Water Quality Assessment with Agro-Environmental Indexing of Non-point Sources, Trinity River Basin

X. Chen, W. L. Harman, M. Magre, E. Wang, R. Srinivasan, J. R. Williams

Abstract. *A comprehensive water quality assessment was conducted to determine the potential impacts of agriculture on surface and groundwater quality. The* **EPIC** *(***E***nvironmental* **P***olicy* **I***ntegrated* **C***limate) model was used to simulate cropping systems in the Trinity River Basin in Texas for 12 eight-digit hydrologic unit areas (HUA) using combinations of 29 soil series, 9 crops, and 3 tillage technologies. The study utilizes an indexing method to facilitate communicating the relative impacts of soils, crops, tillage, and management practices on the following agro-environmental indicators of water quality: (1) surface water runoff, (2) soil erosion, (3) nitrate-nitrogen (NO_3-N) loss in runoff, (4) phosphorus (P) loss in runoff, (5) NO_3-N loss in sediment, (6) P loss in sediment, and (7) NO_3-N leaching loss.*

A frequency analysis was also conducted to provide an overview of the impacts; indicated by averaging broad groupings of precipitation, soil types by percent clay, percent slope, tillage practices, and crop rotations produced. When grouped by soil type, high clay content soils on average minimized NO_3-N leaching of all soil types. In contrast, clay and loam soils increased runoff over sandy soils. Additionally, clay and loam soils lost more NO_3-N and P in runoff as well as in sediment than sandy soils. With respect to tillage practice, no-till and reduced tillage generally reduced erosion compared with conventional tillage practices. NO_3-N and P losses in sediment were reduced using no-till and reduced tillage, but the NO_3-N and P losses in runoff were not particularly affected, on average, by tillage practice. With regard to crop selection and rotation, the degree of agro-environmental impact from nutrient losses was largely correlated with the applications of N and P.

Though the simulation results largely agreed with previous experiences of agricultural researchers, the ultimate implication of this study is that creating indices for a multitude of comparisons of simulated water quality or other environmental impacts in complex agricultural systems can be communicated and summarized with a high degree of specificity. However, indexing simulation results for comparative analyses was less than satisfactory, on occasion, when an index value was very large usually caused by a small value for the baseline crop. In many cases, the impact of the alternative would not be considered as extreme, though the large index value might imply the agro-environmental impact to be severe. The major advantage of indexing is the ease of communicating diverse results in an uncomplicated manner. Thus, indexing provides a means of communicating water quality impacts of complex production elements in agriculture to citizens, policy makers, and other decision-makers not familiar with them.

Keywords. ***EPIC*** *model, Simulation, Indexing, Water quality, Non-point source, Environment, Trinity River, Texas.*

The Trinity River Basin (TRB) has been identified by the Texas Natural Resources Conservation Commission (NRCC) as a river of concern with regard to water quality. As a result, this basin was selected for developing a non-point source index of water quality, particularly one that facilitates summarizing analytical results in a way that enhances communication of the impacts of a complex agricultural system on water quality.

The TRB is large and diverse in land uses. Twelve 8-digit hydrologic unit areas (HUA) are outlined in figure 1, reaching from northwest of Fort Worth, Texas, to the Gulf Coast east of Houston, Texas (including all or part of 31 counties, see table 1). Agricultural activities are prominent over the region, as are industrial and urban activities. Figure 1 indicates widely varying land uses including the major use of land as non-irrigated agricultural cropland, and rangeland plus forest land. Lesser areas are in urban uses.

Total cropland and improved pasture exceeds 25 900 km^2 or 55% of the TRB, varying by HUA from a low of 28% in no. 12030101 (fig. 1) to a high of 90% in no. 12030109. Rangeland comprises nearly 4662 km^2 or 10% of the basin, ranging from a high of about 48% in no. 12030101 to a low of zero in no. 12030203. Land in various types of forest amounts to nearly 11 396 km^2 or 24% of the basin, varying from a high of 59% in no. 12030203 to a low of 3% in no. 12030109.

This study focuses on cropland and improved pastureland and the agricultural practices used in crop and hay production. Major crops produced in the basin and considered in this study include corn, sorghum, wheat, cotton, rice, and soybeans with a substantial portion devoted to improved pastures such as bermudagrass for grazing and hay production. Secondary crops include

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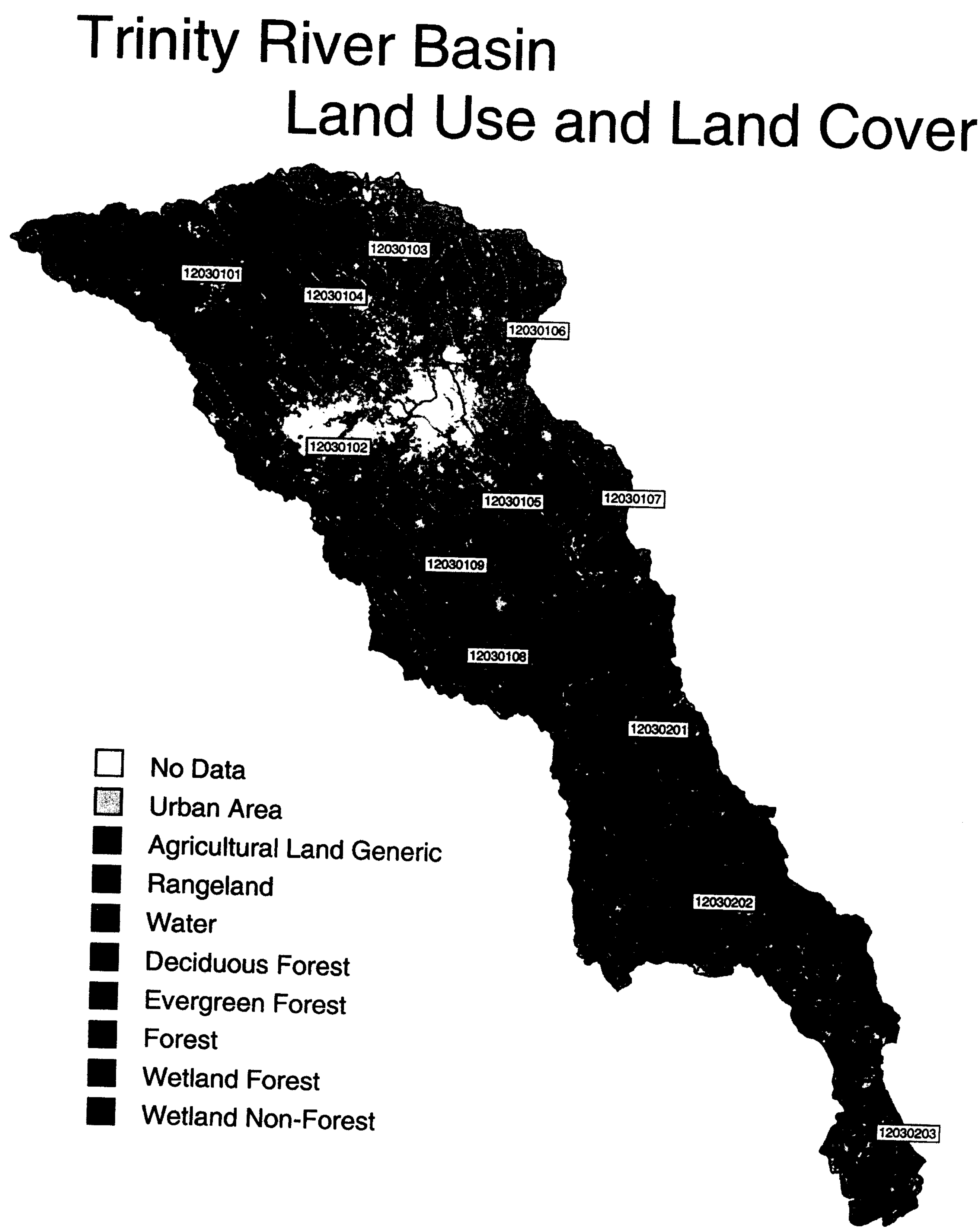

Figure 1–Trinity River Basin land use and land cover.

peanuts, oats, and rye. The study does not include assessments of production practices used in vegetable, fruit, nut, forestry or other specialty crop production. While poor stewardship of the land and environment in these latter activities can be localized, production activities of these crops do not require widespread uses of fertilizers and therefore are of lesser importance regarding the regional water quality focus of this study.

Table 1. Counties, weather stations, and land use by HUA, Trinity River Basin

HUA	Counties	Weather Stations	Land Uses (%)			
			Agricultural	Range	Forest	Other
12030101	Archer, Jack, Wise, Clay, Montgomery	Weatherford,Tex.	28.35	48.30	17.48	5.87
12030102	Park, Tarrant, Johnson	Weatherford,Tex.	62.06	4.21	8.55	25.18
12030103	Cooke, Grayson, Denton	Gainesville,Tex.	71.13	10.48	7.78	10.61
12030104	Montgomery, Wise, Denton	Gainesville,Tex.	51.61	34.03	10.20	4.16
12030105	Dallas, Ellis, Kaufman, Navarro	Kaufman, Tex.	68.81	2.40	9.60	19.19
12030106	Grayson, Collin, Rockwall, Dallas	Sherman, Tex.	79.58	0.20	4.60	15.62
12030107	Kaufman, Van Zandt, Henderson	Kaufman, Tex.	80.47	0.79	10.28	8.46
12030108	Hill, Navarro	Mexia, Tex.	79.56	9.54	5.68	5.22
12030109	Johnson, Hill, Ellis, Navarro	Hillsboro, Tex.	89.57	2.29	2.96	5.18
12030201	Freestone, Anderson, Henderson, Houston	Palestine, Tex.	46.72	5.88	44.15	3.25
12030202	Leon, Houston, Madison, Trinity, Walker, Polk, San Jacinto	Livingston, Tex.	31.97	0.92	59.26	7.85
12030203	Liberty, Chambers	Conroe, Tex.	28.40	0.00	58.91	12.69

The analysis focuses on common and new or advanced agricultural practices and their potential of safeguarding water quality by developing an index of relativity. The agro-environmental index compares several improved cultural practices including alternative crop rotations, which serve to safeguard water quality.

The objectives of this article are to:

1. Develop several field level cultural practices and cropping alternatives to estimate water quality impacts of current and improved agricultural cropping systems.
2. Index long-term agro-environmental estimates of alternative production systems to analyze and communicate the relative impacts on water quality.

Methods

Watershed characteristics which are necessary inputs to simulate agro-environmental impacts in the watershed include identifying crops and grasses typically grown in the area; whether the land is irrigated or non-irrigated farmland; the associated soil types and slopes; and customary management and tillage practices. To develop the most likely combinations of soil type, cropping systems, and management practices, several sources of data that identify typical characteristics of the basin and each watershed within the basin were consulted to characterize "typical" situations. The primary crops grown in the area as well as the soil type and associated management practices were identified based on cross-referencing several sources of information.

HUMUS (Hydrologic Unit Model of the U.S.) data were used to provide information on location, land use, and soil type by HUA (Srinivasan et al., 1993). From the location of each HUA, the nearest major weather station was located in the proximity of the HUA, if not within the boundaries. Table 1 lists the weather station used in each HUA.

Soil type, land use/land cover, and crop history from the USDA Natural Resources Inventory (NRI) survey was used to cross-reference information and develop combinations of soils and crops to represent each HUA. Twenty-nine soil series were identified for the study area from HUMUS. Crop rotations were identified in the NRI historical data series, and by expert opinion (J. R. Williams and W. L. Harman, personal communication).

Additionally, typical slopes and slope lengths were obtained from NRI observations and if several observations of the same soil occurred, the slope of the largest area was used (table 2). Primary soil series for each HUA were selected by cross-referencing each county soil survey to validate the soils indicated by HUMUS and the NRI survey. Each group of soils represents 75% or more of the cropland area of each HUA. The soils database was built

Table 2. Major soils, classification, and characteristics by HUA, Trinity River Basin

HUA	Major Soils	Soil Classification	Slope (%)	Clay (%)
12030101	Truce FSL	Fine, Mixed, Thermic *Udic Paleustalfs*	2.0	14.0
	Windthorst FSL	Fine, Mixed, Thermic *Udic Paleustalfs*	3.6	11.5
	Bastsil FSL	Fine-loamy, Siliceous, Thermic *Udic Paleustalfs*	1.2	13.5
	Pulexas FSL	Coarse-loamy, Siliceous, Thermic *Typic Ustifluvents*	1.0	12.5
	Bonti FSL	Fine, Mixed, Thermic *Ultic Paleustalfs*	2.0	15.0
12030102	Houston C	Fine, Smectitic, Thermic *Udic Haplusterts*	1.3	55.0
	Heiden C	Fine, Smectitic, Thermic *Udic Haplusterts*	2.3	50.0
12030103	Tinn C	Fine, Smectitic, Thermic *Typic Hapluderts*	0.8	50.0
	Heiden C		2.8	50.0
	Slidell C	Fine, Smectitic, Thermic *Udic Hapluderts*	1.9	50.0
	Normangee CL	Fine, Smectitic, Thermic *Udertic Haplustalfs*	2.3	30.0
	Wilson CL	Fine, Smectitic, Thermic *Oxyaquic Vertic Haplustalfs*	1.3	31.0
	Branyon C	Fine, Smectitic, Thermic *Udic Haplusterts*	0.9	50.0
	Ponder L	Fine, Smectitic, Thermic *Vertic Haplustalfs*	1.7	26.5
	Houston C		1.6	55.0
	Sanger C	Fine, Smectitic, Thermic *Udic Haplusterts*	1.9	50.0
12030104	Sanger C		1.6	50.0
	Somervell GrvL	Loamy-skeletal,Carbonatic, Thermic *Typic Calciustolls*	1.5	26.5
12030105	Trinity C	Very-fine, Smectitic, Thermic *Typic Hapluderts*	0.5	70.0
	Austin SC	Fine-silty,Carbonatic, Thermic *Udorthentic Haplustolls*	2.1	45.0
	Burleson C	Fine, Smectitic, Thermic *Udic Haplusterts*	0.9	50.0
	Houston C		1.5	55.0
12030106	Trinity C		0.5	70.0
	Fairlie C	Fine, Smectitic, Thermic *Udic Haplusterts*	2.0	42.5
	Houston C		1.9	55.0
12030107	Houston C		2.2	55.0
	Wilson CL		1.5	31.0
12030108	Trinity C		1.0	70.0
	Crockett FSL	Fine, Smectitic, Thermic *Udertic Paleustalfs*	2.3	12.5
	Heiden C		1.8	50.0
	Mabank FSL	Fine, Smectitic, Thermic *Oxyaquic Vertic Paleustalfs*	1.0	17.5
12030109	Houston C		2.0	55.0
	Heiden C		3.6	50.0
	Burleson C		1.2	50.0
	Trinity C		0.4	70.0
12030201	Trinity C		0.4	70.0
	Darco FSL	Loamy, Siliceous, Thermic *Grossarenic Paleudults*	1.0	6.0
	Trep FSL	Loamy, Siliceous, Thermic *Arenic Paleudults*	1.0	4.0
12030202	Pickton LFS	Loamy, Siliceous, Thermic *Grossarenic Paleudalfs*	4.5	8.0
	Texark SC	Very-fine, Smectitic, Thermic *Aquic Hapluderts*	0.2	59.5
12030203	Bernard CL	Fine, Smectitic, Thermic *Vertic Argiaquolls*	0.3	27.5
	Lake Charles C	Fine, Smectitic, Hyperthermic *Typic Hapluderts*	0.2	50.0
	Vamont SC	Fine, Smectitic, Thermic *Oxyaquic Hapluderts*	0.2	50.0
	Beaumont C	Fine, Smectitic, *Hyperthermic Chromic Dystraquerts*	0.2	52.5

Note: C — Clay, L — Loam, CL — Clay loam, SC — Silty clay, FSL — Fine sandy loam, LFS — Loamy fine sand, GrvL — Gravel loam.

using the Map Unit Use File (MUUF), a database that provides soil input properties (Baumer et al., 1994).

Management practices including tillage alternatives were based largely on central Texas crop budgets developed previously (V. Benson, unpublished data). Two tillage practices were used for most crops except cotton, rice, soybeans, and peanuts. The two practices included (1) a moderate level of residue maintenance commonly practiced in the area referred to as reduced tillage, and (2) no-tillage where all plowing operations were replaced by chemical weed control. A more intensified level of tillage, conventional tillage, was used for cotton, peanuts, rice, and soybeans wherein economical and effective use of incorporated herbicides commonly requires conventional disk tillage. This common tillage method is used for weed control also. Disking destroys residues quickly versus the use of a field cultivator, chisel plow, or sweep for reduced tillage which preserves limited residue on the surface for increased erosion control (Alberts and Neibling, 1994). Livestock grazing is usually followed by a point chisel operation to alleviate topsoil compaction in all systems except perennial bermudagrass pastures.

After compiling the soil and crop data and developing the production systems, the EPIC model was used to simulate selected combinations of row crop, small grain, and bermudagrass hay production systems for each of the soils in an HUA. EPIC is a daily time-step model in which crop growth processes, water and nutrient uptake, and soil and pesticide losses are simulated using daily weather conditions. It predicts crop growth, crop yields, and soil and pesticide losses at the edge of the field. It can be used with either actual weather or simulated weather. A supporting database includes many soils and weather stations in the U.S. and the world. It was originally developed to estimate the impacts of long-term erosion on the nation's soil productivity for the Soil and Water Conservation Act of 1985 (Williams et al., 1989). About 900 benchmark soils and 500,000 crop/tillage/soil conservation strategies were analyzed across the U.S.

A period of 60 years was selected to provide sufficient variation for simulating random weather events. This length of simulation provides 30 years production, runoff, erosion, and nutrient losses for each of two crops in a rotation, or 60 years of continuous cropping. The continuous crops and rotations selected for this analysis along with their abbreviated notations used in describing the systems follow:

- Continuous corn, reduced till (RtCN/CN).
- Continuous sorghum, reduced till (RtSG/SG).
- Continuous cotton, both conventional and reduced till (CtCT/CT and RtCT/CT).
- Continuous cotton followed by a reduced till rye cover crop for winter grazing, both conventional till and reduced till cotton (CtCT/RtRYcc and RtCT/RtRYcc).
- Continuous peanuts, conventional till (CtPN/PN).
- Continuous peanuts followed by both no-till and reduced till rye cover crops for winter grazing, conventional tillage is used for peanuts due to hazard of southern blight enhanced by surface residues (CtPN/RtRYcc and CtPN/NtRYcc).
- Wheat for grain, reduced till in all rotations (RtWH/WH).
- Wheat for grain/wheat graze-out, both reduced tillage and no-tillage are used for graze-out wheat following wheat grain harvest (cattle completely utilize the graze-out wheat) (RtWH/RtWHGZ and RtWH/NtWHGZ).
- Oats for grain/oats graze-out, again both reduced tillage and no-tillage are used for the graze-out oats (RtOA/RtOAGZ and RtOA/NtOAGZ).
- Sorghum/wheat for grain in which wheat is reduced till and sorghum is both reduced and no-till (RtSG/RtWH and NtSG/RtWH).
- Corn/wheat for grain in which wheat is reduced till and corn is both reduced and no-till (RtCN/RtWH and NtCN/RtWH).
- Cotton/wheat for grain in which wheat is reduced till and cotton is both conventional and reduced till (CtCT/RtWH and RtCT/RtWH).
- Sorghum/cotton in which sorghum is reduced till and cotton is both conventional and reduced till (RtSG/CtCT and RtSG/RtCT).
- Sorghum/soybean in which sorghum is reduced till and soybean is both conventional till and reduced till (RtSG/CtSB and RtSG/RtSB).
- Corn/cotton in which corn is reduced till and cotton is conventional and reduced till (RtCN/CtCT and RtCN/RtCT).
- Corn/soybean in which corn is reduced till and soybean is both conventional till and reduced till (RtCN/CtSB and RtCN/RtSB).
- Rice/soybean/rice, irrigated, conventional till (ICtRI/SB/RI).
- Soybean/rice/soybean, irrigated, conventional till (ICtSB/RI/SB).
- Bermudagrass hay overseeded with no-till winter wheat for graze-out (BERM/NtWHGZ).
- Bermudagrass hay (BERM).

Not all rotations were evaluated for each HUA; only those indicated by NRI survey data. Bermudagrass hay was produced in each HUA in the TRB to provide a baseline production system for comparison of index values. Bermudagrass hay is a perennial hay crop; is seldom if ever tilled; and is broadcast fertilized with dry nutrients applied to the soil surface, non-incorporated. All weed control is by chemicals. This cropping system was selected as the standard by which all other production systems would be compared. It is relatively non-intrusive regarding tillage and requires moderate amounts of N and P for satisfactory hay yields. Each production system other than bermudagrass hay is "typically" or "potentially" used in the area, recognizing that variations in cultural practices from the ones developed in the analysis occur in the region.

Validation of the EPIC Model

Validation of simulated crop yields was conducted using historical county crop yields in several HUAs of the TRB. Selected crop, soil, and management combinations in HUA No. 12030109 were used for validations of runoff, erosion, and nutrient losses compared with experimental data.

Validation of Crop Yields

Texas county historical crop yield data for 1992-1997 was utilized for simulated yield validation (Texas

Agricultural Statistics Service, 1992-1997). The reported yield of each crop used in the study was averaged for the period 1992-1997 for all counties with major crop areas in the TRB. Yields of most major crops were reported for 10 to 14 counties.

Trial simulations of 60-year durations were conducted by modifying yield-related model parameters until average simulated yields for most combinations of cultural practices and soil types were in near agreement with the published county average yields. In this study, it was presumed that producers maintained nutrient levels at moderately fertile levels over the long term to facilitate simulating (1) realistic crop yields, (2) crop uptake of nutrients and water, (3) losses of nutrients in runoff, (4) nutrient losses in sediment, and (5) NO_3-N losses by leaching.

Table 3 provides the total N and P applied yearly and per crop for each crop rotation. Rates were not varied with respect to soil, rainfall, or over time. They were developed by adjusting starting nutrient levels such that residual NO_3-N and P levels in the soil at the end of the 60-year simulation would be approximately equal to the initial levels, provided simulated yields were simultaneously validated. A commonly occurring soil in HUA No. 12030109 of the TRB (fig. 1), Houston Black clay (Fine, Smectitic, Thermic *Udic Haplusterts*), was used for the trial simulations. An initial period of six years was simulated to update generic soil data to realistic soil conditions for the long-term simulation, i.e., to develop a starting level of residue, soil moisture, organic carbon, bulk density, pH, soil fertility, and other factors that might have resulted from a previous period of a particular production system.

Table 3. Crop alternatives and fertilizer rates used in analysis

Crop Alternatives/Rotation	Nitrogen (kg/ha)	Phosphorous (kg/ha)
Bermuda hay	70	24.6
Bermuda hay/wheat graze-out	70/46	24.6/0
Continuous corn	201.6	15
Continuous cotton	15	51.5
Continuous peanuts	16.8	66.1
Continuous sorghum	127.7	32.5
Continuous wheat	54.9	11.2
Corn/wheat grain	201.6/21.3	15/11.2
Corn/cotton	201.6/15	15/51.5
Corn/soybean	201.6/0	15/59.9
Cotton/wheat grain	15/54.9	51.5/11.2
Cotton/rye cover crop, grazed	4.5/40.9	51.5
Oats grain/oats graze-out	69.4/40.9	11.2/0
Peanuts/rye cover crop, grazed	16.8/0	66.1/0
Rice/soybean/rice	343.3/0/343.3	50.4/0/50.4
Sorghum/cotton	127.7/15	32.5/51.5
Sorghum/soybean	127.7/0	32.5/59.9
Sorghum/wheat grain	127.7/54.9	32.5/11.2
Soybean/rice/soybean	0/343.3/0	0/50.4/0
Wheat grain/oats grain	54.9/69.4	11.2/11.2
Wheat grain/wheat grazing	21.3/65.5	11.2/0

Validation of Runoff, Erosion, and Nutrient Losses

EPIC simulates an integrated soil/crop/hydrology ecosystem similar to that suggested by Laflen and Colvin (1981). The simulation results were similar to experimental results on a Houston Black clay soil at the USDA-ARS Grassland, Soil, and Water Conservation Research Laboratory, Temple, Texas. Due to the limited number of continuous corn simulations characteristic of the few cropping situations in the TRB, the more commonly occurring sorghum is used most often for the model validation of runoff, erosion, and nutrient losses.

In one experiment comparing bermudagrass sod with chisel-tilled corn land after harvest, 3 h of water applied at a 125 mm/h rate from a rainfall simulator increased erosion 20 times resulting in total N losses in sediment of 12 times more from corn land than bermudagrass sod. However, NH_4-N and P losses in runoff were lower from chisel-tilled corn land (Torbert et al., 1999).

Similarly, over the 60-year simulation period, reduced tillage of continuous sorghum increased annual simulated erosion nearly 16 times over bermudagrass hay, and NO_3-N losses in sediment were four times larger than bermudagrass hay. NO_3-N loss in runoff from sorghum averaged only 39% of bermudagrass, and runoff P loss was marginally higher than bermudagrass. It should be noted that nutrient loss comparisons between experiments and simulations can be affected by the form and amount of nutrient added as fertilizer. In the simulation, bermudagrass hay received 33.6 kg P/ha whereas in the experiment, it received 73.9 kg P/ha, both as surface-applied granular mixes. The higher application rate of P in the experiment probably explains the increased loss of soluble P in the experiment from sod compared to corn land in contrast to the lower loss from sod than sorghum in the simulation.

Timmons et al. (1973) reported that nutrient losses declined as the intensity increased of fertilizer incorporation. Simulations of HUA No. 12030109 on the Houston Black clay soil again supported this in almost every cropping system. The primary exceptions were production systems which utilized no-tillage (corn and sorghum), or included crops which required larger amounts of N fertilizer compared with bermudagrass hay, or included winter wheat in which N was applied during the

Table 4. Agro-environmental indices for HUA No. 12030101, Trinity River Basin

Soil/Cropping System TruceFSL Soil	Notation of System	Runoff (mm)	Erosion (t/ha)	NO_3-N Runoff (kg/ha)	P Runoff (kg/ha)	NO_3-N Sed. Loss (kg/ha)	P Sed. Loss (kg/ha)	NO_3-N Leaching (kg/ha)
Bermuda hay, Values		*57.05*	*0.04*	*3.64*	*0.56*	*1.55*	*0.30*	*3.03*
Bermuda hay index:	BERM	100	100	100	100	100	100	100
Berm. hay/NT wht grzout	BERM/NtWHGZ	40	0	16	32	0	0	159
Cont. peanuts, CT	CtPN/PN	224	12000	92	105	1099	3923	628
Cont peanuts/NT rye c.c	CtPN/NtRYcc	119	5500	39	71	714	2213	844
Cont peanuts/RT rye c.c	CtPN/RtRYcc	170	8025	70	95	915	2977	757
Wheat/NT wheat gzout	RtWH/NtWHGZ	167	625	79	14	171	130	694
Wheat/RT wheat gzout	RtWH/RtWHGZ	161	950	78	13	298	223	684
Cont. wheat, RT	RtWH/WH	163	1125	81	23	290	257	632

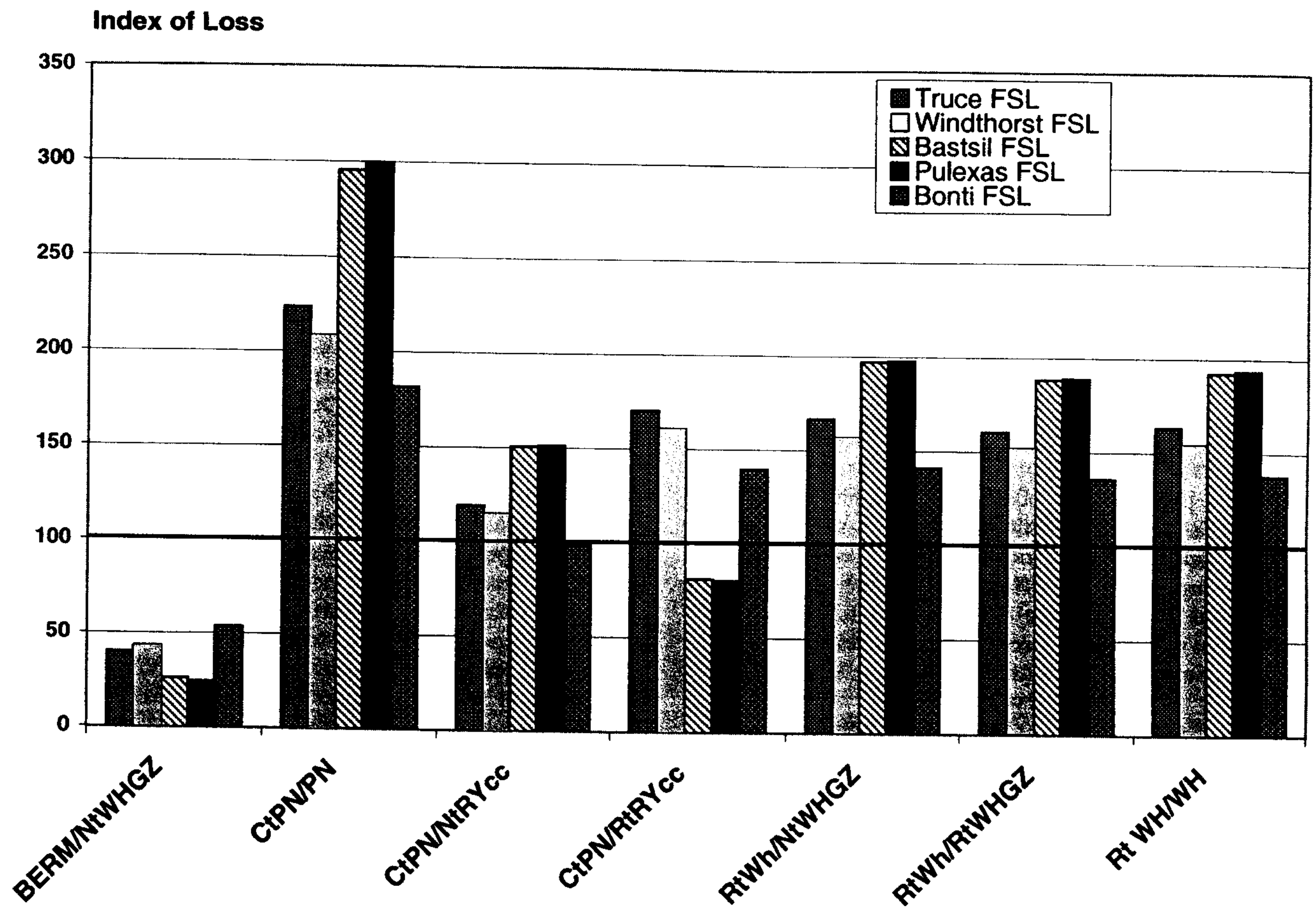

Figure 2–Water runoff losses, HUA12030101.

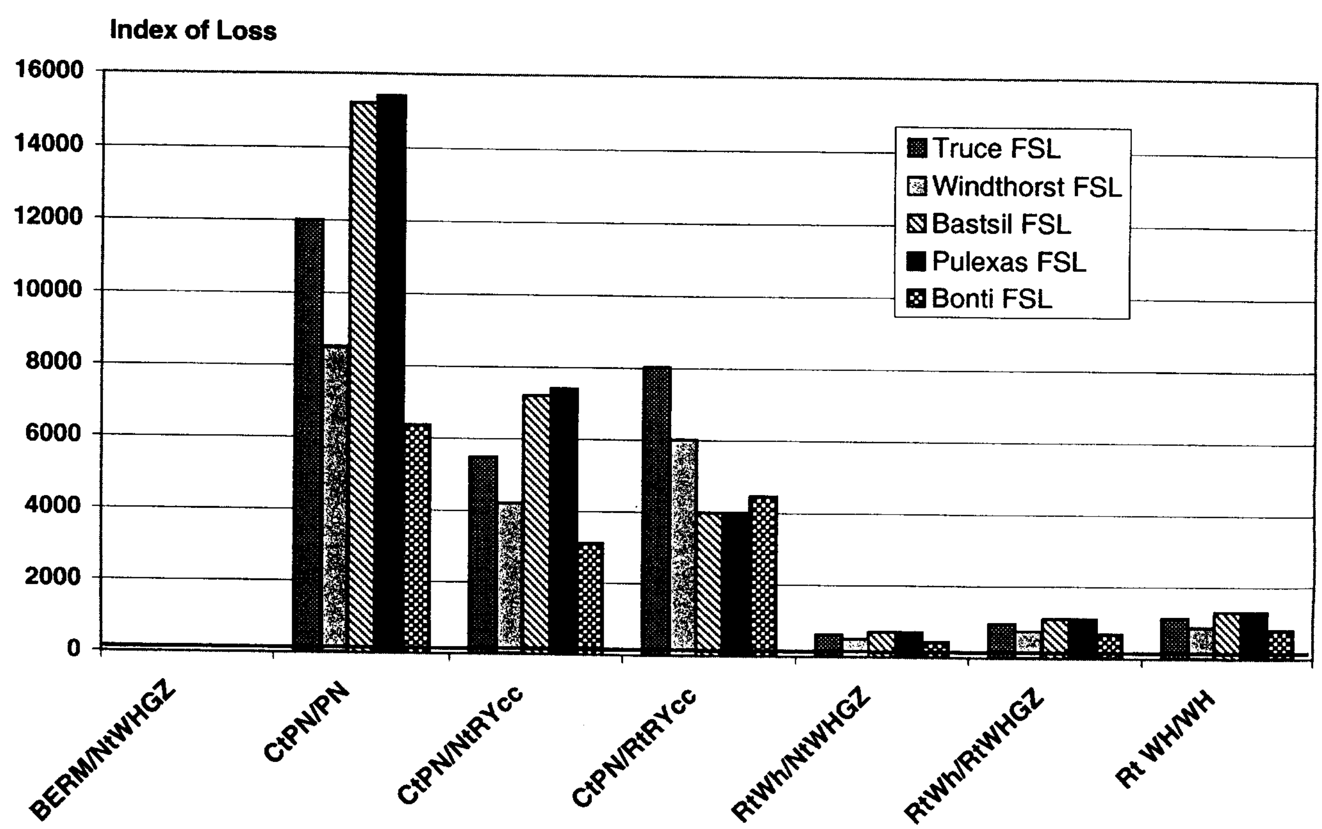

Figure 3–Soil erosion losses, HUA12030101.

late fall before an extended period of slow growth and limited crop cover. For example, bermudagrass hay received 70 kg N/ha, broadcast applied over sod, and reduced till continuous sorghum received 127.7 kg N/ha in the form of injected anhydrous ammonia below the soil surface. Despite the larger injected application of N per year, simulated sorghum runoff losses were significantly less than bermudagrass.

Simulation results were also supported by experimental findings regarding soil erosion, infiltration rate (Potter et al., 1995; Torbert et al., 1996; Tyler and Thomas, 1977), and percolated NO_3-N losses (Chichester, 1977) under various cropping systems. Chichester (1977) reported that leached NO_3-N concentrations and quantities were significantly smaller for meadow grasses than for corn on silt loam soils. Likewise, simulations of loam, clay loam, and fine sandy loam soils indicated leaching of NO_3-N from bermudagrass hay was generally below 1.12 kg/ha compared with significantly larger losses for all other cropping systems. However, loamy sands leached greater amounts when producing bermudagrass. Additionally, leaching losses of N generally increased when no-till and reduced till were utilized in lieu of conventional tillage, especially in row crops. These simulations agree with the findings of Tyler and Thomas (1977).

Results and Discussion

Summarizing many and sometimes diverse results of the 620 simulations is difficult to communicate where concise but precise implications are needed. Comparisons of environmental impacts are made more difficult by the complexity of agronomic, climatic, and soil interrelationships regarding specific water quality indicators. For this reason, an indexing method was devised by which comparative impacts of management and resource variations can be easily understood and communicated to policy makers and others unfamiliar with agriculture.

In the following discussion, only one HUA is illustrated with indices due to space limitations. Complete results for other HUAs can be seen in Srinivasan et al. (1999). Agro-environmental indices of the relative environmental impacts of soil type and slope as well as cropping system which included crop rotation, tillage practice, and fertilizer applications were developed in a way that uses bermudagrass hay production as the baseline cropping system with an index of 100. The indices represent average

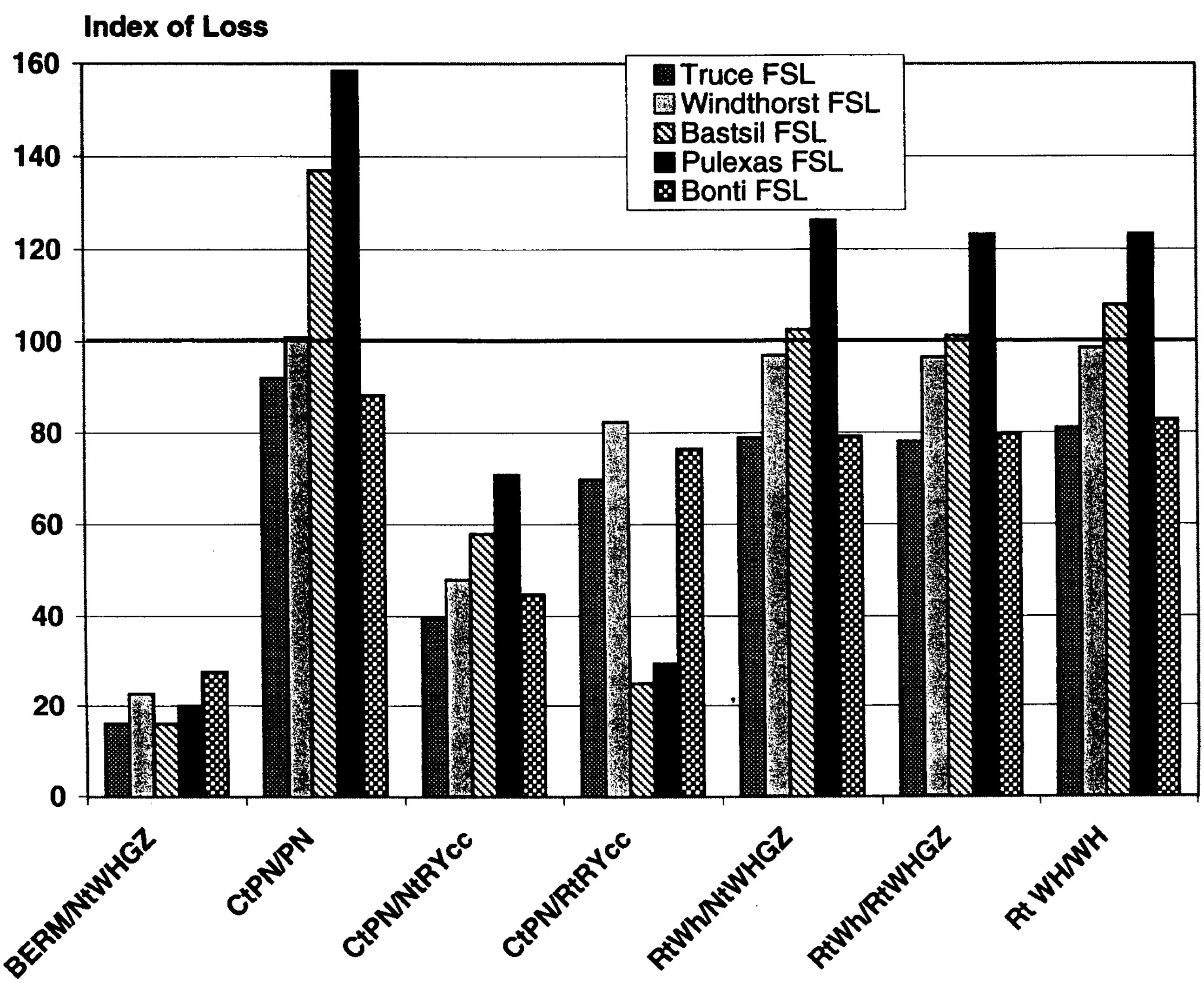

Figure 4–Nitrate losses in runoff, HUA12030101.

annual comparisons whether the comparison is for a single crop in a one-year rotation or multiple crops in two or three-year rotations. No attempt was made in the analysis to indicate which of the multiple crops in a rotation caused the most runoff, erosion, or nutrient loss.

Computed indices of alternative cropping systems and soil situations varied widely depending on the comparison. For example, in HUA No. 12030101 on a Truce fine sandy loam soil (table 4) all indices except for NO_3-N leaching were highest when producing continuous peanuts with conventional tillage, CtPN/PN. The correct interpretation of an index is given by the following example: the yearly average runoff water loss with continuous peanuts using conventional tillage practices from CtPN/PN for the Truce soil with an index of 224 is more than twice the runoff of bermudagrass hay, BERM. In the case of erosion, the index of 12000 indicates120 times more soil was lost from CtPN/PN.

This large index number points out the disadvantage of using an indexing system for comparisons, i.e., when the denominator is very small and the numerator is somewhat larger, a very large index of change results. For example, the 12000 index in erosion was actually simulated to be only 5.38 t/ha erosion (not shown), or 5.34 t/ha more than the 0.04 t/ha erosion of BERM (line 1, table 4). In the following analysis, almost all erosion (and some leaching) indices were associated with this problem since BERM was subject to little erosion and leaching.

Figures 2-8 illustrate the impacts of each of five soils by cropping system in HUA No. 12030101. The bold line indicates an index of 100 for BERM. In figure 2, most systems increased runoff above BERM (bars extend above the bold line). Exceptional systems indicating lower runoff than BERM were BERM/NtWHGZ on all soils and CtPN/RtRYcc on Bastsil and Pulexas soils. The highest indices of about 300 occurred with CtPN/PN on the same two soils. Erosion indices of nearly 16000 were also simulated for these two situations (fig. 3). Little or no erosion was simulated using BERM/NtWHGZ across all soil series. Changing from peanut to wheat production sharply reduced the erosion, but it still increased 5 to 10 times more than by producing BERM.

With regard to NO_3-N and P losses in runoff, figures 4 and 5 contrast the impacts of selecting crops with low P and low N application rates. In figure 4, the average yearly N application rates (table 3) were lowest of the systems in this HUA with the one-year rotations of CtPN/RtRYcc and CtPN/NtRYcc. Although more N was applied to BERM/NtWHGZ, uptake was high resulting in low NO_3-N runoff losses. In figure 5, wheat production systems were low in applied P (table 3) resulting in lowest soluble P runoff losses.

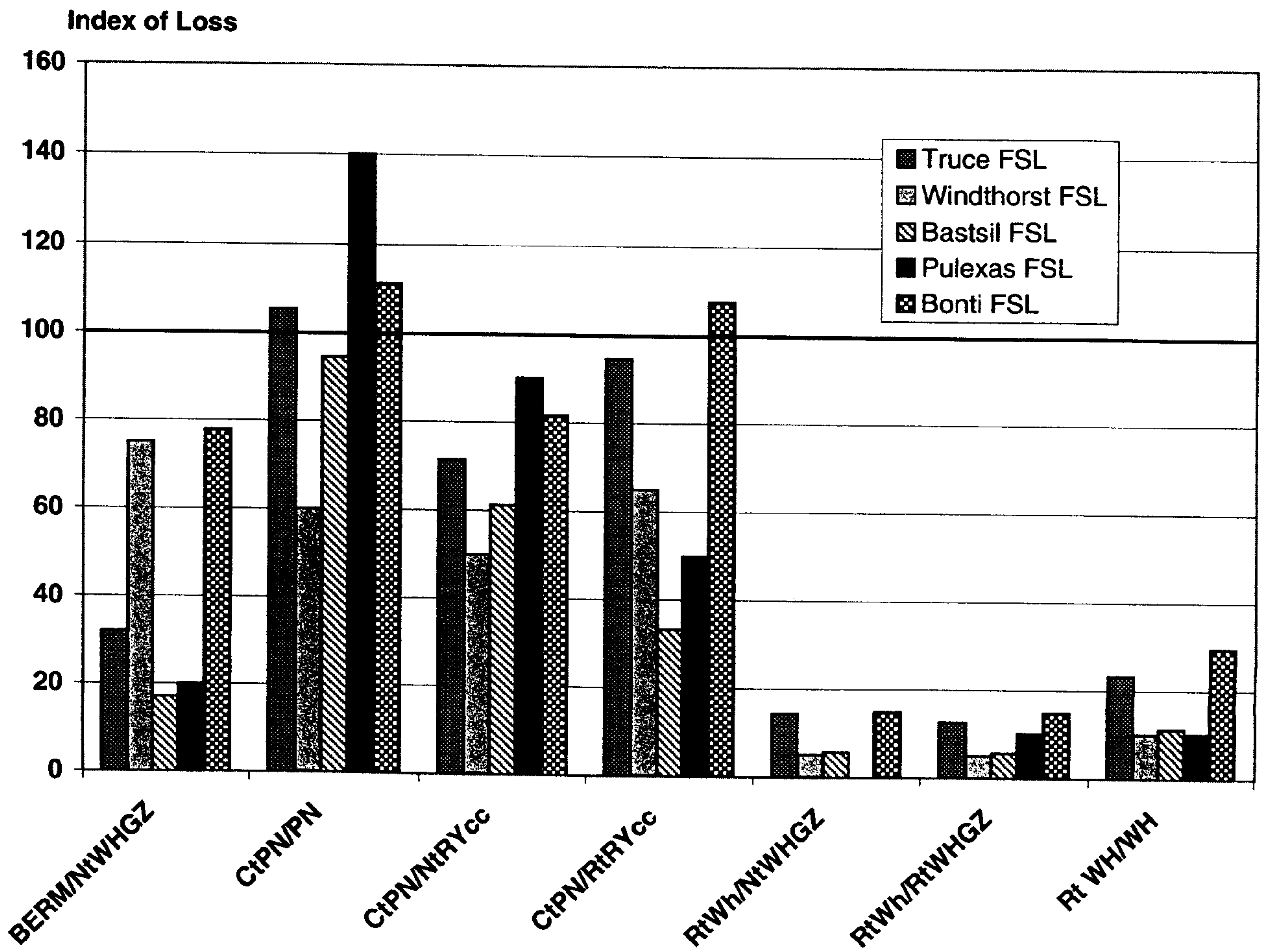

Figure 5–Dissolved P losses in runoff, HUA12030101.

In figures 6 and 7, there were little or no nutrient losses simulated with BERM/NtWHGZ, a result of the near-zero loss of soil by erosion. In figure 7, wheat production systems requiring little applied P were also lowest in P losses in sediment and most were below BERM. The Bastsil, Truce,and Pulexas fine sandy loam soils typically lost the most NO_3-N and P sorbed to sediment.

Leaching losses of NO_3-N are illustrated in figure 8. All systems were higher in leaching losses than BERM with two soil/cropping system situations being near-equal to BERM, BERM/NtWHGZ with the Pulexas soil and CtPN/PN on the Bonti fine sandy loam soil. Leaching indices of 800 to nearly 1300 occurred across the systems with Truce, Windthorst and Bastsil soils being the significant soils incurring leaching losses of NO_3-N.

The agro-environmental indexing system illustrated above was useful in comparing the indicators across soils and cropping systems. The indices were extremely large compared to BERM for only two of the indicators—erosion and NO_3-N leaching. Despite these large indices, they were useful in identifying relative water quality impacts across soil types of alternative cropping systems.

Overview of Results

When analyzing the many detailed results from 620 simulations including multiple soils and cropping systems as above, it is difficult to summarize the major implications and highlight them. The following analysis strives to highlight major results using frequencies of groups of agricultural elements. An overview of the complex analysis is drawn from the broad implications, on average, of the impacts on water quality of (1) climate with respect to rainfall, (2) soil type by percent clay, (3) slope, (4) tillage practice, and (5) crop selection.

Impacts of Climate: Annual Rainfall

The impacts of climate with respect to rainfall differences vary primarily from south to north in the TRB. Annual rainfall varies from approximately 820 mm/yr in the northwest to over 1250 mm/yr in the south near the Gulf Coast. In table 5, using the HUAs as proxies for specific areas of rainfall, those areas receiving more than 950 mm/year increased runoff and nutrient losses of both runoff and sediment. Erosion was unaffected and leaching was reduced as rainfall increased; contrary to expectations, and a likely interaction with land slope.

Further analysis of rainfall by percent land slope (table 5) indicated that erosion increased as higher rainfall

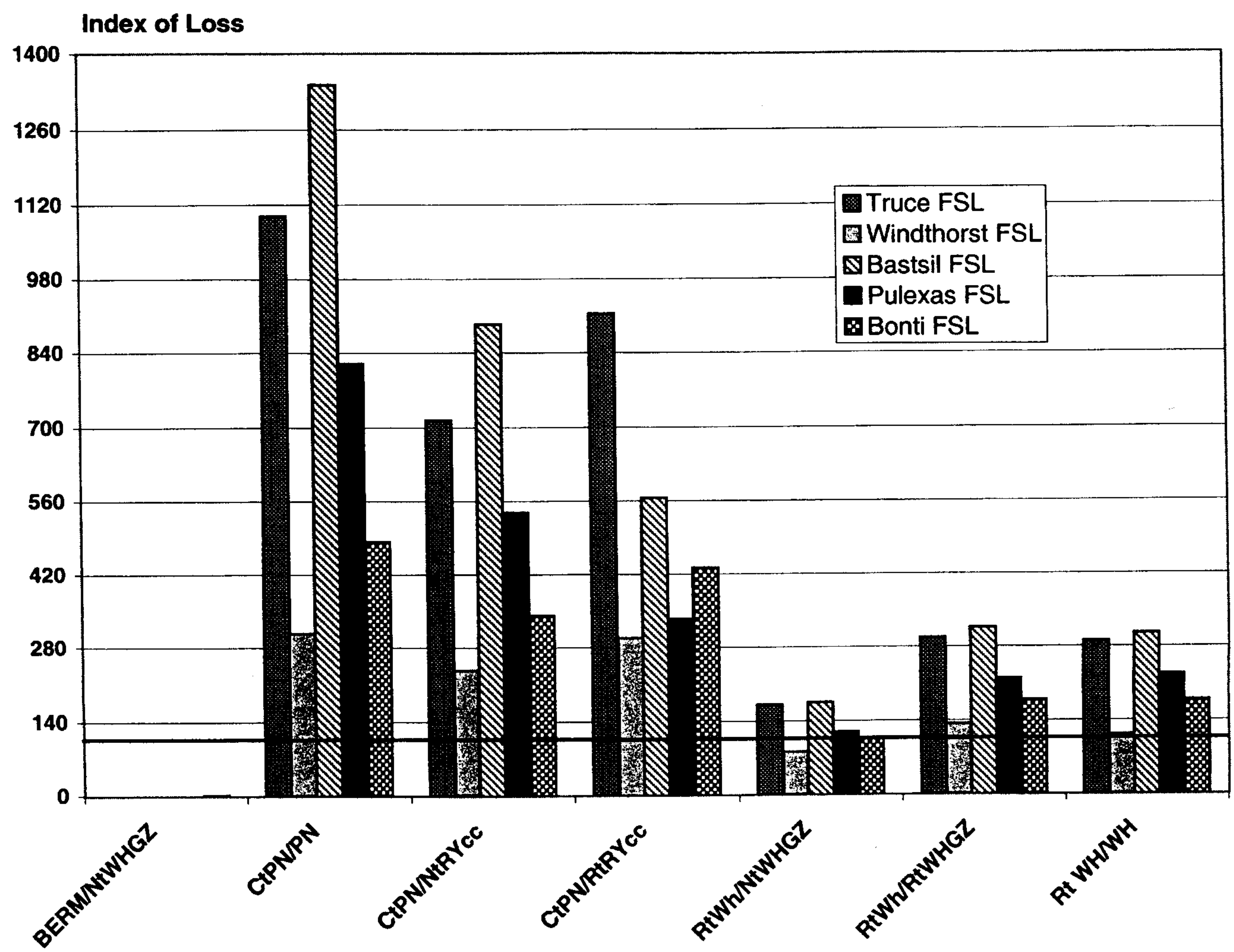

Figure 6–Nitrate losses in sediment, HUA12030101.

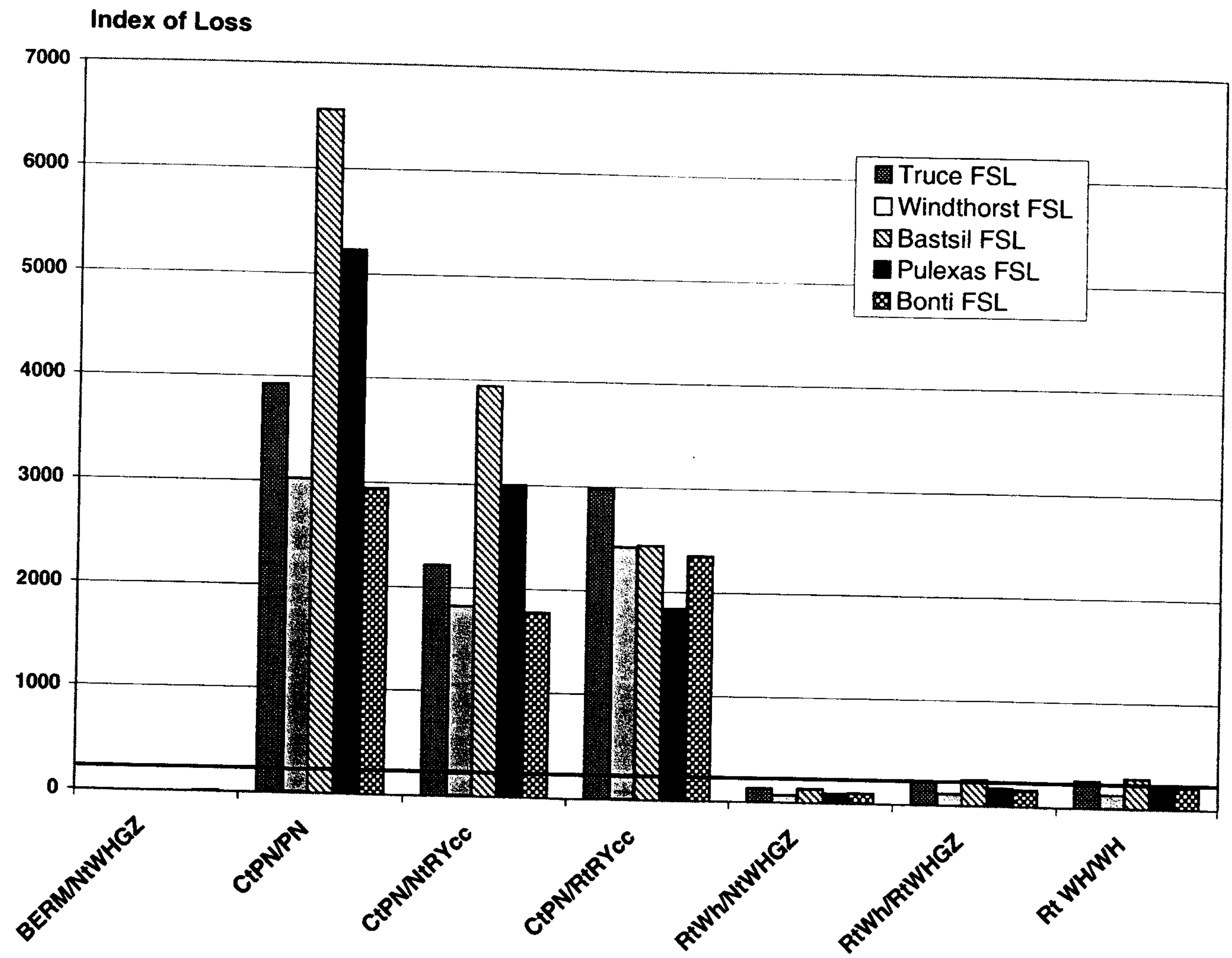

Figure 7–Dissolved P losses in sediment, HUA12030101.

interacted with increased slope. One major exception was the high rainfall situation combined with over 3% slope in which erosion was reduced sharply. Detailed examination of this situation indicated that the 16 observations were from sandy soils whereas most other combinations of rainfall and slope were of sufficient number to include loam and clay loam soils.

Impacts of Soil Type

Soils were categorized into three groups with respect to the percent clay: 0 to 25%, 26 to 50%, and over 50% (table 5). Higher percentages of clay characteristically slow infiltration rates and increase runoff, while low clay contents increase leaching of nutrients. Without regard to slope or cropping system, the high clay containing soils resulted in only 0.56 kg NO_3-N/ha leached per year compared with 16.6 and 8.1 kg/ha losses with the lowest (sands) and medium clay soils, respectively. In contrast, water runoff averaged higher with high clay soils than with sandy soils, 200.5 mm/year versus 109.2 mm/year, respectively. Additionally, with high clay soils, NO_3-N losses averaged over 9.0 kg/ha in runoff and 16.6 kg/ha in sediment. This was compared with 3.5 kg/ha and 4.8 kg/ha, respectively, for sandy soils. Likewise, P losses in both runoff and sediment were higher with high clay and medium clay soils but erosion was about the same between them.

Impacts of Slope

Slopes of soils were characterized into three categories: 0 to 1%, 1.1 to 3%, and over 3% (table 5). Again without regard to soil type or cropping system, slopes in excess of 3% increased erosion and NO_3-N and P losses in sediment. Leaching losses were lowest with near-level slopes, which is contrary to expectations. Also, the reduced runoff and nutrient losses in runoff with steeper slopes was unexpected. Both contrary results indicate there is likely a dominance of high clay soils on near-level slopes.

Impacts of Soil Type in Combination with Slope

Indeed, an analysis of soil type of over 50% clay content in combination with 0 to 1% and 1.1 to 3% slopes lost the most runoff as well as nutrients in runoff. Additionally, leaching was among the lowest in these situations. In contrast, sandy soils (0-25% clay) with 0 to 1% slope eroded the least but leached the most NO_3-N.

Impacts of Tillage Practices

In the frequency analysis of tillage practices, bermudagrass hay over-seeded with no-till wheat for

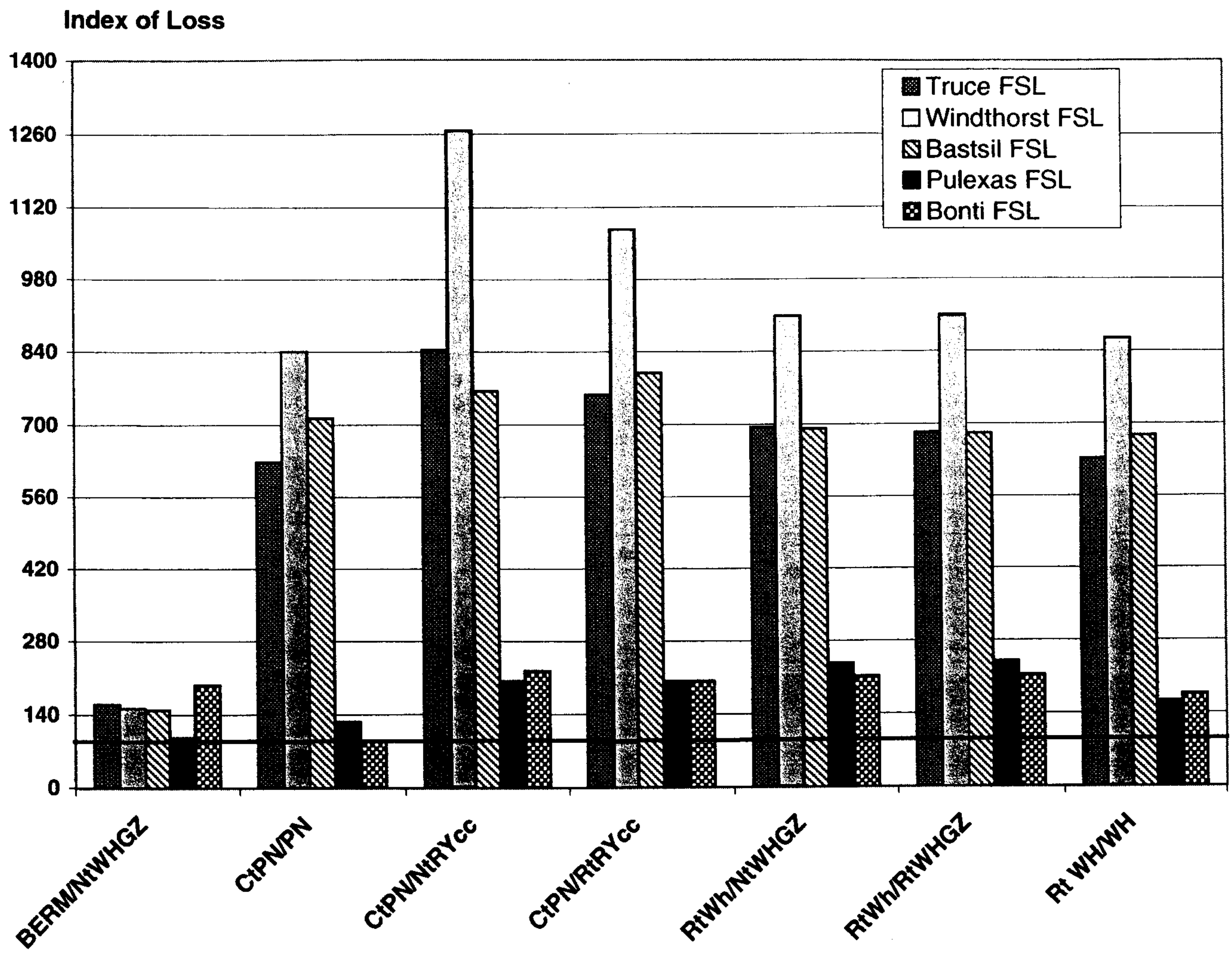

Figure 8–Nitrate losses in leaching, HUA12030101.

grazing, BERM/NtWHGZ, would normally be grouped in the no-till category. However, it was omitted from this analysis and the following interaction analysis of tillage practice with crop selection since it is primarily a non-tilled perennial crop. This facilitated an improved comparison of water quality impacts when row crops and small grains using alternative tillage practices were analyzed.

There was a strong impact of no-tillage practices across all cropping systems and soil situations in reducing erosion (table 5). No-tillage averaged only 0.85 tons/ha erosion yearly. This was compared with approximately 5.4 tons/ha for systems based on conventional tillage as well as conventional tillage/reduced tillage rotations, and 3.0 tons/ha for all systems using only reduced tillage. Runoff was reduced from 197 mm/ha using conventional tillage to 168 mm/ha yearly with reduced tillage. Without regard to crop interaction, no-tillage increased runoff above reduced tillage, but remained below conventional tillage. Sediment losses of both N and P were sharply reduced by adopting reduced and no-till practices, but nutrient losses in runoff and NO_3-N leaching losses indicated no direct correlation. Apparently there is an interaction with another factor such as crop selection.

Impacts of Crop Selection

Agro-environmental impacts of crop selection are influenced by the rates of N and P fertilizers applied to the crop to meet nutrient requirements. Thus, as a production system, they become inseparable and are viewed in this analysis as a single indicator for safeguarding water quality.

Table 3 indicates the amount of N and P applied to each crop or crop rotation. Rates and timing of applications were not adjusted for alternative tillage practices, soil types or precipitation differences. Additionally, simulated rates of N and P were unchanged over time. The highest N applications were applied to corn and next highest to sorghum. No N fertilizer was applied to soybeans and little to peanuts and cotton. These latter crops, however, required modest amounts of P fertilizer whereas wheat, oats, and rye received little P. Variations in nutrient levels were sometimes made for the same crop if in rotation with different crops, depending on the other crop's fertility requirements and the final soil nutrient status compared with the initial status.

Runoff and erosion were lowest when producing BERM and BERM/NtWHTGZ. Likewise, with these two crops nutrient losses in sediment were minimized. Producing small grains cut erosion sharply to 1.1 tons/ha from

Table 5. Frequency summary of simulation results by resource and management element

Item	Observations (no)	Runoff (mm)	Erosion (tons/ha)	Loss in Runoff: NO_3-N (kg/ha)	Loss in Runoff: P (kg/ha)	Loss in Sediment: NO_3-N (kg/ha)	Loss in Sediment: P (kg/ha)	Loss by Leaching: NO_3-N (kg/ha)
Climate: Annual Rainfall								
950 mm or less	292	140.0	2.78	5.79	0.68	11.35	3.38	9.35
Over 950 mm	328	189.3	2.76	7.80	1.11	13.84	4.07	4.05
Rainfall by Percent Slope								
950 mm or less by 0-1%	75	148.2	1.88	6.95	1.10	10.28	3.12	4.22
Over 950 mm by 0-1%	142	211.4	2.72	9.53	1.49	13.53	4.22	1.61
950 mm or less by 1.1-3%	187	135.4	2.56	5.25	0.53	10.63	2.90	12.34
Over 950 mm by 1.1-3%	172	176.6	2.97	6.84	0.87	14.97	4.08	4.22
950 mm or less by over 3%	28	148.6	6.62	6.30	0.58	19.01	7.33	2.87
Over 950 mm by over 3%	16	159.0	1.53	4.77	0.33	5.62	2.85	23.26
Percent Clay								
0-25%	94	109.2	1.64	3.51	0.27	4.79	2.57	16.59
26-50%	291	156.6	2.96	6.17	0.68	12.01	3.35	8.14
Over 50%	235	200.5	2.98	9.04	1.45	16.62	4.71	0.56
Percent Slope								
0-1%	433	187.4	2.37	8.50	1.37	12.30	3.82	2.54
1.1-3%	361	155.0	2.76	6.01	0.69	12.70	3.46	8.47
Over 3%	44	152.4	4.77	5.74	0.49	14.14	5.70	10.28
Percent Slope by Percent Clay								
0-1% by 0-25%	24	107.3	1.03	3.51	0.33	3.95	1.55	12.26
1.1-3% by 0-25%	46	96.0	1.63	3.17	0.24	5.03	2.53	17.74
Over 3% by 0-25%	24	136.3	2.24	4.14	0.25	5.16	3.66	18.72
0-1% by 26-50%	79	161.5	1.68	6.64	0.98	10.33	2.57	2.91
1.1-3% by 26-50%	192	153.0	2.98	5.83	0.55	11.36	3.18	11.12
Over 3% by 26-50%	20	171.7	7.80	7.66	0.77	24.92	8.15	0.16
0-1% by over 50%	112	222.8	3.15	10.89	1.87	15.48	5.20	0.20
1.1-3% by over 50%	123	194.8	3.01	8.09	1.28	20.63	5.05	0.27
Tillage Practice								
No-tillage (Nt)	50	187.5	0.85	8.87	0.70	6.68	1.25	7.93
Reduced tillage/ No-tillage (Rt/Nt)	54	170.9	0.78	6.55	0.21	6.30	0.90	7.31
Reduced tillage (Rt)	279	167.8	3.04	6.53	0.65	14.35	3.79	7.96
Conv. tillage/ Reduced tillage (Ct/Rt)	99	185.0	5.38	7.61	1.26	20.38	7.02	5.93
Conventional tillage (Ct)	45	196.5	5.38	6.61	1.82	21.57	9.41	3.83
Crop Selection								
BERM & BERM/Nt WHGZ	194	111.6	0.09	6.23	1.41	2.01	0.38	3.09
Small grain crops (SG)	178	189.6	1.07	7.39	0.26	9.09	1.32	4.53
RC/SG rotations 155	198.8	2.66	8.43	1.46	14.97	3.99	3.63	
Row crops (RC)	93	177.5	5.51	7.08	1.15	20.84	7.65	3.94
Crop Selection by Tillage Practice								
SG/SG by Rt/Nt	54	170.9	0.78	6.55	0.21	6.30	0.90	7.31
SG/SG by Rt/Rt	101	172.9	1.27	6.42	0.24	9.35	1.42	7.48
RC/SG by Nt	50	187.5	0.85	8.87	0.70	6.68	1.25	7.93
RC/SG by Nt/Rt	70	168.0	4.47	7.23	0.47	16.45	4.10	9.85
RC/SG by Ct/Rt	36	160.9	3.78	5.19	1.54	15.10	5.75	6.92
RC/SG by Ct/Ct	18	206.1	1.99	7.43	2.72	16.82	5.50	6.92
RC/RC by Rt/Rt	108	162.9	3.75	6.17	1.15	17.65	5.81	7.17
RC/RC by CT/Rt	63	198.7	6.29	9.00	1.10	23.40	7.75	5.37
RC/RC by Ct/Ct	27	190.1	7.64	6.06	1.23	24.74	12.01	5.74

5.5 tons/ha for row crops and 2.7 tons/ha for row crop/small grain rotations. Likewise, nutrient losses in sediment were significantly reduced with NO_3-N losses dropping from 20.8 kg/ha with row crops and 15.0 kg/ha with row crop/small grain rotations to 9.1 kg/ha with small grain production. Likewise, selecting small grains for production compared with row crops minimized both P losses in runoff and in sediment. Surprisingly, runoff and NO_3-N leaching as well as runoff losses were not reduced when producing small grains. This indicates that there may be an interaction with tillage or slope.

Impacts of Crop Selection Combined with Tillage Practice

Combining crop selection with alternative tillage practices (with BERM/NtWHGZ again deleted from the no-till category for the reason given above) indicated that no-tillage of row crops and no-tillage of row crops in rotation with no-till small grains increased runoff over conventional tilled row crops/reduced-tilled small grains. More specifically, in the individual case of simulating a no-till versus conventionally tilled corn/wheat cropping system, runoff increased using no-tillage, from 151.5 mm per year with conventional tillage to 162.6 mm using no-tillage (not shown in table 5). While these impacts may be contrary to some research findings, they are supported by others (Lindstrom and Orstael, 1984; Baumhardt et al., 1993; Foley et al., 1991; Freebairn and Lupta, 1990). Apparently, there is an interaction with soil type too, especially with high clay soils.

Additionally, in this case, no-tillage of corn significantly decreased erosion to 0.67 t/ha, down from 4.5 t/ha with reduced-till corn (not shown in table 5). Similarly, NO_3-N losses in sediment declined from 15 kg/ha to 4.8 kg/ha using no-till, and P losses in sediment dropped from 2.8 kg/ha to 0.8 kg/ha. Nitrate-N leaching losses declined from 7.4 kg/ha to 6.4 kg/ha.

Conclusions and Analysis Limitations

Scientifically, the simulations of water quality impacts in this study largely agree with previous experiences of agricultural researchers. More importantly, it illustrates that a multitude of water quality impacts across a variety of soils and cropping systems can be communicated and summarized using an indexing system. Though indexing has some limitations, it provides a common scale for communicating impacts of similar non-point source elements in agriculture. Thus, the method provides uncomplicated comparisons of the agro-environmental impacts to citizens, non-agricultural environmentalists, water managers, and policymakers.

The analysis indicated that water quality can be safeguarded in most agricultural situations using no-tillage with residue management to control erosion and nutrient losses, particularly P losses. Furthermore, water quality was safeguarded by selecting crops having year-round, uniform groundcover such as bermudagrass hay which almost stopped erosion and P losses. In contrast, a threat to water quality from sedimentation occurred with either conventional or combined conventional and reduced tillage of row crops. Sediment-sorbed NO_3-N and P losses were also highest with these situations. In some cases, runoff losses were aggravated by no-tillage; specifically in row crops, but this was likely related to the dominance of clay and clay loam soils in the TRB.

Limitations of the analysis include the obvious limitation that neither all soils in the TRB nor all production systems were represented in the analysis. Selected soils represented over 75% of the cropland and improved pasture area of the HUAs. No specialty crops were included in the production systems. Producers, however, since the passage of the 1996 farm legislation are free to plant their choice of crops and acreage without regard to historical crop acreage allotments or land set-aside (idle) restrictions. Additionally, the conservation reserve program (CRP) which permitted large acreages of cropland to be seeded to grass or planted to trees beginning in 1986 (for a 10-year period) has likely changed some land uses. These alternative land uses were not considered in the analysis nor were current program revisions which may cause a shift of CRP grassland and trees back to cropland.

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References

Alberts, E. E., and E. H. Neibling. 1994. Influence of crop residues on water erosion, Ch. 3. In *Managing Agricultural Residues*, ed. P. W. Urger. Boca Raton, Fla.: Lewis Publisher.

Baumer, P., P. Kenyon, and J. Bettis. 1994. *MUUF v2.14 User's Manual*. Lincoln, Neb.: Natural Resources Conservation Service, National Soil Survey Center.

Baumhardt, R. L., J. W. Keeling, and C. W. Wendt. 1993. Tillage and residue effects on infiltration into soils cropped to cotton. *Agron. J.* 85(2): 379-383.

Chichester, F. W. 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. *J. Environ. Qual.* 6(2): 211-217.

Foley, J. L., R. J. Loch, S. F. Flennille, and R. D. Cennolly. 1991. Affects of tillage, stubble and rainfall energy on infiltration. *Soil Tillage Res.* 20(1): 45.

Freebairn, D. M., and S. C. Lupta. 1990. Microrelief, rainfall and cover effects on infiltration. *Soil Tillage Res.* 16(4): 307.

Laflen, J. M., and T. S. Colvin. 1981. Effect of crop residue on soil loss from continuous row cropping. *Transactions of the ASAE* 24(3): 605-609.

Lindstrom, J. J., and C. A. Orstael. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. *J. Soil Water Conserv.* 39(2): 149-152.

Potter, K. N., H. A. Potter, and J. E. Morrison Jr. 1995. Tillage and residue effects on infiltration and sediment losses on vertisols. *Transactions of the ASAE* 38(5): 1413-1419.

Srinivasan, R., J. Arnold, R. S. Muttiah, C. Walker, and P. T. Dyke. 1993. Hydrologic Unit Model for United States (HUMUS). In *Proc. Advances in Hydro-Science and Engineering*. Oxford, Miss.: CCHE, School of Engineering, University of Mississippi.

Srinivasan, R., W. L. Harman, M. Magre, X. Chen, and E. Wang. 1999. Water quality implications of Texas agriculture: An agro-environmental index of non-point sources, Trinity River Basin. Technical Report. Temple, Tex.: Blackland Research Center, Texas Agricultural Experiment Station.

Timmons, D. R., R. E. Burwell, and R. F. Holt. 1973. Nitrogen and phosphorous losses in surface runoff from agricultural land as influenced by placement of broadcast fertilizer. *Water Resour. Res.* 9(3): 658-667.

Torbert, H. A., K. N. Potter, and J. E. Morrison Jr. 1996. Management effects on nitrogen and phosphorous losses in runoff on expansive clay soils. *Transactions of the ASAE* 37(2): 161-166.

Torbert, H. A., K. N. Potter, D. W. Hoffman, T. J. Gerik, and C. W. Richardson. 1999. Surface residue and soil moisture affects fertilizer loss in simulated runoff. on a heavy clay soil. *Agron. J.* 91(4): 606-612.

Tyler, D. D., and G. W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. *J. Environ. Qual.* 6(1): 63-66.

Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spanel. 1989. The EPIC crop growth model. *Transactions of the ASAE* 32(2): 497-511.