermuda-winter wheat grown on the solid manure fields.

b Reduction of the nutrient application rate when using the "updated rates" for this cropping system-manure type combination resulted in 51 simulated fields instead of 40.

Table 19. Comparison of key APEX edge-of-field environmental indicators (kg/ha) for three different 10-year environmental baseline runs[a]

Environmental Indicator	Manure Type	10-year; no HUs and original rates		10-year; no HUs and updated rates		10-year; with HUs and updated rates[a]	
		Bermuda	Bermuda-Wheat	Bermuda	Bermuda-Wheat	Bermuda	Bermuda-Wheat
Organic N loss in sediment	I	3.7	4.6	3.8	4.6	3.6	6.0
	M	5.6	12.5	5.6	10.6	5.0	10.6
N loss in runoff	I	3.3	6.7	4.3	6.7	4.1	6.5
	M	1.3	1.8	1.3	1.6	1.2	1.6
N loss in subsurface flow	I	4.7	10.2	6.8	10.2	6.5	8.8
	M	1.6	5.0	1.6	4.3	1.6	4.3
P loss in sediment	I	5.3	6.3	5.9	6.3	5.6	8.1
	M	1.9	4.6	1.9	3.9	1.6	3.9
P loss in runoff	I	5.1	5.3	6.9	5.3	6.8	5.2
	M	5.8	5.0	5.8	4.2	5.7	4.2

[a] "No HU," indicates that the coastal bermuda harvests were simulated using fixed dates while "with HU," indicates that the coastal bermuda harvests were adjusted by APEX using heat unit scheduling; "original rates" indicates that no adjustments were made in nutrient application rates while "updated rates" indicates that nutrient application rates adjustments were incorporated for irrigated continuous coastal bermuda and coastal bermuda-winter wheat grown on the solid manure fields.

Table 20. Measurements of ammonia emission from surface applied cattle manure

NH_3 volatilized as a % of Total N	NH_3 volatilized as a % of NH_4	The % of the total N in applied manure that is NH_4	Comments[a]	Reference
26.6 - 29.9	52.2 - 55.6	49-54	Dairy cattle slurry; three experiments; 96 hr; grassland	Klarenbeek et al. 1993
17	45	38	Cattle slurry; grassland; warm, dry weather in late spring	Ryden 1986
23.9	39.9	60	Dairy cattle slurry; 76 hr	Pain et al. 1989
28.5	61.0	42	Average of two experiments; dairy cattle slurry; perennial ryegrass	Thompson et. al. 1987
12.1	40.9	23-34	Dairy cattle slurry; average of two experiments; grassland	Lockyer et al. 1989
19.6 - 49	33.3 - 82.9	58-64	Cattle slurry; 42 treatments; applications to stubble, clover, grass, etc.	Sommer et al. 1991
18 - 59	26 - 100	55-70	Cattle slurry; 15 treatments; 5 cm high ley grass; 6 days; temp. range of 0.2 - 15.7°C	Sommer and Christenson 1991
12-18	24 - 33	46-61	Liquid dairy cattle manure; bare soil; 6-7 days; 3 different years in Spring	Beauchamp et al. 1982
24.1	51.5	46	Beef cattle slurry; grassland; 7 days	Stevens and Logan 1987
17.5 - 26	40 - 60	44	Dairy cattle slurry; grassland; 6 days; six different application rates	Thompson et al. 1990
14.5 - 27.5	61 - 99	19-32	Solid dairy cattle manure; 4 experiments over two years; 5-25 days	Lauer et al. 1976

[a] Some of the manure identified as "cattle slurry" may have come from dairy cows but was not specifically stated. Time periods (e.g. 96 hrs) denote experiment time lengths while crop type (e.g. graassland) indicates type of crop the manure was applied

Table 21. Means of Yield and Hydrologic Indicators over liquid and solid waste fields[a]

Environmental Indicator	Manure Type[b]	Bermuda	Sorghum	Bermuda-Wheat	Sorghum-Wheat	Wheat
Yield of first crop (tons/ha)	I	13.7	10.8	9.5	10.6	6.8
	M	15.3	10.1	10.6	5.2	5.8
Yield of second crop (tons/ha)	I	0.0	0.0	8.0	4.2	0.0
	M	0.0	0.0	6.3	8.5	0.0
Irrigation (mm)	I	502.0	265.0	750.0	531.0	263.0
	M	0.0	0.0	0.0	0.0	0.0
Evapotranspiration (mm)	I	924.0	776.5	1128.4	1012.9	821.2
	M	738.3	654.6	797.8	739.0	673.8
Runoff (mm)	I	114.7	217.8	155.8	213.8	170.9[e]
	M	86.7	173.9	90.4	152.6	165.4[e]
Subsurface flow (mm)	I	46.7	36.0	69.5	38.1	24.7
	M	23.5	21.9	28.7	24.9	19.7
Percolation (mm)	I	334.3	171.3	315.3	194.7	184.7
	M	77.6	86.5	12.2	13.2	77.1
Erosion (tons/ha)	I	0.6	11.0[c]	1.1	2.8	4.3[e]
	M	0.1	5.1[c]	0.4	1.2	6.9[e]

[a] Pairs not marked with superscripts are at least significant at the 1% level

[b] I=irrigated (liquid manure); m=solid manure

[c] Means are not significantly different at the 1% level of significance

[d] Means are not significantly different at the 5% level of significance

[e] Means are not significantly different at the 10% level of significance

Table 22. Means of Nitrogen Indicators over liquid and solid waste fields (kg/ha)[a]

Environmental Indicator	Manure Typeb	Bermuda	Sorghum	Bermuda-Wheat	Sorghum-Wheat	Wheat
Organic N loss in sediment	I	3.6	11.3	4.7	10.2	6.4
	M	5.6	41.0	12.5	22.3	40.8
N loss in runoff	I	3.4	11.0	7.0	8.8	9.8
	M	1.3	5.5	1.8	3.8	5.6
Mineralization of N	I	145.6	89.5	239.4	224.9	122.2
	M	299.4	192.0	496.0	370.9	230.9
Nitrification	I	237.0	127.2	352.7	242.2	126.4
	M	29.4	16.2	46.0	32.2	16.2
N loss in subsurface flow	I	4.6	6.6	10.2	5.1	4.9
	M	1.6	3.2	5.0	3.8	3.3
N loss in percolate	I	12.7[d]	9.1	25.1	22.3	10.6[c]
	M	10.4[d]	4.0	5.1	6.4	16.6[c]
Denitrification	I	37.9[e]	35.3	34.5	30.8	43.5
	M	39.3[e]	44.6	58.6	33.9	57.3
Total nitrate in soil profile	I	28.9	60.2[e]	25.0	20.6[c]	57.8[e]
	M	23.0	55.8[e]	35.3	23.8[c]	49.1[e]
Volatilization of N	I	211.9	108.2	326.1	230.4	109.1
	M	26.2	13.4	39.3	27.1	13.5
Mineral N applied[e]	I	682.3	364.0	1046.3	728.0	364.0
	M	59.0	31.5	90.5	63.0	31.5
Organic N applied	I	122.9	65.6	188.4	131.1	65.6
	M	781.0	416.6	1197.7	833.3	416.6
N in yield of 1st crop	I	295.3	129.3	140.1	110.7	104.9
	M	240.5	122.5	127.9	92.6	91.1
N in yield of 2nd crop	I	0.0	0.0	232.5	145.2	0.0
	M	0.0	0.0	187.3	126.8	0.0
Ammonia N applied[f]	I	673.5	359.3	1032.8	718.6	359.3
	M	57.3	30.6	87.9	61.2	30.6
Commercial mineral N applied	I	0.0	0.0	0.0	0.0	0.0
	M	0.0	0.0	0.0	0.0	0.0

[a] Pairs not marked with superscripts are at least significant at the 1% level

[b] I = irrigated (liquid manure); m=solid manure

[c] Means are not significantly different at the 1% level of significance

[d] Means are not significantly different at the 5% level of significance

[e] Means are not significantly different at the 10% level of significance

[f] The mineral N applied includes the applied ammonia N; the percentage of mineral N that is ammonia is equal to the ammonia fractions listed in Tables 8 and 10

Table 23. Means of Phosphorus Indicators over liquid and solid waste fields (kg/ha)[a]

Environmental Indicator	Manure Type	Bermuda	Sorghum	Bermuda-Wheat	Sorghum-Wheat	Wheat
P loss in runoff	I	5.1	3.0	5.4[c]	5.5[e]	2.7[d]
	M	5.8	4.5	5.0[c]	5.9[e]	3.0[d]
Labile P	I	303.0	243.4	389.0	284.8	219.2[d]
	M	391.3	289.1	558.0	414.3	243.2[d]
P loss in sediment	I	5.3	16.5[c]	6.4	10.6	9.4
	M	1.9	15.1[c]	4.6	8.5	15.0
Mineralization of P	I	41.7	30.1	102.9	75.9	46.7
	M	61.3	44.1	122.6	87.9	59.7
Mineral P applied	I	259.9	138.7	398.6	277.3	138.7
	M	237.3	126.6	363.9	253.2	126.6
P in yield of 1st crop	I	62.2	30.2	35.3	22.8	32.7
	M	57.3	28.2	28.8	20.7	31.0
P in yield of 2nd crop	I	0.0	0.0	43.2	29.7	0.0
	M	0.0	0.0	37.9	24.6	0.0
Organic P applied	I	140.0	74.7	214.6	149.3	74.7
	M	127.8	68.2	195.9	136.3	68.2

[a] Pairs not marked with superscripts are at least significant at the 1% level

[b] I=irrigated (liquid manure); M=solid manure

[c] Means are not significantly different at the 1% level of significance

[d] Means are not significantly different at the 5% level of significance

[e] Means are not significantly different at the 10% level of significance

ENDNOTES

1. In-stream monitoring of the UNBRW was initiated in 1992 by the Texas Institute for Applied Environmental Research; however, only the monitoring data collected from September 1993 on are suitable for model calibration.

2. Precipitation data was only available for the final 12 months for a few of the rain gauges.

3. A subsequent execution of APEX and SWAT has extended the environmental baseline through August of 1995, providing an additional eight month time period for model validation.

4. The majority of the structures on dairies in the UNB River Watershed are called waste storage ponds rather than lagoons, he latter term being used for systems that actually provide waste treatment (i.e. two-stage lagoon systems). However, lagoon is used here to maintain consistency with the terminology used in APEX.

5. These are also referred to as normal (design runoff) and maximum "depths", which is why the volume units are given in mm (these depths are translated into volumes in the lagoon submodel).

6. APEX version 5140 was used for this project. APEX7040 has since become available that more accurately simulates coastal bermuda overseeded with winter wheat.

7. According to McFarland (1997), up to five cuttings of coastal bermuda can be taken in many years from an irrigated continuous coastal bermuda field, if moisture conditions are adequate. However, five cuttings are never achieved for coastal grown on solid waste disposal fields.

8. The accumulated heat units are adjusted back to nearly zero following each harvest when multiple crop harvests are simulated within a single growing season (Williams 1997).

9. The modifications to N response are incorporated in APEX7040.

10. NH_4 and HH_3 are essentially interchangeable in APEX, i.e. the applied NH_4 is assumed to be completely converted to NH_3 upon application.

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