Phosphorus loss

Modeling the phosphorus cycle

Phosphorus, like nitrogen, is an essential element needed for crop growth. It is a basic building block for compounds that store and transfer energy, nucleic acids, and other organic compounds. Unlike nitrogen, phosphorus is not found in a gaseous form, and so the cycle does not have an atmospheric component. It is most commonly found in rock formations and sediments as phosphate salts. It is also found as part of the organic material in soil. Weathering processes dissolve the phosphates, and plants uptake phosphorus from the soil water in the form of hydrated phosphate ions—soluble phosphorus. Phosphorus is released back to the soil as crop residue decomposes, and the cycle repeats. Phosphates are not very water-soluble, and quantities of soluble phosphorus in soil are generally small, ranging from 0.2 to 0.3 milligrams per liter.

Farmers apply commercial phosphorus fertilizers to supplement the usually low quantities available in the soil. Over-application can lead to the buildup of phosphorus in the soil. As the phosphorus levels build up in the soil, the potential for phosphorus in a soluble form increases (Sharpley et al. 1999). Dissolved phosphorus that is transported from farm fields to lakes, rivers, and streams can lead to excessive aquatic plant growth, resulting in eutrophication. Phosphorus is sometimes the limiting factor for biomass production in freshwater ecosystems; even small amounts (concentrations as low as 0.02 mg/L) added to the system can produce significant increases in plant and algal growth (Sharpley et al. 1999).

Generally, the factors that cause phosphorus movement are similar as those that cause nitrogen movement. Transport mechanisms are erosion, surface water runoff from rainfall and irrigation, and leaching. Factors that influence the source and amount of phosphorus available to be transported are soil properties, and the rate, form, timing, and method of phosphorus applied. The phosphate ion attaches strongly to soil particles and makes up a part of soil organic particles. Any erosion of these particles will transport phosphorus from the site. Phosphorus can also be transported as soluble material in runoff and leaching water. When water moves over the soil surface, as it does in runoff events, or passes through the soil profile during leaching, soluble phosphorus will be transported with the water. Applying phosphorus fertilizer or manures on the soil surface will subject them to both runoff and erosion, particularly if the application takes place just before a rainfall, irrigation, or wind event that can carry the phosphorus material off site. If, however, the fertilizer or manure material is incorporated into the soil profile, it becomes protected from the transport mechanisms of wind and water. Leaching of phosphorus is at a higher risk through coarse textured soils or organic soils that have low clay content.

Phosphorus is primarily lost from farm fields through three processes: attached to the sediment that erodes from the field, dissolved in the surface water runoff, or dissolved in leachate and carried through the soil profile. On cultivated fields, most is lost through erosion, whereas on non-tilled fields most phosphorus losses are dissolved in surface water runoff or in leachate. Cultivated acres with phosphorus-rich soils, however, can also lose significant amounts of phosphorus dissolved in the runoff or the leachate.

EPIC simulates the phosphorus cycle as shown in figure 26. EPIC simulates mineral and organic fractions of soil phosphorus. The mineral fraction consists of available (soluble), active (loosely labile), and stable (fixed) pools. Only phosphorus compounds that are soluble in water are available for plants to use. The soluble and active pools are assumed to be in rapid equilibrium (several days or weeks). The soluble pool is input and the size of the active and stable pools relative to the soluble pool is set by EPIC based on the amount of past soil weathering. The active pool is in slow equilibrium with the stable pool. Fertilizer phosphorus is assumed to be in soluble form which is mixed uniformly to a specific depth. Thus, fertilizer phosphorus contributes directly to the soluble pool. Organic phosphorus is divided into the fresh residue pool, consisting of phosphorus in the microbial biomass, manures, and crop residues, and the active and stable humus pools. Humic mineralization occurs in the active pool only. The model accounts for transformations between pools within each fraction and also between the organic and mineral fractions. Plant use of phosphorus is estimated using the supply and demand approach, which balances soluble phosphorus in the soil with an ideal phosphorus concentration in the plant for a given day.

Phosphorus in the surface layer is partitioned into adsorbed and solution phases using a constant partition coefficient similar to the method described by Leonard and Wauchope (1980). Adsorbed phosphorus attaches to soil particles in the soil matrix, thereby removing the material from solution. Sediment transport of phosphorus is simulated with a loading function similar to that used for organic nitrogen transport. The amount of soluble phosphorus removed in surface water runoff is predicted using soluble phosphorus concentration in the top 10 millimeters of soil, runoff volume, and partition coefficient. A similar method is used to predict soluble phosphorus lost with percolation water as leachate. Part of the phosphorus is removed from the field with the harvested crop and remaining crop residue is added into the organic pools where it is available for mineralization. Transformations of organic phosphorus in crop residues and soil organic matter are similar to the transformations of crop residues, soil organic matter, and organic nitrogen in the PAPRAN model (Seligman and Keulen 1981).

Over years of farming, cropland soils tend to either gain or lose phosphorus. In cases where soils experience net losses (mining), reductions in soil quality, soil productivity, and crop yields can be expected to follow. Mined soils can be restored through conservation management practices that increase soil organic material and eventually re-establish a balanced phosphorus cycle.

Model simulation results for phosphorus inputs

Phosphorus inputs from commercial fertilizers and manure, as represented in the EPIC model simulations, totaled 2.2 million tons per year (table 52). Most of the phosphorus was applied as commercial fertilizer. Manure phosphorus accounted for about 20 percent of the phosphorus applied; in comparison, only about 5 percent of the nitrogen sources came from manure. For the 298 million acres of cropland included in the study, the average phosphorus application rate was about 15 pounds per acre per year—about 12 pounds per acre as commercial fertilizer phosphorus (in inorganic form) and about 3 pounds per acre as manure phosphorus (in both inorganic and organic form), on average (table 53). (Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.)

Figure 26 Phosphorus cycle as modeled in EPIC

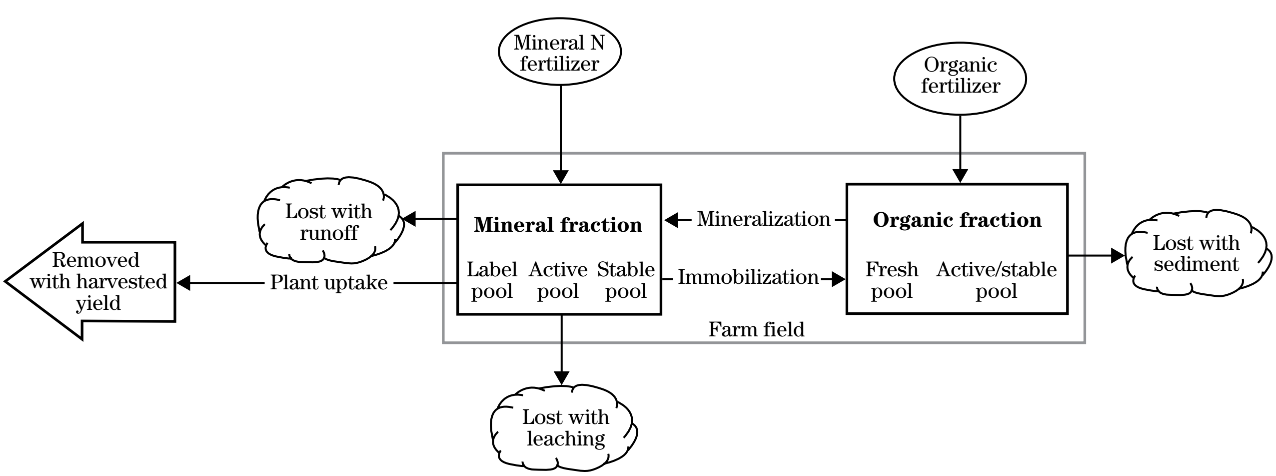


Table 52 Sources of phosphorus inputs–by region and by crop (average annual values)

	Acres		Commercial fertilizer		Manure		Sum of inputs	
	1,000s	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region								
Northeast	13,642	4.6	100,822	5.8	50,486	10.9	151,308	6.9
Northern Great Plains	72,397	24.3	299,275	17.3	71,124	15.3	370,399	16.9
South Central	45,350	15.2	231,967	13.4	41,300	8.9	273,266	12.4
Southeast	13,394	4.5	101,836	5.9	50,268	10.8	152,104	6.9
Southern Great Plains	32,096	10.8	136,179	7.9	39,427	8.5	175,606	8.0
Upper Midwest	112,581	37.7	797,236	46.1	178,282	38.3	975,518	44.4
West	9,018	3.0	63,430	3.7	34,094	7.3	97,525	4.4
All regions	298,478	100.0	1,730,744	100.0	464,982	100.0	2,195,726	100.0
By crop								
Barley	4,635	1.6	40,070	2.3	1,100	0.2	41,170	1.9
Corn	78,219	26.2	805,945	46.6	247,947	53.3	1,053,892	48.0
Corn silage	5,197	1.7	40,338	2.3	99,277	21.4	139,615	6.4
Cotton	16,858	5.6	98,627	5.7	6,793	1.5	105,420	4.8
Grass hay	14,596	4.9	31,354	1.8	42,290	9.1	73,644	3.4
Legume hay	24,776	8.3	86,013	5.0	8,681	1.9	94,695	4.3
Oats	3,772	1.3	18,847	1.1	431	0.1	19,278	0.9
Peanuts	1,843	0.6	13,284	0.8	823	0.2	14,107	0.6
Potatoes	987	0.3	28,946	1.7	711	0.2	29,658	1.4
Rice	3,637	1.2	17,773	1.0	4	0.0	17,777	0.8
Spring wheat	20,503	6.9	97,332	5.6	2,092	0.4	99,424	4.5
Sorghum	10,897	3.7	62,707	3.6	8,681	1.9	71,388	3.3
Soybeans	67,543	22.6	178,549	10.3	31,974	6.9	210,523	9.6
Winter wheat	45,014	15.1	210,958	12.2	14,178	3.0	225,136	10.3
All crops	298,478	100.0	1,730,744	100.0	464,982	100.0	2,195,726	100.0

Note: Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 53 Sources of phosphorus inputs on a per-acre basis–by region and by crop within regions (average annual values)

	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Sum of inputs (lb/a)
By region					
Northeast	All crops	13,642	14.8	7.4	22.2
Northern Great Plains	All crops	72,397	8.3	2.0	10.2
South Central	All crops	45,350	10.2	1.8	12.0
Southeast	All crops	13,394	15.2	7.5	22.7
Southern Great Plains	All crops	32,096	8.5	2.5	10.9
Upper Midwest	All crops	112,581	14.2	3.2	17.3
West	All crops	9,018	14.1	7.6	21.6
All regions	All crops	298,478	11.6	3.1	14.7
By crop within region*					
Northeast	Corn	2,943	23.4	11.2	34.6
	Corn silage	1,482	18.6	33.7	52.3
	Grass hay	2,369	4.5	2.2	6.6
	Legume hay	4,052	7.0	0.4	7.3
	Oats	362	22.9	0.4	23.3
	Soybeans	1,305	20.1	7.2	27.3
	Winter wheat	853	21.1	1.4	22.6
Northern Great Plains	Barley	3,243	14.9	0.1	15.0
	Corn	15,466	12.2	6.4	18.6
	Corn silage	810	10.2	27.6	37.9
	Grass hay	2,443	4.5	1.5	6.0
	Legume hay	6,152	6.9	0.5	7.5
	Oats	1,255	7.3	0.0	7.3
	Spring wheat	18,916	8.6	0.0	8.6
	Sorghum	1,595	11.2	2.4	13.6
	Soybeans	9,562	2.6	0.5	3.1
	Winter wheat	12,748	6.2	0.4	6.6
South Central	Corn	5,956	23.6	3.8	27.4
	Cotton	5,487	12.9	0.2	13.1
	Grass hay	3,347	3.9	11.6	15.5
	Legume hay	1,630	6.9	0.4	7.3
	Peanuts	880	13.6	1.0	14.6
	Rice	3,004	7.9	0.0	7.9
	Sorghum	2,729	11.8	1.0	12.9
	Soybeans	14,083	5.4	0.7	6.1
	Winter wheat	7,896	9.7	0.1	9.9

Table 53 Sources of phosphorus inputs on a per-acre basis–by region and by crop within regions (average annual values)—Continued

	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Sum of inputs (lb/a)
Southeast	Corn	3,028	22.8	11.3	34.1
	Corn silage	412	22.3	26.1	48.3
	Cotton	2,422	16.7	1.2	17.9
	Grass hay	2,000	4.1	11.4	15.5
	Legume hay	1,183	6.9	0.6	7.5
	Peanuts	479	14.3	1.6	15.9
	Soybeans	2,419	13.7	10.0	23.7
	Winter wheat	1,216	14.4	3.1	17.5
Southern Great Plains	Corn	2,665	11.2	19.3	30.5
	Cotton	7,316	10.1	0.1	10.2
	Legume hay	677	6.9	1.3	8.2
	Oats	503	6.5	0.2	6.7
	Peanuts	484	16.0	0.1	16.1
	Sorghum	4,895	10.7	1.9	12.6
	Winter wheat	15,037	6.4	0.5	6.9
Upper Midwest	Corn	47,941	23.2	5.1	28.3
	Corn silage	1,947	14.0	42.2	56.2
	Grass hay	4,044	4.5	1.6	6.2
	Legume hay	9,233	7.0	0.4	7.3
	Oats	1,388	7.9	0.1	8.0
	Spring wheat	815	14.8	0.1	14.9
	Sorghum	1,604	12.2	0.5	12.7
	Soybeans	40,049	4.9	0.4	5.3
	Winter wheat	5,147	23.7	0.1	23.8
West	Barley	958	22.5	1.3	23.8
	Corn silage	297	13.4	85.6	99.0
	Cotton	1,631	7.3	5.5	12.8
	Legume hay	1,847	6.9	3.8	10.7
	Potatoes	329	76.0	1.7	77.8
	Rice	599	18.6	0.0	18.6
	Spring wheat	772	27.1	5.2	32.2
	Winter wheat	2,118	5.9	4.1	10.1

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.
Note: Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

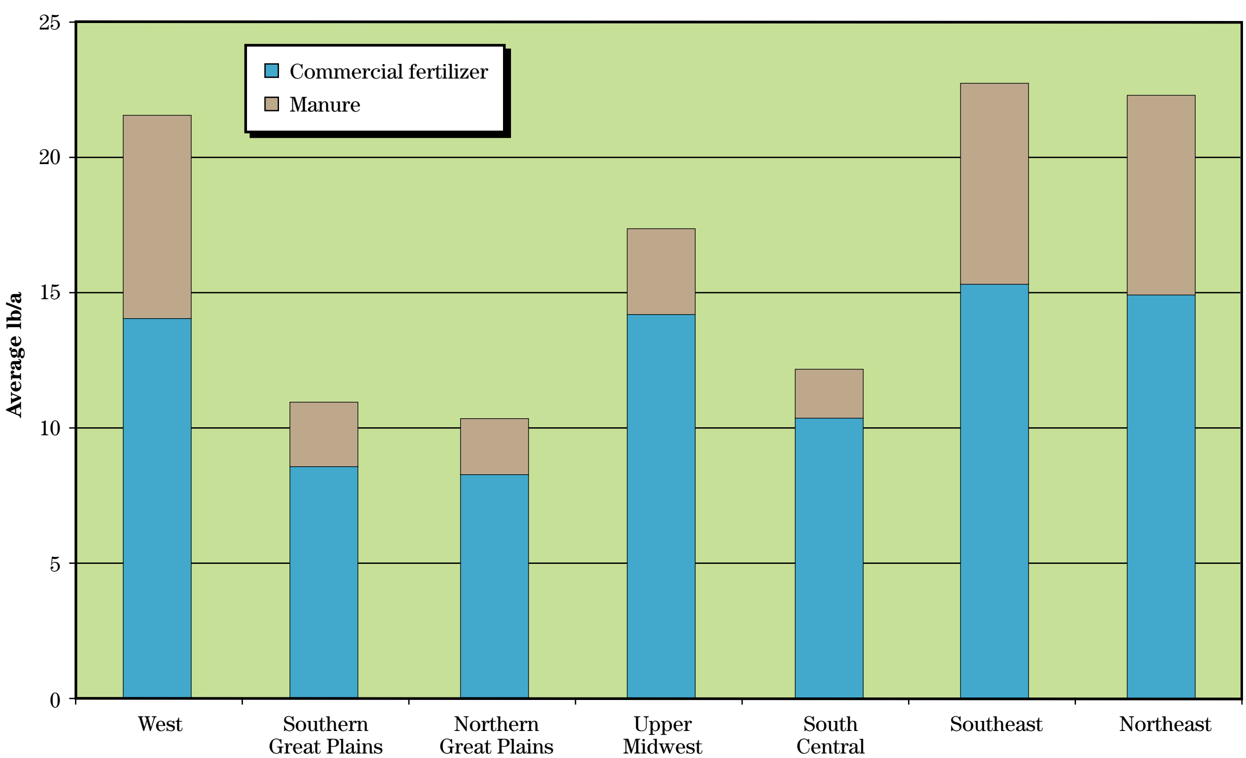
Spatial trends in phosphorus application rates

The spatial distribution of phosphorus applications represented in the EPIC model simulations are shown in map 26 for commercial fertilizer and map 27 for manure. The manure application rates shown in map 27 reflect the same spatial trends as in map 14 for manure nitrogen, where the yellow, orange, and red colors are indicative of intensive livestock production. There are marked differences, however, in the spatial trends for phosphorus and nitrogen applied as commercial fertilizer. As was the case for the commercial nitrogen fertilizer map, phosphorus application rates vary substantially within localized areas reflecting the crop mix and differences in application rates by crop. The yellows and greens in the maps are below the overall average phosphorus application rate. The reds and oranges represent areas with above-average application rates. In contrast to the spatial trends in nitrogen application rates, average phosphorus application rates were much lower throughout areas west of the Mississippi River than cropland in the East, reflecting much lower percentages of acres receiving commercial phosphorus fertilizers for crops grown in those parts of the country. The highest commercial phosphorus fertilizer application rates shown in map 26 are in the potato growing areas of the country, and the lowest occur throughout most of the Great Plains states.

Phosphorus input estimates by region

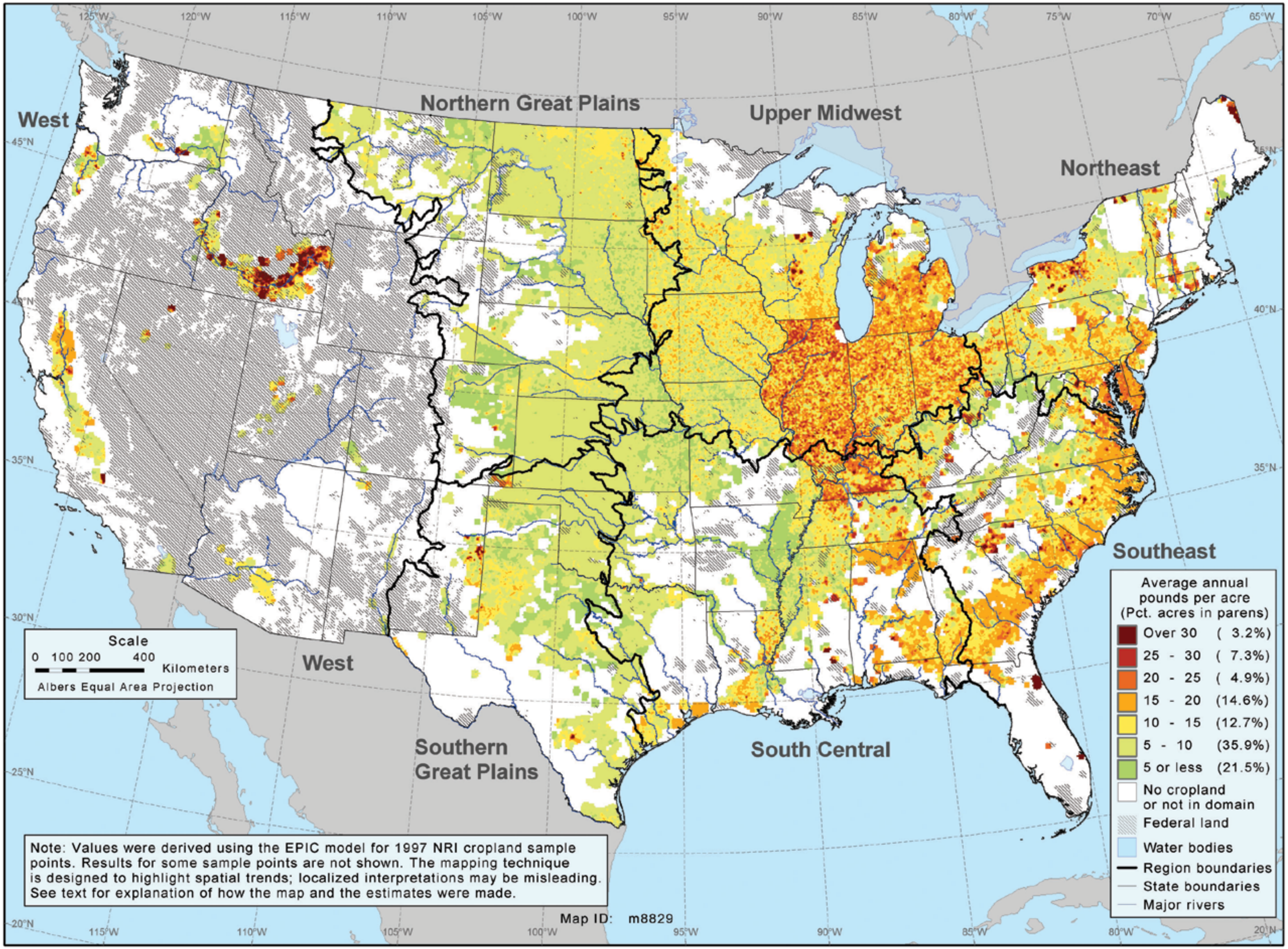
The highest per-acre phosphorus applications, on average, were in three regions—the Southeast region (23 lb/a), the Northeast region (22 lb/a), and the West region (22 lb/a) (fig. 27, table 53). About a third of the phosphorus applied in these regions was as manure applications. The South Central, Northern Great Plains, and Southern Great Plains regions had much lower phosphorus inputs, averaging about 10 to 12 pounds per acre, with only about a fifth coming from manure. The Upper Midwest region had an average phosphorus application of 17 pounds per acre, but accounted for 44 percent of all the phosphorus applied. As observed for nitrogen, phosphorus application in the Upper Midwest region was disproportionately high relative to acres of cropland (table 52).

Figure 27 Sources of per-acre phosphorus inputs–by region

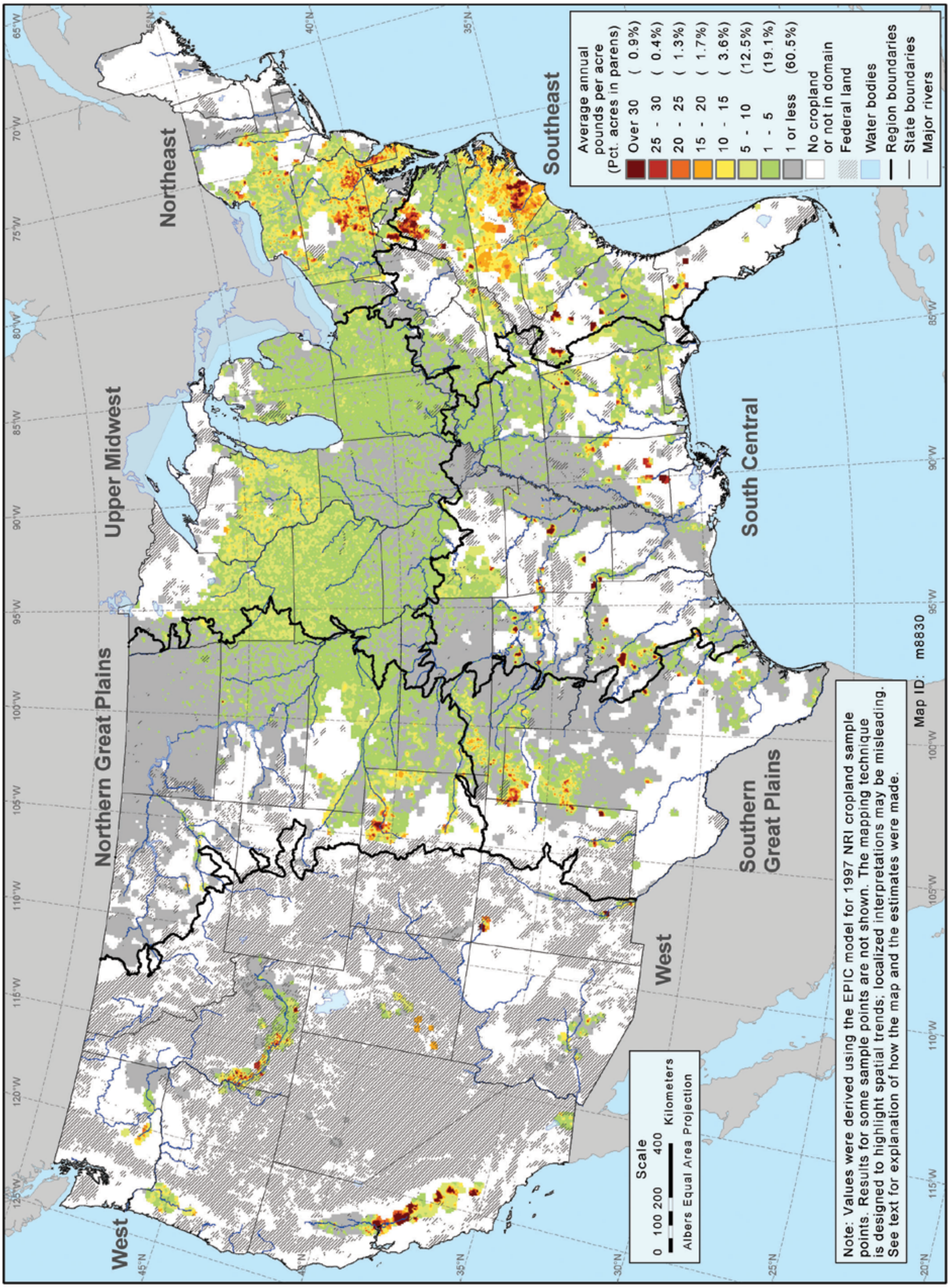


Note: Sources of phosphorus are reported here as elemental phosphorus.

Map 26 Average annual commercial fertilizer application rates for phosphorus (elemental P) in model simulations



Map 27 Average annual manure phosphorus application rates (elemental P) in model simulations



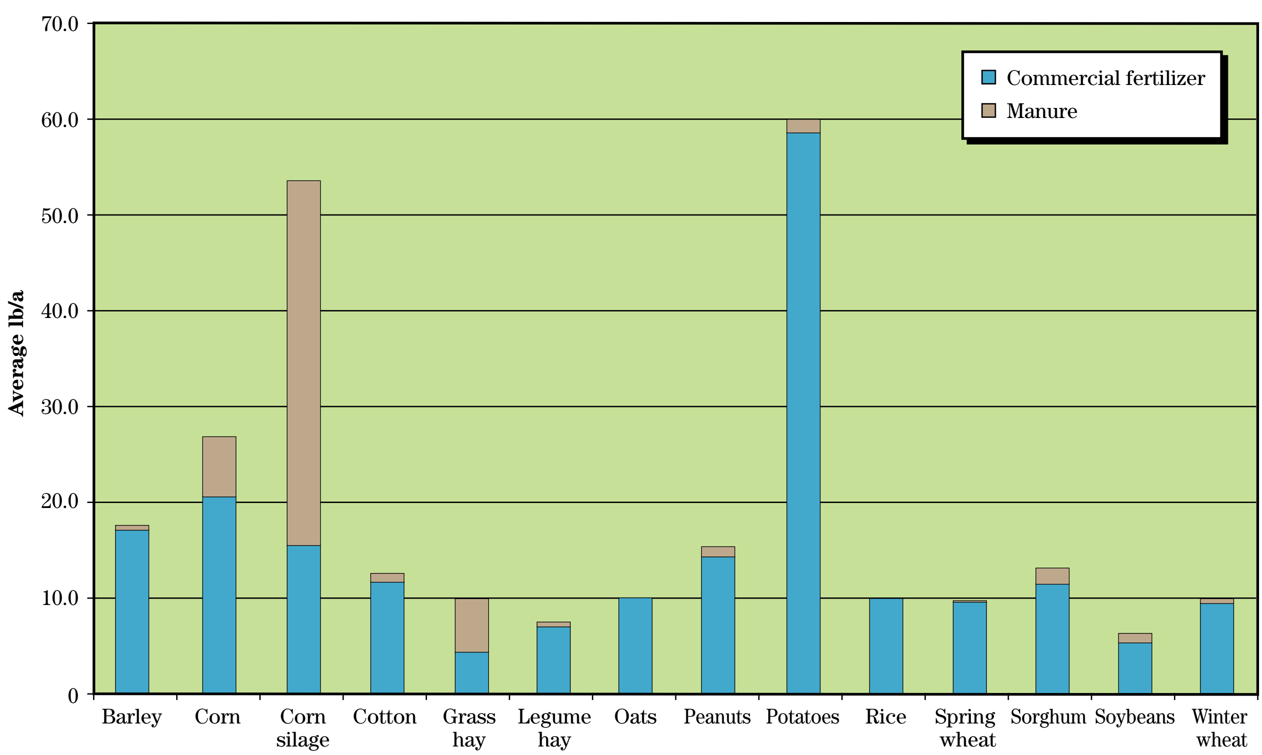
Phosphorus input estimates by crop

Over half of the phosphorus input was applied to corn and corn silage acres in these model simulations (table 52). The average phosphorus application rate (both commercial fertilizer and manure) was about 27 pounds per acre for corn and about 54 pounds per acre for corn silage. Most of the phosphorus applied to corn silage (71%) was applied as manure (fig. 28). Application rates for corn and corn silage were higher than all other crops in each region where these crops are commonly grown (table 53). Potatoes had the highest phosphorus application rate overall, averaging 60 pounds per acre and consisting almost entirely of phosphorus from commercial fertilizers (fig. 28). In the West region, phosphorus applications for potatoes averaged 78 pounds per acre, second only to corn silage in that region (table 53). For other crops, phosphorus application rates averaged less than 20 pounds per acre in most regions, and often less than 10 pounds per acre (table 53).

Model simulation results for phosphorus loss

Model simulation results indicated that a total of 360,000 tons of phosphorus was lost from cropland fields each year (table 54). This represents about 16 percent of the 2.2 million tons of phosphorus applied as commercial fertilizer and manure. In contrast, 28% of the nitrogen sources were lost from cropland fields each year. The average per-acre rate for phosphorus loss was 2.4 pounds per cropland acre. The predominate loss pathway (63% of total phosphorus loss) was phosphorus lost with waterborne sediment, with an average loss of 1.5 pounds per acre per year. Soluble phosphorus dissolved in surface water runoff, averaging about 0.5 pounds per acre per year, accounted for nearly 20 percent of the total phosphorus loss, whereas phosphorus dissolved in leachate accounted for less than 2 percent. Phosphorus loss with windborne sediment averaged 0.4 pounds per acre per year and accounted for 15 percent of the total phosphorus loss.

Figure 28 Sources of per-acre phosphorus inputs–by crop



Note: Sources of phosphorus are reported here as elemental phosphorus.

Table 54 Phosphorus loss estimates–by region and by crop (average annual values)

	Acres	Dissolved in surface water runoff		Dissolved in leachate		Lost with waterborne sediment		Lost with windborne sediment		Sum of all loss pathways	
	(Percent)	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region											
Northeast	4.6	4,811	6.9	684	9.5	23,387	10.3	282	0.5	29,163	8.1
Northern Great Plains	24.3	5,628	8.0	145	2.0	24,441	10.7	21,294	38.5	51,506	14.3
South Central	15.2	18,271	26.1	2,573	35.6	42,014	18.4	1,543	2.8	64,401	17.9
Southeast	4.5	5,850	8.4	984	13.6	10,814	4.7	19	0.0	17,667	4.9
Southern Great Plains	10.8	1,976	2.8	177	2.5	8,356	3.7	28,372	51.3	38,881	10.8
Upper Midwest	37.7	31,742	45.4	2,550	35.3	116,841	51.3	3,553	6.4	154,686	42.9
West	3.0	1,689	2.4	109	1.5	2,012	0.9	247	0.4	4,057	1.1
All regions	100.0	69,967	100.0	7,222	100.0	227,863	100.0	55,309	100.0	360,361	100.0
By crop											
Barley	1.6	682	1.0	20	0.3	1,671	0.7	777	1.4	3,151	0.9
Corn	26.2	30,909	44.2	2,057	28.5	118,168	51.9	20,200	36.5	171,334	47.5
Corn silage	1.7	2,299	3.3	158	2.2	18,067	7.9	1,552	2.8	22,075	6.1
Cotton	5.6	3,102	4.4	802	11.1	15,205	6.7	14,737	26.6	33,846	9.4
Grass hay	4.9	3,753	5.4	439	6.1	2,666	1.2	8	0.0	6,866	1.9
Legume hay	8.3	1,594	2.3	380	5.3	52	0.0	2	0.0	2,028	0.6
Oats	1.3	815	1.2	64	0.9	2,872	1.3	366	0.7	4,116	1.1
Peanuts	0.6	245	0.4	131	1.8	869	0.4	772	1.4	2,018	0.6
Potatoes	0.3	369	0.5	40	0.6	1,088	0.5	340	0.6	1,836	0.5
Rice	1.2	2,418	3.5	420	5.8	2,871	1.3	13	0.0	5,721	1.6
Spring wheat	6.9	1,924	2.7	10	0.1	6,047	2.7	3,574	6.5	11,555	3.2
Sorghum	3.7	1,552	2.2	132	1.8	6,646	2.9	7,582	13.7	15,912	4.4
Soybeans	22.6	14,558	20.8	1,975	27.3	37,553	16.5	2,993	5.4	57,079	15.8
Winter wheat	15.1	5,748	8.2	594	8.2	14,087	6.2	2,393	4.3	22,822	6.3
All crops	100.0	69,967	100.0	7,222	100.0	227,863	100.0	55,309	100.0	360,361	100.0

Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

The spatial distribution of the sum of all phosphorus loss pathways is shown in map 28. The areas most susceptible to phosphorus losses are colored dark red, representing 4 percent of the cropland acres included in the study, and red, representing 6 percent of the cropland. The largest area of cropland most susceptible to phosphorus loss is in Pennsylvania, western Maryland, and parts of New York; the average phosphorus loss exceeds 9 pounds per acre per year in many areas in south central Pennsylvania. Another large vulnerable area extends south from southern Indiana, southern Illinois, and eastern Kentucky to central Louisiana. Smaller vulnerable areas include: the rice growing region in Louisiana and southeast Texas; the Texas panhandle region where windborne sediment losses are high; an area in eastern Iowa; northwestern Illinois; and southwestern Wisconsin; a small area in eastern North Carolina where average losses exceed 9 pounds per acre per year; and the Willamette River Basin in Oregon. Other hot spots are more localized.

Per-acre phosphorus loss estimates for four loss pathways

The spatial distribution of phosphorus loss for three of the phosphorus loss pathways is shown in maps 29–31. Class breaks used to make the maps are the same for phosphorus lost with waterborne and windborne sediment, but differ in the map showing phosphorus dissolved in surface water runoff because of the much lower levels. The spatial distribution of phosphorus dissolved in leachate is not shown because of the low level of phosphorus loss for this loss pathway. (Phosphorus dissolved in lateral subsurface flow is theoretically possible, but was negligible in these model simulations and thus not addressed in the analysis.)

Phosphorus lost with waterborne sediment—Map 29 shows the spatial distribution of phosphorus lost with waterborne sediment. The red and brown colored areas in the map have average loss estimates of 5 pounds per acre per year or more and represent about 6 percent of the acres included in the study. The cropland areas most susceptible to phosphorus loss were similar to those for nitrogen (map 17), except in regions where phosphorus was applied less frequently than nitrogen (such as the wheat growing areas). The area of highest vulnerability for phosphorus loss with waterborne sediment—central and southern Pennsylvania and northern Maryland—is more pronounced for phosphorus loss than for nitrogen loss. Similarly, the Midwest and areas along the Ohio River and lower Mississippi River, which are vulnerable areas for both nitrogen and phosphorus loss with waterborne sediment, tend to have fewer localized areas with the highest phosphorus loss estimates than was the case for nitrogen. The least vulnerable acres—colored green or gray in the map and having average loss estimates of 1 pound per acre or less—represent over half of the cropland acres.

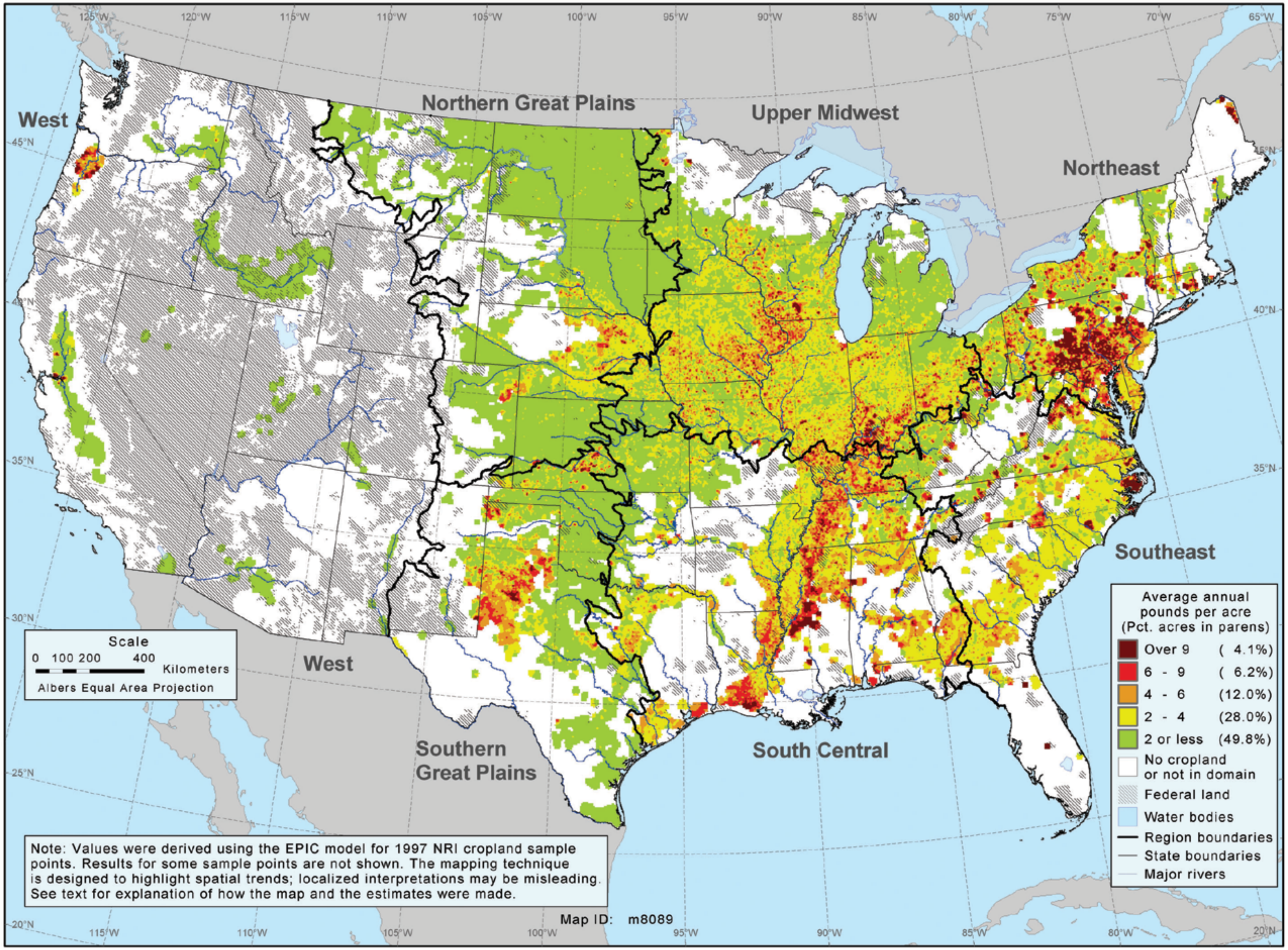
Phosphorus lost with windborne sediment—Areas of greatest vulnerability for phosphorus lost with windborne sediment are in the most vulnerable wind erosion areas, as shown in map 30.

Phosphorus dissolved in surface water runoff—The spatial distribution of phosphorus loss dissolved in surface water runoff is shown in map 31. The red areas in the map have average estimates of phosphorus dissolved in surface water runoff of more than 2 pounds per acre per year. These areas represent about 2 percent of the acres included in the study. The least vulnerable areas—colored green in the map—have average loss estimates of 0.5 pounds per acre per year or less, and represent two-thirds of the cropland acres.

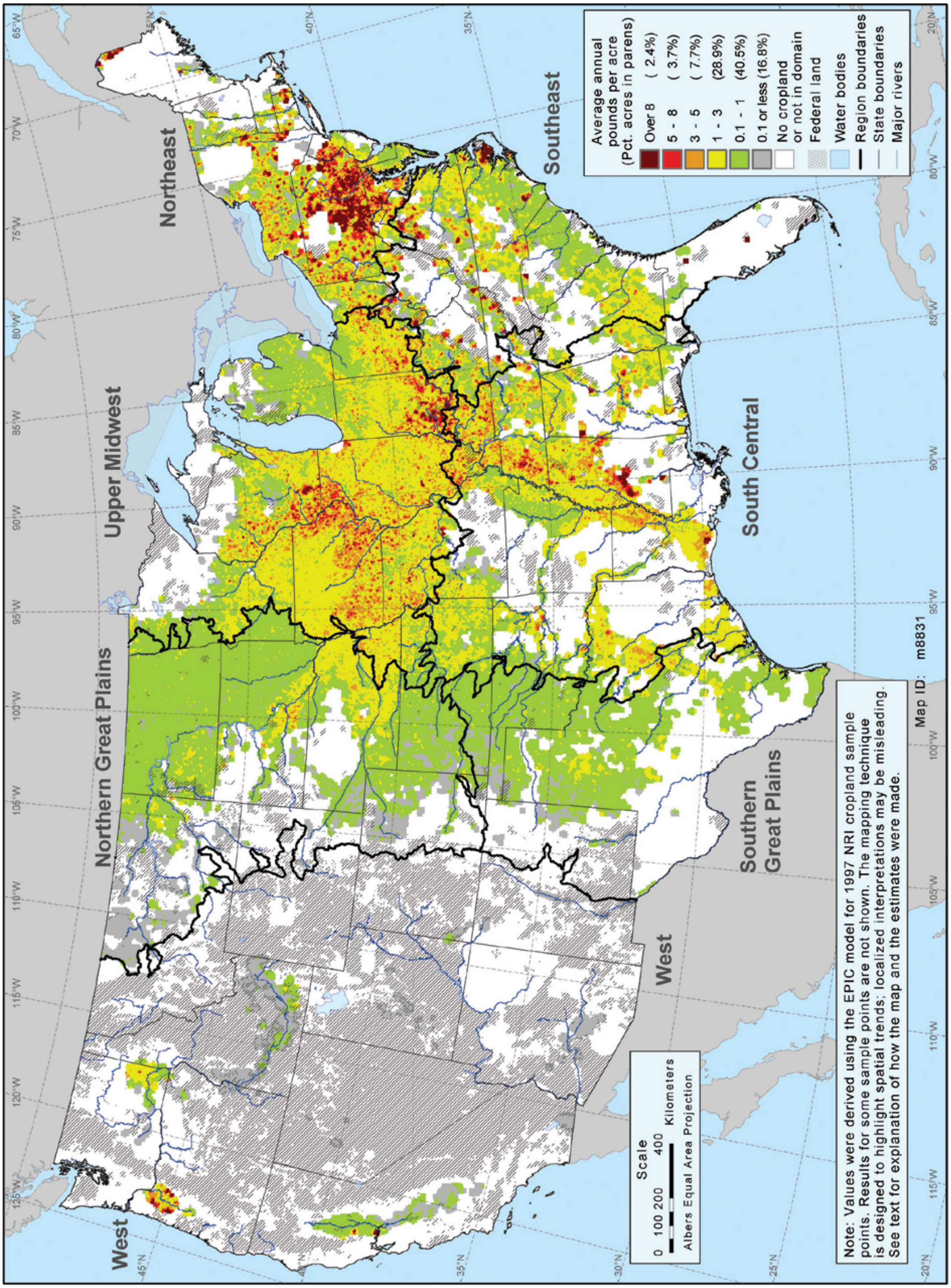
While generally similar to the spatial distribution of nitrogen dissolved in surface water runoff (map 19), the spatial distribution of phosphorus dissolved in surface water runoff differs in some important ways. Most notably, the areas in the West that had the highest potential for loss of nitrogen dissolved in surface water runoff had, for the most part, low vulnerability for dissolved phosphorus runoff loss. Similarly, the rice-growing area along the Mississippi River in Arkansas was highly vulnerable to nitrogen runoff, but only modestly so for phosphorus. The rice growing region in Texas and southern Louisiana, however, had both high nitrogen and phosphorus loss dissolved in runoff. Hot spots in Virginia and North Carolina were much more pronounced for phosphorus than for nitrogen. In addition, an area of high levels of phosphorus dissolved in surface water runoff, but modest amounts of nitrogen loss dissolved in surface water runoff was in southern Illinois, eastern Kentucky and eastern Tennessee, and parts of northern Alabama.

Phosphorus dissolved in leachate—Phosphorus loss dissolved in leachate averaged less than 0.1 pounds per acre per year, with average estimates for some crops in some regions only as high as 0.3 pounds

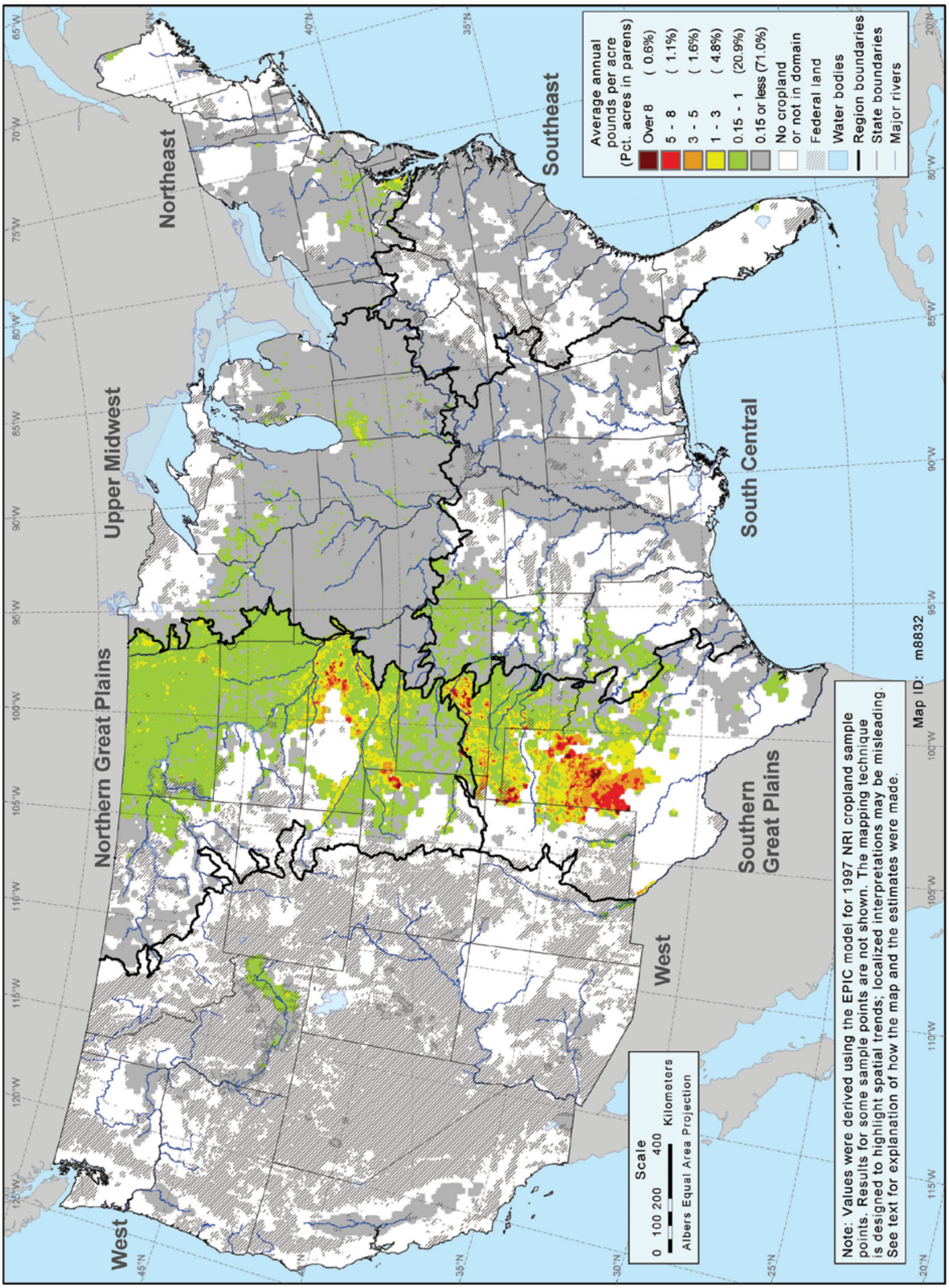
Map 28 Estimated average annual per-acre phosphorus loss summed over all loss pathways (elemental P)



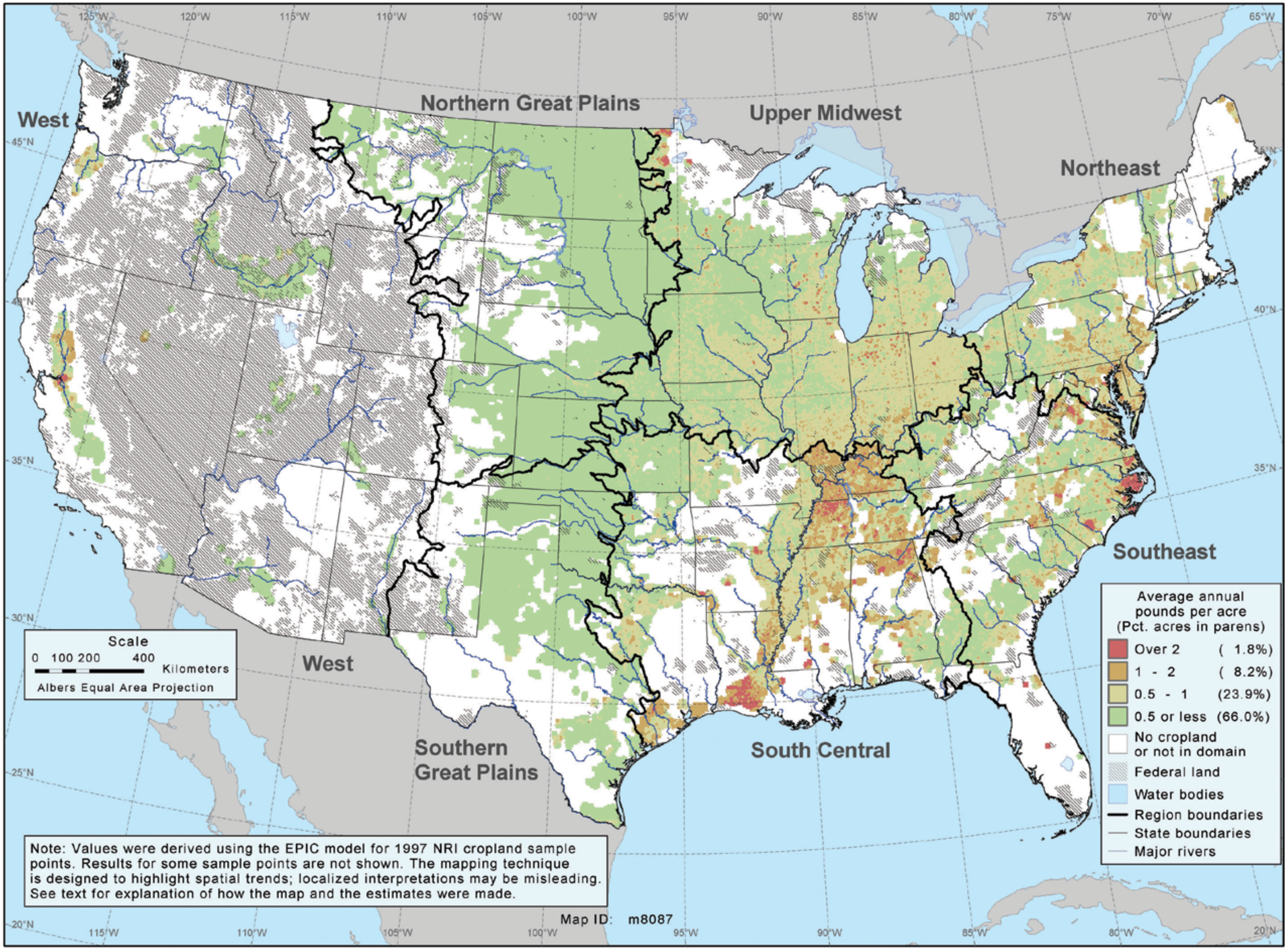
Map 29 Estimated average annual per-acre phosphorus lost with waterborne sediment (elemental P)



Map 30 Estimated average annual per-acre phosphorus lost with windborne sediment (elemental P)



Map 31 Estimated average annual per-acre phosphorus dissolved in surface water runoff (elemental P)



per acre per year (table 55). The amount dissolved in leachate was minimal except in coarse textured and organic soils.

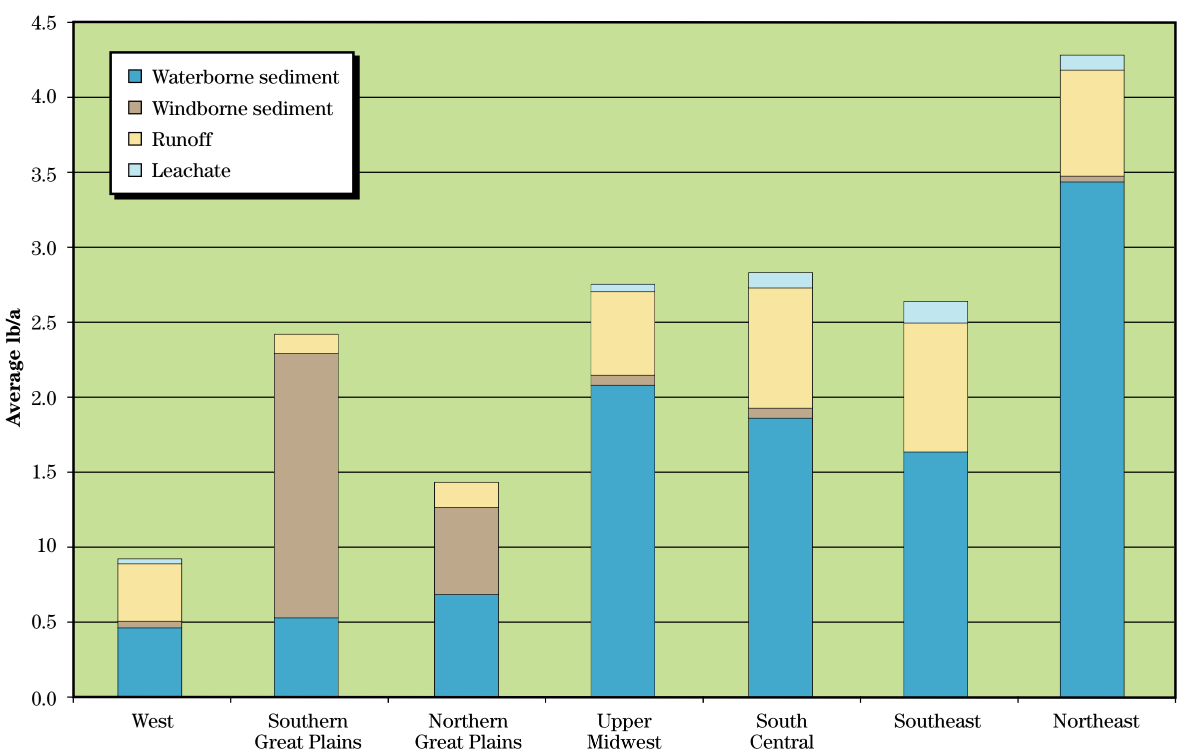
Per-acre phosphorus loss by region

Northeast region—Phosphorus losses were highest in the Northeast region, averaging 4.3 pounds per cropland acre per year (fig. 29, table 55), about twice the national average. Most (80%) was lost with waterborne sediment, but an average of 0.7 pounds per acre per year was lost as dissolved phosphorus in surface water runoff, representing about 15 percent of the total loss in the Northeast region. Overall, phosphorus loss in the Northeast region represented about 19 percent of the annual phosphorus inputs.

Corn silage in the Northeast had the highest phosphorus loss of any crop in any region, averaging nearly 14 pounds per acre per year for phosphorus loss summed over all pathways. Phosphorus loss for corn acres was also among the highest in any region, averaging nearly 8 pounds per acre per year.

South Central, Upper Midwest, and Southeast regions—The South Central, Upper Midwest, and Southeast regions each averaged about 2.6 to 2.8 pounds of phosphorus loss per acre of cropland (table 55, fig. 29). The majority of phosphorus loss in these regions was with waterborne sediment (61–76%). Per-acre losses of phosphorus dissolved in runoff and leachate were greater in the Southeast and South Central regions than in other regions, averaging 0.9 and 0.8 pounds per acre for runoff, respectively, and 0.15 and 0.11 pounds per acre for leachate, respectively. Phosphorus dissolved in surface water runoff accounted for 33 and 28 percent of phosphorus losses in the Southeast and South Central regions, respectively. Estimates of phosphorus loss in surface water runoff was lower in the Upper Midwest region, but still significant. High losses of phosphorus dissolved in runoff and leachate are indicative of high phosphorus levels in cropland soils, as the propensity for phosphorus to dissolve in water increases dramatically as soil phosphorus levels increase.

Figure 29 Average annual per-acre estimates of phosphorus loss–by region



Note: Phosphorus loss is reported here as elemental phosphorus.

Table 55 Phosphorus loss estimates on a per-acre basis–by region and by crop within regions (average annual values)

	Crop	Acres (1,000s)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
By region							
Northeast	All crops	13,642	0.7	0.1	3.4	<0.1	4.3
Northern Great Plains	All crops	72,397	0.2	<0.1	0.7	0.6	1.4
South Central	All crops	45,350	0.8	0.1	1.9	0.1	2.8
Southeast	All crops	13,394	0.9	0.2	1.6	<0.1	2.6
Southern Great Plains	All crops	32,096	0.1	<0.1	0.5	1.8	2.4
Upper Midwest	All crops	112,581	0.6	0.1	2.1	0.1	2.8
West	All crops	9,018	0.4	<0.1	0.5	0.1	0.9
All regions	All crops	298,478	0.5	<0.1	1.5	0.4	2.4
By crop within region*							
Northeast	Corn	2,943	1.2	0.1	6.2	0.1	7.7
	Corn silage	1,482	1.1	0.1	12.5	0.1	13.8
	Grass hay	2,369	0.6	0.1	0.6	<0.1	1.3
	Legume hay	4,052	0.2	0.1	<0.1	<0.1	0.3
	Oats	362	1.1	0.1	4.0	<0.1	5.2
	Soybeans	1,305	0.8	0.2	2.6	0.1	3.6
	Winter wheat	853	0.7	0.1	2.3	<0.1	3.2
Northern Great Plains	Barley	3,243	0.2	<0.1	0.5	0.4	1.1
	Corn	15,466	0.3	<0.1	1.4	1.5	3.2
	Corn silage	810	0.3	<0.1	2.2	2.3	4.8
	Grass hay	2,443	0.1	<0.1	0.1	<0.1	0.2
	Legume hay	6,152	0.1	<0.1	<0.1	<0.1	0.1
	Oats	1,255	0.1	<0.1	0.7	0.4	1.3
	Spring wheat	18,916	0.1	<0.1	0.6	0.4	1.1
	Sorghum	1,595	0.1	<0.1	1.1	1.5	2.7
	Soybeans	9,562	0.2	<0.1	0.7	0.5	1.3
	Winter wheat	12,748	0.1	<0.1	0.2	0.1	0.4
South Central	Corn	5,956	1.7	0.1	3.8	0.1	5.8
	Cotton	5,487	0.7	0.2	3.7	<0.1	4.5
	Grass hay	3,347	0.8	0.1	0.5	<0.1	1.4
	Legume hay	1,630	0.2	0.1	<0.1	<0.1	0.2
	Peanuts	880	0.3	0.2	1.0	0.2	1.7
	Rice	3,004	1.3	0.3	1.8	<0.1	3.4
	Sorghum	2,729	0.5	0.1	2.0	0.5	3.1
	Soybeans	14,083	0.7	0.1	1.2	<0.1	2.0
	Winter wheat	7,896	0.5	0.1	1.2	<0.1	1.8

Table 55 Phosphorus loss estimates on a per-acre basis–by region and by crop within regions (average annual values)—Continued

	Crop	Acres (1,000s)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
Southeast	Corn	3,028	1.9	0.1	2.5	<0.1	4.6
	Corn silage	412	1.4	0.1	6.9	<0.1	8.3
	Cotton	2,422	0.5	0.2	1.9	<0.1	2.5
	Grass hay	2,000	0.5	0.1	0.5	<0.1	1.2
	Legume hay	1,183	0.2	0.1	<0.1	<0.1	0.2
	Peanuts	479	0.3	0.2	1.0	<0.1	1.5
	Soybeans	2,419	0.7	0.2	0.9	<0.1	1.8
	Winter wheat	1,216	0.8	0.2	1.8	<0.1	2.8
Southern Great Plains	Corn	2,665	0.3	<0.1	1.1	4.1	5.5
	Cotton	7,316	0.1	<0.1	0.8	4.0	4.9
	Legume hay	677	0.1	<0.1	<0.1	<0.1	0.1
	Oats	503	0.3	<0.1	0.6	0.1	1.1
	Peanuts	484	0.1	<0.1	0.8	2.9	3.8
	Sorghum	4,895	0.1	<0.1	0.6	2.3	3.1
	Winter wheat	15,037	0.1	<0.1	0.3	0.2	0.6
Upper Midwest	Corn	47,941	0.8	0.1	3.4	0.1	4.3
	Corn silage	1,947	0.8	<0.1	5.9	0.2	7.0
	Grass hay	4,044	0.5	<0.1	0.3	<0.1	0.8
	Legume hay	9,233	0.1	<0.1	<0.1	<0.1	0.2
	Oats	1,388	0.5	<0.1	1.8	0.1	2.4
	Spring wheat	815	0.9	<0.1	0.8	0.1	1.8
	Sorghum	1,604	0.4	<0.1	1.9	0.1	2.4
	Soybeans	40,049	0.4	<0.1	1.1	<0.1	1.6
	Winter wheat	5,147	0.7	<0.1	1.1	<0.1	1.9
West	Barley	958	0.3	<0.1	0.9	0.1	1.4
	Corn silage	297	1.1	0.1	0.7	0.1	2.0
	Cotton	1,631	0.2	<0.1	0.1	<0.1	0.4
	Legume hay	1,847	0.2	<0.1	<0.1	<0.1	0.2
	Potatoes	329	0.5	<0.1	0.2	0.5	1.2
	Rice	599	1.2	0.1	0.4	<0.1	1.6
	Spring wheat	772	0.4	<0.1	0.6	0.1	1.1
	Winter wheat	2,118	0.2	<0.1	0.8	<0.1	1.1

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

The highest per-acre phosphorus loss estimates were for corn and corn silage in the Southeast and Upper Midwest regions, and corn and cotton acres in the South Central region (table 55).

The South Central region had the largest percentage of annual phosphorus inputs lost from farm fields of all the regions—24 percent. Phosphorus loss as a percent of inputs was 12 percent in the Southeast region and 16 percent in the Upper Midwest region.

Southern Great Plains region—The average per-acre phosphorus loss in the Southern Great Plains region was 2.4 pounds per acre, equal to the national average (table 55). However, the principal loss pathway in the Southern Great Plains region was with windborne sediment. Phosphorus lost with windborne sediment accounted for 73 percent of the phosphorus loss in this region. Waterborne sediment accounted for most of the remaining phosphorus loss. The highest per-acre phosphorus loss estimates in the region were for corn and cotton. Overall phosphorus loss in the Southern Great Plains region represented 22 percent of the phosphorus inputs, the second highest percentage among the seven regions.

Northern Great Plains region—The Northern Great Plains region had low phosphorus losses from cropland fields, averaging only 1.4 pounds per cropland acre per year (fig. 29, table 55). This region also had the lowest per-acre loss of nitrogen. Farmer surveys show that wheat, which is the dominant crop in this region, often receives the lowest phosphorus application rates of any of the major field crops, and more than half of the wheat acres receive no phosphorus application. About equal amounts of phosphorus are lost with windborne and waterborne sediment, and only about 11 percent is lost as dissolved phosphorus in surface water runoff. Total phosphorus loss as a percent of inputs was 14 percent.

West region—The lowest per-acre phosphorus loss was in the West region, where phosphorus loss from all pathways averaged about 1 pound per acre, despite relatively high phosphorus inputs. Only 4 percent of the phosphorus applied was lost from cropland fields in the West region, compared to the national average of 16 percent. About half was lost with waterborne sediment and most of the rest as dissolved phosphorus in surface water runoff.

Per-acre phosphorus loss by crop

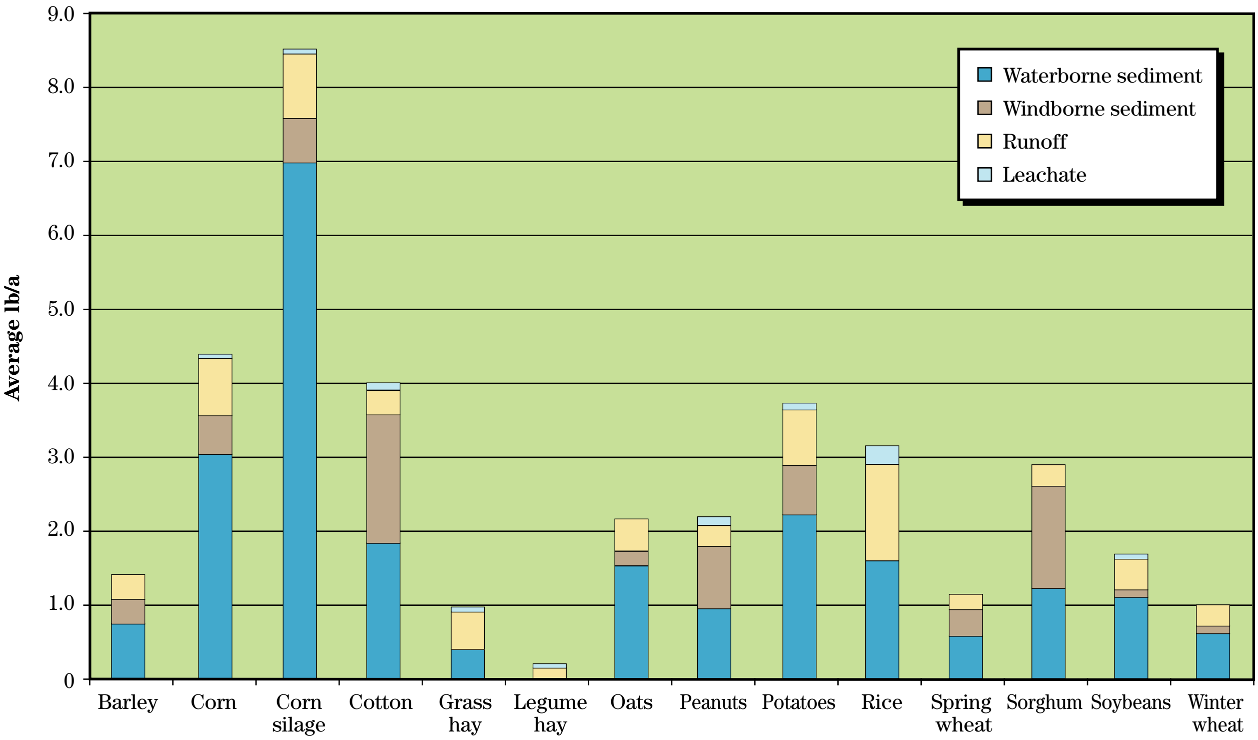
As shown previously for nitrogen loss, per-acre phosphorus loss estimates varied significantly by crop; however, crops with the highest phosphorus losses were not the same as those with the highest nitrogen losses. The crop with the highest per-acre phosphorus loss was corn silage (fig. 30), which had the second-highest phosphorus application rate, dominated by manure phosphorus. The average phosphorus loss for corn silage was 8.5 pounds per acre. Corn had the next highest average per-acre phosphorus loss at 4.4 pounds per acre, followed closely by cotton and potatoes. Potatoes, which had the highest average phosphorus application rate, had an average phosphorus loss of 3.7 pounds per acre, representing 6 percent of the phosphorus inputs. Legume hay had the lowest phosphorus loss, averaging only 0.2 pounds per acre. Phosphorus losses for barley, grass hay, spring wheat, and winter wheat were also low, averaging at or about 1 pound per acre per year.

For most comparisons between irrigated crops and non-irrigated crops, per-acre phosphorus loss estimates were about the same (table 56). Phosphorus loss for most crops in the West region was markedly lower than for non-irrigated crops, however. In contrast, phosphorus loss estimates for most crops in the Southern Great Plains region and for corn in the Northern Great Plains region was markedly higher for irrigated acres, primarily because phosphorus lost with windborne sediment was higher on these irrigated acres. In the Upper Midwest and South Central regions, corn had markedly lower phosphorus loss estimates for irrigated acres than for non-irrigated acres, primarily because phosphorus lost with waterborne sediment was lower on irrigated acres. Cotton acres in the South Central region and sorghum acres in the Southern Great Plains region also had markedly lower phosphorus loss estimates for irrigated acres than non-irrigated acres.

Tons of phosphorus loss

Total phosphorus loadings are obtained when the acres of cropland are taken into account. Estimates of the annual tons of phosphorus for each of the three principal loss pathways are shown in maps 32 through 34. Each dot on these three maps represents 100 tons of phosphorus loss from cropland acres to facilitate comparisons among the pathways. (Note that the nitrogen loading maps presently earlier were based on each dot representing 500 tons.)

Figure 30 Average annual per-acre estimates of phosphorus loss–by crop



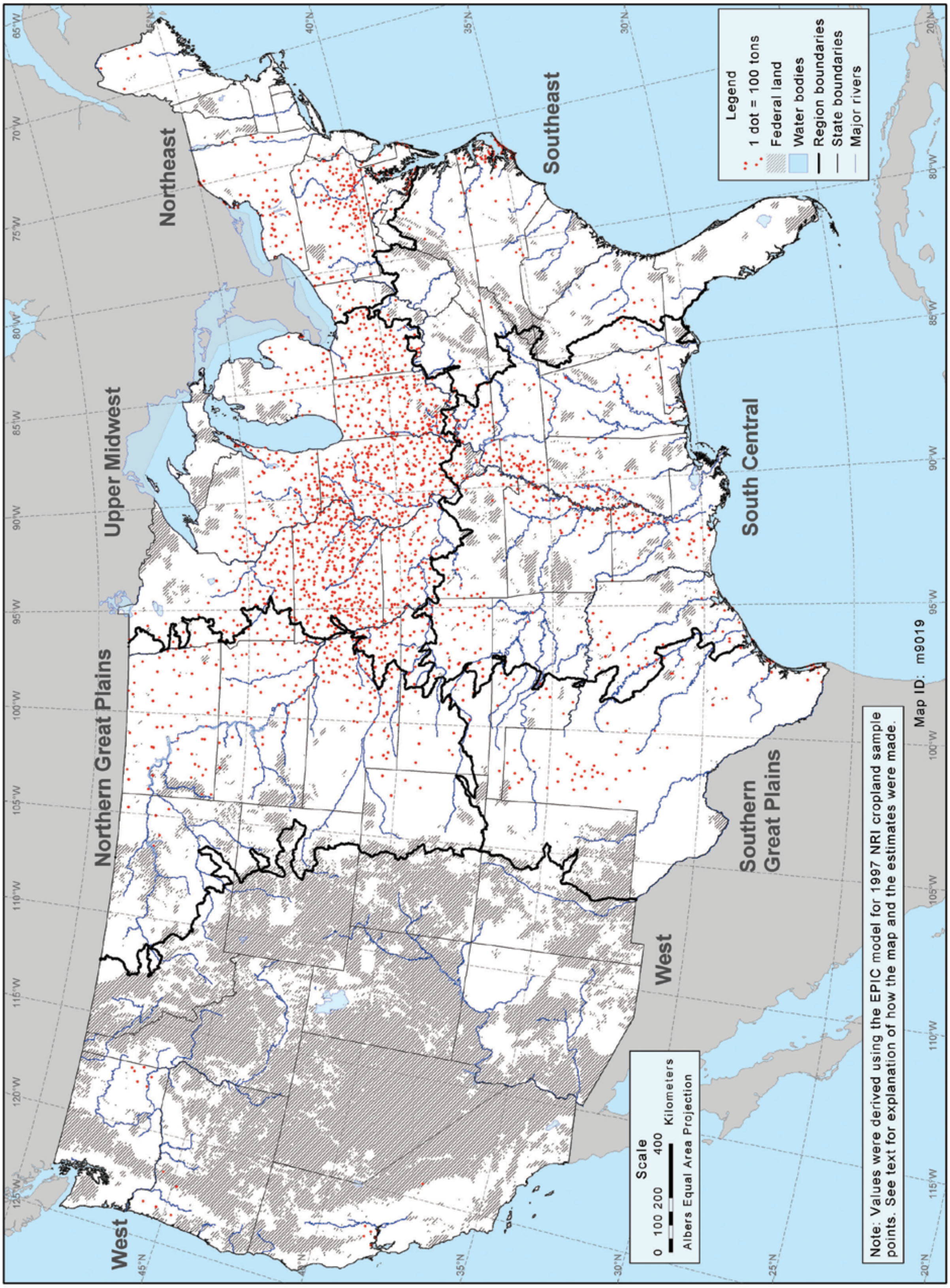
Note: Phosphorus loss is reported here as elemental phosphorus.

Table 56 Comparison of phosphorus loss estimates for irrigated crops to estimates for non-irrigated crops (average annual values)

		Acres (1,000s)		Sum of all loss pathways (lb/a)		Dissolved in surface water runoff (lb/a)		Dissolved in leachate (lb/a)		Lost with waterborne sediment (lb/a)		Lost with windborne sediment (lb/a)	
Region	Crop*	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Northern Great Plains	Corn	6,680	8,785	3.7	3.0	0.4	0.2	0.2	<0.1	1.4	1.4	1.8	1.3
	Legume hay	1,336	4,816	0.2	0.1	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Soybeans	984	8,578	1.6	1.3	0.1	0.2	0.2	<0.1	0.8	0.7	0.5	0.5
	Winter wheat	662	12,086	0.6	0.4	0.2	0.1	0.1	<0.1	0.1	0.2	0.1	0.1
South Central	Corn	671	5,285	5.0	7.0	1.2	1.8	1.6	1.1	2.0	4.0	0.2	0.1
	Cotton	1,505	3,983	5.2	6.5	0.6	0.7	2.2	1.7	2.4	4.1	<0.1	<0.1
	Rice	3,004	0	5.7	NA	1.3	NA	2.5	NA	1.8	NA	<0.1	NA
	Soybeans	3,585	10,498	2.6	3.0	0.6	0.7	1.0	1.0	1.0	1.3	<0.1	0.1
	Winter wheat	554	7,341	3.0	2.3	0.6	0.5	1.4	0.6	0.9	1.2	<0.1	<0.1
Southeast	Cotton	307	2,115	3.5	4.3	0.3	0.5	1.9	1.9	1.3	1.9	<0.1	<0.1
Southern Great Plains	Corn	1,993	672	6.5	2.6	0.2	0.4	0.1	0.1	0.9	1.6	5.2	0.6
	Cotton	2,831	4,486	5.6	4.8	0.3	0.1	0.2	0.1	0.9	0.7	4.3	3.8
	Legume hay	414	263	0.2	0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Peanuts	325	159	4.3	3.8	0.1	0.2	0.3	0.3	0.7	0.9	3.2	2.4
	Sorghum	1,147	3,748	2.2	3.5	0.2	0.1	0.1	0.1	0.4	0.7	1.5	2.6
	Winter wheat	1,991	13,046	0.5	0.7	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.2
Upper Midwest	Corn	1,517	46,424	3.6	4.8	0.6	0.8	1.1	0.5	1.8	3.5	0.1	0.1
	Soybeans	641	39,409	2.3	2.0	0.3	0.4	1.1	0.5	0.8	1.2	<0.1	<0.1
West	Barley	601	357	0.7	2.7	0.4	0.2	0.1	<0.1	0.1	2.3	0.1	0.1
	Corn silage	297	0	2.5	NA	1.1	NA	0.6	NA	0.7	NA	0.1	NA
	Cotton	1,631	0	0.5	NA	0.2	NA	0.1	NA	0.1	NA	<0.1	NA
	Legume hay	1,688	159	0.3	0.4	0.2	0.2	0.1	<0.1	<0.1	0.1	<0.1	<0.1
	Potatoes	329	0	1.2	NA	0.5	NA	<0.1	NA	0.2	NA	0.5	NA
	Rice	599	0	2.4	NA	1.2	NA	0.9	NA	0.4	NA	<0.1	NA
	Spring wheat	575	197	0.7	2.4	0.4	0.3	0.1	0.1	0.1	1.9	0.1	0.2
	Winter wheat	1,052	1,066	1.3	1.6	0.3	0.1	0.6	0.2	0.3	1.3	<0.1	<0.1

NA=not applicable.
* Irrigated crops with more than 250,000 acres in a region are included in the table. These 26 crop-region combinations represent 92 percent of the irrigated acres included in the study.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29

Map 32 Estimated average annual tons of phosphorus lost with waterborne sediment (elemental P)



Map 33 Estimated average annual tons of phosphorus lost with windborne sediment (elemental P)

Map 34 Estimated average annual tons of phosphorus dissolved in surface water runoff (elemental P)

In terms of loadings, the Upper Midwest region accounted for 43 percent of the total tons of phosphorus loss, over twice as much as any of the other six regions and disproportionately high relative to the percentage of acres represented by the region (table 57). About 37 percent of acres included in the study are in the Upper Midwest region. This disproportionality is largely explained, however, by the high proportion of phosphorus inputs for this region—44 percent.

Phosphorus losses were also disproportionately high relative to cropland acres in the Northeast region (table 57). Cropland acres in the Northeast represented only 4.6 percent of all cropland acres included in the study, but phosphorus losses represented 8 percent of total losses. This is also explained by the disproportionately high phosphorus inputs—7 percent of total phosphorus inputs occurred in the Northeast region.

The West region had the lowest phosphorus loadings, representing only 1 percent of total phosphorus losses. Phosphorus loss in the West region, as well as the Northern Great Plains region, was disproportionately low relative to cropland acres (table 57).

Among the 14 crops, corn accounted for the largest share of total phosphorus loss—48 percent, which is nearly twice the percentage of corn acres but equal to the share of phosphorus inputs for corn (table 57). Phosphorus loss was also disproportionately high for cotton and corn silage. Soybeans accounted for the second highest phosphorus loadings—16 percent, which was disproportionately low relative to acres (table 57). Crops associated with the lowest phosphorus loadings were oats, peanuts, potatoes, rice, and barley, largely because of the small number of acres for these crops. Legume hay was also among the crops with the lowest phosphorus loadings, accounting for only 0.6 percent of the total loadings while representing about 8 percent of the cropland acres.

Effects of soil properties on phosphorus loss

The relationships between phosphorus loss and soil texture and hydrologic soil group were nearly identical to relationships observed for nitrogen for each loss pathway (tables 58 and 59). Organic soils had extremely high losses, averaging 13.2 pounds per acre per year. Coarse and moderately course soils had the lowest losses for waterborne sediment and the highest losses for windborne sediment (table 58). For phosphorus loss dissolved in surface water runoff, hydrologic soil groups C and D had the highest losses and hydrologic soil groups A and B had the lowest losses (after adjusting for organic soils). For phosphorus dissolved in leachate, hydrologic soil group A soils and coarse textured and organic soils had the highest losses (except for the very small group of "other texture" soils).

Example of spatial variability of phosphorus loss

As shown previously for sediment and nitrogen losses, phosphorus losses also vary considerably at the local level. Figure 31 presents similar results for phosphorus loss for the two Iowa watersheds. Overall, commercial fertilizer and manure phosphorus inputs were about the same in both watersheds—about 16 pounds per acre, of which about a fourth was from manure applications. Total phosphorus loss was higher in the Lower Iowa watershed (4.4 lb/a/yr) than in the Floyd watershed (2.7 lb/a/yr).

Variability in phosphorus loss summed over all pathways by soil cluster was quite high in the Lower Iowa watershed, ranging from 0.5 to 14.3 pounds per acre. Variability was less in the Floyd watershed, where total phosphorus loss ranged from 0.6 to 4.0 pounds per acre. In the Lower Iowa watershed, the highest losses occurred on soils with few acres—the nine soil clusters with the highest losses (6 lb/a or more) accounted for 29 percent of the total phosphorus loss, but represented only 14 percent of the cropland acres. In the Floyd watershed, about 43 percent of the total phosphorus loss was associated with the three soil clusters with the highest loss rates (greater than 3 lb/a), representing 30 percent of the acres. Many of the soils with high phosphorus loss were different from the soils with high nitrogen loss in both watersheds, primarily because over 80 percent of the phosphorus loss was with waterborne sediment, whereas significant portions of nitrogen loss was through volatilization and leaching in these two watersheds.

Effects of tillage practices on phosphorus loss

Tillage practices were shown to have a significant influence on sediment loss and wind erosion estimates (tables 24 and 30) and a less pronounced influence on nitrogen loss estimates (table 41). The effect of tillage practices was larger for phosphorus loss than for nitrogen loss because the predominant loss pathway for phosphorus was waterborne and windborne sediment. As discussed earlier in this report (see table 12 and related discussion), the subset of model runs where all three tillage systems—conventional tillage, mulch till-

Table 57 Percentages by region and crop of the total for cropland acres, total phosphorus loss, and total phosphorus inputs

	Percent of total cropland acres	Percent of total phosphorus losses	Percent of all phosphorus sources
By region			
Disproportionately high phosphorus loss relative to acres			
Northeast	4.6	8.1	6.9
Upper Midwest	37.7	42.9	44.4
Disproportionately low phosphorus loss relative to acres			
Northern Great Plains	24.3	14.3	16.9
West	3.0	1.1	4.4
Phosphorus loss approximately proportional to acres			
South Central	15.2	17.9	12.4
Southeast	4.5	4.9	6.9
Southern Great Plains	10.8	10.8	8.0
All regions	100.0	100.0	100.0
By crop			
Disproportionately high phosphorus loss relative to acres			
Corn	26.2	47.5	48.0
Corn silage	1.7	6.1	6.4
Cotton	5.6	9.4	4.8
Disproportionately low phosphorus loss relative to acres			
Soybeans	22.6	15.8	9.6
Grass hay	4.9	1.9	3.4
Legume hay	8.3	0.6	4.3
Winter wheat	15.1	6.3	10.3
Spring wheat	6.9	3.2	4.5
Phosphorus loss approximately proportional to acres			
Barley	1.6	0.9	1.9
Oats	1.3	1.1	0.9
Peanuts	0.6	0.6	0.6
Potatoes	0.3	0.5	1.4
Rice	1.2	1.6	0.8
Sorghum	3.7	4.4	3.3
All crops	100.0	100.0	100.0

Table 58 Sources of phosphorus applied and estimates of phosphorus loss (elemental P)–by soil texture class (average annual values)

Soil texture class	Percent of cropland acres	Commercial fertilizer (lb/a)	Manure (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Sum of all losses (lb/a)
Coarse	5.1	13.46	5.51	0.40	1.77	0.28	0.14	2.58
Moderately coarse	10.9	12.46	4.12	0.83	0.64	0.39	0.08	1.94
Medium	51.4	11.86	3.08	1.79	0.22	0.49	0.04	2.55
Moderately fine	6.0	9.00	1.56	1.77	0.24	0.56	0.04	2.60
Fine	26.2	10.89	2.60	1.39	0.32	0.38	0.03	2.12
Organic	0.4	15.89	6.37	6.33	0.08	6.66	0.12	13.20
Other	0.0	10.19	6.09	0.24	0.10	0.35	0.42	1.12
All	100	11.60	3.12	1.53	0.37	0.47	0.05	2.42

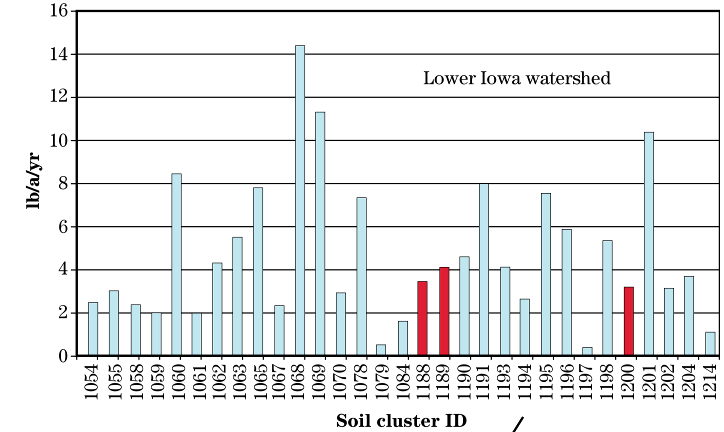
Table 59 Sources of phosphorus applied and estimates of phosphorus loss (elemental P)–by hydrologic soil group (average annual values)

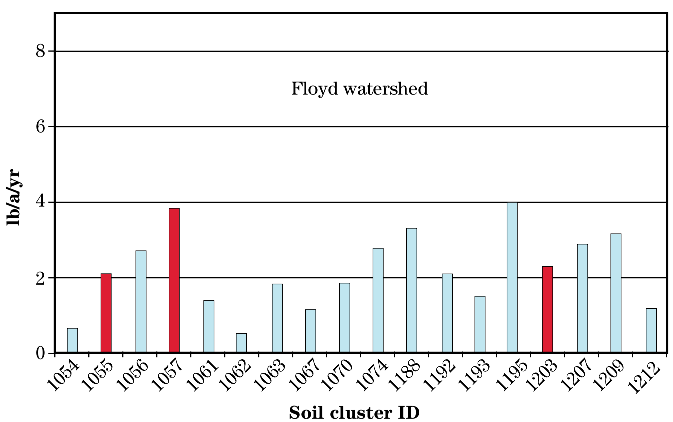
Soil hydrologic soil group	Percent of cropland acres	Commercial fertilizer (lb/a)	Manure (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Sum of all losses (lb/a)
A	3.8	12.56	4.87	0.43	1.74	0.43	0.15	2.42
B	55.5	11.77	3.34	1.31	0.39	0.34	0.04	2.07
C	25.7	12.28	3.04	2.03	0.16	0.63	0.05	2.85
D	15.1	9.55	1.97	1.73	0.30	0.70	0.04	2.66
All	100.0	11.60	3.12	1.53	0.37	0.47	0.05	2.37

* Excluding organic soils.

Figure 31 Variability in phosphorus loss estimates (sum of all loss pathways) within two IA watersheds

Soil cluster	Representative soil	Texture group	Hydrologic soil group	Soil cluster	Representative soil	Texture group	Hydrologic soil group
1054	Fairhaven	Medium	B	1189	Lagoda	Medium	B
1055	Kossuth	Moderately fine	B	1190	Sharpsburg	Moderately fine	B
1056	Alton	Moderately fine	C	1191	Adair	Medium	C
1057	Galva	Moderately fine	B	1192	Kenyon	Medium	B
1058	Hoopeston	Moderately coarse	B	1193	Marshall	Moderately fine	B
1059	Coland	Moderately fine	B	1194	Sparta	Coarse	A
1060	Tama	Medium	B	1195	Huntsville	Medium	B
1061	Coppock	Medium	B	1196	Downs	Medium	B
1062	Shelby	Moderately fine	B	1197	Village	Medium	B
1063	Turlin	Medium	B	1198	Lineville	Medium	C
1065	Fayette	Medium	B	1200	Humeston	Medium	C
1067	Nodaway	Medium	B	1201	Lamoni	Fine	C
1068	Gara	Medium	C	1202	Wabash	Moderately fine	D
1069	Lindley	Medium	C	1203	Terril	Medium	B
1070	Colo	Moderately fine	B	1204	Floyd	Medium	B
1074	Ida	Medium	B	1207	Monona	Medium	B
1078	Adair	Moderately fine	C	1209	Racine	Medium	B
1079	Lamont	Moderately coarse	B	1212	Spicer	Moderately fine	B
1084	Dickinson	Moderately coarse	B	1214	Chelsea	Coarse	A
1188	Ely	Medium	B				





Note: Phosphorus loss is reported here as elemental phosphorus.

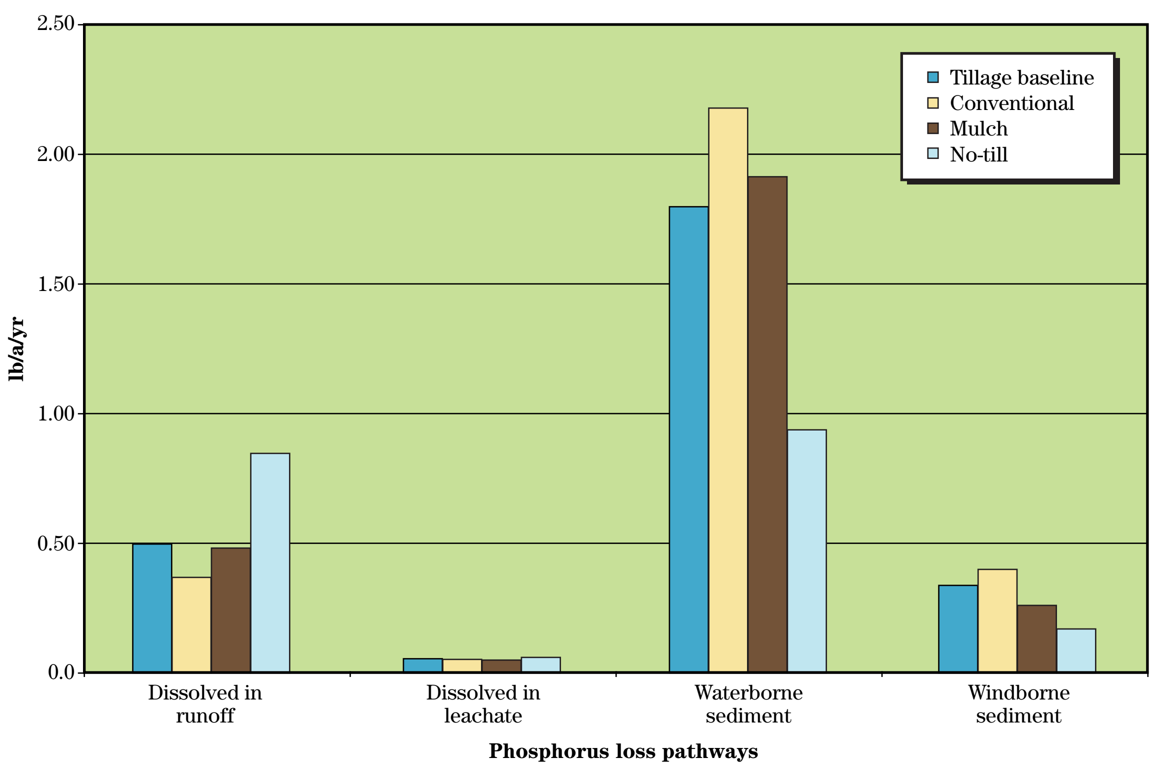
age, and no-till—were present within a URU was used as the domain for examining the effects of tillage.

For the 208 million acres in the tillage comparison subset, the tillage-effects baseline phosphorus loss (sum of all loss pathways) averaged 2.6 pounds per acre per year (table 60), which is nearly the same as the estimate for the full set of NRI sample points included in the study. Model simulation results showed that phosphorus loss summed over all loss pathways would have averaged 3.0 pounds per acre per year if conventional tillage had been used on all acres, indicating that the tillage practices currently in use have reduced phosphorus loss by 13 percent. As shown for sediment loss, phosphorus loss estimates for mulch tillage were similar to the tillage-effects baseline. Phosphorus loss estimates assuming mulch tillage was used on all acres averaged about 10 percent less than if conventional tillage had been used on all acres. Simulation of full implementation of no-till resulted in an average phosphorus loss of 2.0 pounds per acre per year, a decrease of about 0.6 pounds per acre, on average. Full implementation of no-till would have the greatest effect in the Northeast region.

The effect of tillage on phosphorus loss estimates varied by crop (table 60). The largest reductions in phosphorus loss for full implementation of mulch tillage compared to the baseline were for barley, spring wheat, and oats. With full implementation of no-till, phosphorus loss reductions of more than 1 pound per acre, on average, would be obtained for sorghum and corn silage.

The effect of tillage on average phosphorus loss estimates for all acres in the tillage-effects domain is shown in figure 32. For phosphorus dissolved in surface water runoff, no-till losses were actually greater

Figure 32 Effects of tillage practices on phosphorus loss estimates–by loss pathway



Note: Phosphorus loss is reported here as elemental phosphorus.

Table 60 Effects of tillage practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)

	Acres in tillage comparison subset (1,000s)	Phosphorus loss, all pathways				Change relative to the tillage-effects baseline			Change relative to conventional tillage	
		Tillage-effects baseline	Conventional tillage	Mulch tillage	No-till	Conventional tillage	Mulch tillage	No-till	Mulch tillage	No-till
By region										
Northeast	6,034	7.5	8.3	7.6	5.3	0.8	0.1	-2.2	-0.7	-3.0
Northern Great Plains	56,551	3.7	4.1	4.0	3.3	0.4	0.3	-0.4	-0.1	-0.8
South Central	24,879	2.8	3.1	3.1	2.3	0.3	0.3	-0.5	0.0	-0.8
Southeast	4,442	3.1	3.5	3.2	2.4	0.4	0.2	-0.7	-0.2	-1.1
Southern Great Plains	17,746	1.6	1.8	1.3	1.0	0.2	-0.2	-0.6	-0.5	-0.8
Upper Midwest	96,330	1.6	1.8	1.4	1.0	0.2	-0.2	-0.7	-0.4	-0.8
West	1,661	1.5	1.6	1.4	1.3	0.1	-0.1	-0.3	-0.2	-0.3
By crop										
Barley	3,256	1.3	1.4	0.8	0.7	0.1	-0.5	-0.6	-0.7	-0.7
Corn	71,016	4.5	4.9	4.6	3.5	0.4	0.1	-0.9	-0.3	-1.3
Corn silage	4,082	9.1	9.5	9.4	7.0	0.4	0.3	-2.0	-0.1	-2.5
Oats	2,078	2.1	2.3	1.7	1.5	0.2	-0.4	-0.6	-0.6	-0.8
Spring wheat	18,074	1.1	1.3	0.6	0.5	0.2	-0.5	-0.6	-0.7	-0.8
Sorghum	7,697	3.2	3.4	3.1	2.0	0.3	0.0	-1.2	-0.3	-1.5
Soybeans	62,967	1.7	2.1	1.9	1.1	0.4	0.2	-0.5	-0.2	-0.9
Winter wheat	38,473	1.0	1.1	0.8	0.8	0.1	-0.2	-0.2	-0.3	-0.3
All crops and regions	207,642	2.6	3.0	2.7	2.0	0.4	0.1	-0.6	-0.3	-1.0

Note: The subset used for this analysis includes only those URU where all three tillage systems were present. The tillage-effects baseline results represent the mix of tillage systems as reported in the Crop Residue Management Survey for 2000 (CTIC 2001). Tillage-effects baseline results reported in this table will differ from results reported in table 55 because they represent only about 70 percent of the acres in the full database. Results presented for each tillage system represent phosphorus loss estimates as if all acres had been modeled using a single tillage system.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

than the other tillage scenarios. This increase in dissolved phosphorus loss with no-till is more than offset, however, by the decreases in waterborne sediment.

Effects of three conservation practices on phosphorus loss
In addition to tillage effects, three conservation practices—contour farming, stripcropping, and terraces—were shown to have a significant influence on sediment loss and a positive—but more modest—influence on nitrogen loss estimates (tables 25 and 42). As shown for tillage practices, these three conservation practices were much more effective in reducing phosphorus loss than in reducing nitrogen loss. For comparison to the results for the model runs that included conservation practices, an additional set of model runs were conducted after adjusting model settings to represent no practices. The difference between the no-practices scenario and the conservation-practices baseline scenario (consisting of the original model runs for NRI sample points with conservation practices) is used here to assess the extent to which conservation practices reduced the phosphorus loss estimates (table 13 and related discussion).

For the 31.7 million acres modeled with conservation practices, phosphorus loss estimates (sum of all loss pathways) averaged 2.5 pounds per acre per year (table 61), which was close to the estimate for the full set of NRI sample points included in the study. If conservation practices had not been accounted for in the model simulations, phosphorus loss estimates on these acres would have averaged 3.4 pounds per acre per year, representing a reduction in phosphorus loss of about 1 pound per acre. These model simulations suggest, therefore, that the conservation practices reported by the NRI reduce phosphorus loss by about 28 percent, on average, for acres with one or more of the three practices.

The bulk of the reductions in phosphorus loss resulted from reductions in waterborne sediment in all but the Southern Great Plains region, where reductions in windborne sediment were also important. There was little difference in phosphorus dissolved in surface water runoff between the two scenarios. However, phosphorus dissolved in leachate was about 0.3 pounds per acre higher for the conservation-effects baseline scenario than for the no-practices scenario, indicating a trade-off between sediment and phosphorus reduction from erosion control practices and a slight increase in phosphorus leaching.

As observed for nitrogen loss, the largest reductions in phosphorus loss occurred for contour farming alone (1.4 lb/a/yr) and contour farming in combination with stripcropping (2.7 lb/a/yr). The most prevalent practice set—contour farming and terraces—reduced phosphorus loss estimates about 1.0 pounds per acre per year. Terraces only or stripcropping only resulted in the smallest reductions—less than 0.4 pounds per acre per year on average.

The effects of conservation practices varied considerably by region as shown in table 61. The largest phosphorus loss reductions occurred in the Northeast and Upper Midwest regions, which were also the regions with the highest sediment loss reductions attributable to the three conservation practices. Phosphorus loss reductions for acres with one or more of the three conservation practices in these two regions were about 2.0 pounds per acre per year, on average. The largest reduction in phosphorus loss was for the combination of contour farming and stripcropping in the Northeast region, which reduced phosphorus loss by 3 pounds per acre per year—37 percent.

Assessment of critical acres for phosphorus loss

Two of the phosphorus loss pathways are used to identify critical acres for phosphorus loss:

- phosphorus lost with waterborne sediment
- phosphorus dissolved in surface water runoff

Phosphorus lost with windborne sediment is well represented by critical acres identified for wind erosion. Phosphorus dissolved in leachate had levels too low to be useful as a criterion for identifying critical acres.

Specific regions of the country have been shown in this study to have a much higher potential for phosphorus loss from these two loss pathways than other areas of the country. Moreover, as shown in maps 29 and 31 and in the example for the two Iowa watersheds, phosphorus loss estimates often varied considerably within relatively small geographic areas. Estimates of the average phosphorus loss by region and by crops within regions mask much of this under-

Table 61 Effects of three conservation practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)

Region	Conservation practices	Number of NRI sample points	Acres (1,000s)	Phosphorus loss: Conservation-practices aseline scenario	No-practices scenario	Difference	Percent difference relative to no-practices scenario
All regions	Contour farming only	3,728	5,965	4.1	5.6	-1.4	-26
	Contour farming and stripcropping	1,183	1,764	3.7	6.4	-2.7	-42
	Contour farming and terraces	7,883	14,728	2.0	3.0	-1.0	-34
	Contour farming, stripcropping, and terraces	31	64	2.1	3.2	-1.1	-35
	Stripcropping only	1,308	2,930	2.0	2.4	-0.4	-18
	Terraces only	3,268	6,285	1.9	2.1	-0.2	-8
	All practices	17,401	31,737	2.5	3.4	-1.0	-28
Northeast	Contour farming only	338	485	7.0	8.8	-1.7	-20
	Contour farming and stripcropping	454	595	5.2	8.2	-3.0	-37
	Stripcropping only	423	526	6.3	8.2	-1.9	-23
	All practices	1,215	1,606	6.1	8.4	-2.3	-27
Southeast	Contour farming only	275	456	4.6	5.0	-0.4	-9
	Contour farming and terraces	132	234	2.4	2.5	0.0	-1
	Terraces only	52	92	3.2	2.7	0.5	20
	All practices	459	782	3.8	4.0	-0.2	-5
South Central	Contour farming only	110	172	5.0	5.8	-0.8	-14
	Contour farming and terraces	1,173	1,963	2.3	3.2	-0.8	-26
	Terraces only	1,169	1,974	2.5	2.6	-0.1	-3
	All practices	2,452	4,109	2.5	3.0	-0.5	-16
Upper Midwest	Contour farming only	2,625	4,239	4.0	5.7	-1.7	-30
	Contour farming and stripcropping	702	1,106	3.0	5.6	-2.6	-46
	Contour farming and terraces	3,621	5,293	2.4	4.6	-2.2	-47
	Stripcropping only	156	231	3.9	5.1	-1.1	-23
	Terraces only	637	985	3.0	3.6	-0.6	-18
	All practices	7,741	11,853	3.1	5.0	-1.9	-38

Table 61 Effects of three conservation practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)—Continued

Region	Conservation practices	Number of NRI sample points	Acres (1,000s)	Phosphorus loss: Conservation-practices aseline scenario	Phosphorus loss: No-practices scenario	Phosphorus loss: Difference	Phosphorus loss: Percent difference relative to no-practices scenario
Northern Great Plains	Contour farming only	268	365	1.9	2.6	-0.7	-26
	Contour farming and terraces	1,370	3,553	1.0	1.2	-0.3	-23
	Stripcropping only	602	1,945	0.4	0.4	0.0	-5
	Terraces only	213	495	1.1	1.3	-0.2	-12
	All practices	2,453	6,357	0.8	1.1	-0.2	-20
Southern Great Plains	Contour farming only	104	235	3.0	3.0	0.0	-2
	Contour farming and terraces	1,585	3,681	4.0	3.7	0.3	9
	Stripcropping only	80	149	2.1	2.4	-0.3	-13
	Terraces only	1,122	2,677	3.0	2.8	0.2	6
	All practices	2,891	6,743	1.2	1.3	-0.1	-6
West	Terraces only	72	58	1.8	2.0	-0.2	-10

Note: Results for conservation practices and combinations of practices based on less than 20 NRI sample points are not shown in the regional breakdowns, but these data are included in the aggregated results for all regions.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

lying variability. Tables 62 and 63 demonstrate the extent of both regional and local variability by presenting the percentiles for each of the phosphorus loss pathways for each region.

For phosphorus lost with waterborne sediment, the mean of the distribution exceeded the median for all regions (table 62), indicating that the bulk of the phosphorus loss estimates for this pathway is below the average and that there is a minority of sample points with very high loss estimates. This disproportionality was pronounced for 2 regions—the Northeast and West. In the West region, the mean exceeded the 75th percentile. In most regions, the 90th percentile loss estimate was twice as high as the average loss estimate, and over three times higher in the Northeast region.

All regions exhibited disproportionality for phosphorus dissolved in surface water runoff (table 63), but overall the disproportinality was less than for phosphorus lost with waterborne sediment. In the Southeast region, however, the disproportionality was strong as indicated by the mean being nearly equal to the 75th percentile.

Five categories of critical acres for phosphorus lost with waterborne sediment, representing different degrees of severity, are defined on the basis of national level results.

- acres where phosphorus loss is above the 95th percentile for all acres included in the study (5.550 lb/a/yr)
- acres where phosphorus loss is above the 90th percentile for all acres included in the study (3.633 lb/a/yr)
- acres where phosphorus loss is above the 85th percentile for all acres included in the study (2.781 lb/a/yr)
- acres where phosphorus loss is above the 80th percentile for all acres included in the study (2.165 lb/a/yr)
- acres where phosphorus loss is above the 75th percentile for all acres included in the study (1.798 lb/a/yr)

Five categories of critical acres for phosphorus dissolved in surface water runoff were defined in a similar manner:

- acres where phosphorus loss is above the 95th percentile for all acres included in the study (1.274 lb/a/yr)
- acres where phosphorus loss is above the 90th percentile for all acres included in the study (1.000 lb/a/yr)
- acres where phosphorus loss is above the 85th percentile for all acres included in the study (0.827 lb/a/yr)
- acres where phosphorus loss is above the 80th percentile for all acres included in the study (0.712 lb/a/yr)
- acres where phosphorus loss is above the 75th percentile for all acres included in the study (0.621 lb/a/yr)

The regional representation of critical acres is shown in tables 64 and 65 for each of the five categories. Over 90 percent of the acres with per-acre estimates of phosphorus lost with waterborne sediment in the top 5 percent were in three regions—the Upper Midwest region (55% of critical acres), South Central region (18%), and Northeast region (20%). These are the same three regions with the majority of the critical acres for sediment loss and for nitrogen lost with waterborne sediment. For phosphorus dissolved in surface water runoff, the South Central (50%) and Upper Midwest (23%) regions had the majority of acres in the top 5 percent. In the Northeast region, half of the cropland acres were designated as critical acres in the top 25 percent for phosphorus dissolved in surface water runoff.

These critical acres accounted for the bulk of the 69,967 tons per year of phosphorus dissolved in surface water runoff and the 227,863 tons per year of phosphorus lost with waterborne sediment. The 95th percentile category, representing the 5 percent of acres with the highest per-acre losses, accounted for 24 percent of the total tons of phosphorus dissolved in surface water runoff and 31 percent of the total tons of phosphorus lost with waterborne sediment. The 25 percent of acres with the highest per-acre losses accounted for 61 percent of the total tons of phosphorus dissolved in surface water runoff and 71 percent of the total tons of phosphorus lost with waterborne sediment. Following is the percentile breakdown:

Percentile	Percent of total tons of phosphorus dissolved in surface water runoff	Percent of total tons of phosphorus lost with waterborne sediment
95th	24.3	31.2
90th	36.3	45.8
85th	46.0	56.2
80th	54.2	64.2
75th	61.3	70.6

Table 62 Percentiles of phosphorus lost with waterborne sediment (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	3.429	0.000	0.000	0.005	0.746	4.715	10.899	15.531
Northern Great Plains	72,396,500	36,035	0.675	0.002	0.022	0.137	0.516	0.875	1.621	2.187
South Central	45,349,900	27,465	1.853	0.004	0.129	0.576	1.264	2.349	4.058	6.033
Southeast	13,394,400	8,955	1.615	<.001	0.004	0.122	0.672	1.677	3.471	6.579
Southern Great Plains	32,096,000	14,495	0.521	0.025	0.053	0.172	0.334	0.679	1.192	1.674
Upper Midwest	112,580,900	74,691	2.076	<.001	0.026	0.562	1.310	2.719	4.807	6.864
West	9,018,400	5,644	0.446	0.000	0.000	0.010	0.083	0.355	1.192	1.737
All regions	298,478,000	178,567	1.527	<.001	0.011	0.260	0.758	1.798	3.633	5.550

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 63 Percentiles of phosphorus dissolved in surface water runoff (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	0.705	0.113	0.152	0.218	0.627	1.013	1.360	1.663
Northern Great Plains	72,396,500	36,035	0.155	0.019	0.025	0.061	0.116	0.205	0.330	0.418
South Central	45,349,900	27,465	0.806	0.159	0.219	0.340	0.589	0.969	1.773	2.321
Southeast	13,394,400	8,955	0.873	0.098	0.130	0.227	0.446	0.865	1.548	2.066
Southern Great Plains	32,096,000	14,495	0.123	0.011	0.017	0.034	0.068	0.147	0.322	0.448
Upper Midwest	112,580,900	74,691	0.564	0.092	0.136	0.297	0.496	0.723	1.012	1.192
West	9,018,400	5,644	0.375	0.029	0.052	0.090	0.208	0.427	0.952	1.235
All regions	298,478,000	178,567	0.469	0.028	0.051	0.119	0.310	0.621	1.000	1.274

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 64 Critical acres for phosphorus lost with waterborne sediment

		Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 25% nationally	
Region	Acres	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	3,017,000	20.2	4,012,600	13.4	4,656,800	10.4	5,330,600	8.9	5,562,700	7.5
Northern Great Plains	72,396,500	90,700	0.6	622,800	2.1	1,668,200	3.7	3,666,800	6.1	4,963,400	6.7
South Central	45,349,900	2,658,200	17.8	5,497,800	18.4	8,741,700	19.5	12,411,000	20.8	15,673,300	21.0
Southeast	13,394,400	865,900	5.8	1,246,200	4.2	1,663,300	3.7	2,333,200	3.9	3,114,700	4.2
Southern Great Plains	32,096,000	12,300	0.1	147,800	0.5	247,500	0.6	812,500	1.4	1,290,000	1.7
Upper Midwest	112,580,900	8,215,000	55.0	18,176,300	60.9	27,562,100	61.6	34,841,100	58.4	43,648,700	58.5
West	9,018,400	63,800	0.4	145,300	0.5	225,400	0.5	298,800	0.5	365,100	0.5
All regions	298,478,000	14,922,900	100.0	29,848,800	100.0	44,765,000	100.0	59,694,000	100.0	74,617,900	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 62. Other columns correspond to table 62 in a similar manner.

Table 65 Critical acres for phosphorus dissolved in surface water runoff

		Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 2% nationally	
Region	Acres	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	1,674,300	11.2	3,575,700	12.0	5,314,500	11.9	6,124,400	10.3	6,849,500	9.2
Northern Great Plains	72,396,500	36,300	0.2	71,600	0.2	187,600	0.4	394,700	0.7	1,059,400	1.4
South Central	45,349,900	7,381,400	49.5	10,851,300	36.4	14,308,400	32.0	18,031,600	30.2	21,559,900	28.9
Southeast	13,394,400	1,886,700	12.6	2,684,700	9.0	3,462,300	7.7	4,361,600	7.3	4,945,800	6.6
Southern Great Plains	32,096,000	33,700	0.2	85,000	0.3	194,100	0.4	288,700	0.5	451,000	0.6
Upper Midwest	112,580,900	3,474,100	23.3	11,750,900	39.4	20,174,300	45.1	29,226,500	49.0	38,262,900	51.3
West	9,018,400	429,900	2.9	819,400	2.7	1,058,500	2.4	1,249,400	2.1	1,490,100	2.0
All regions	298,478,000	14,916,400	100.0	29,838,600	100.0	44,699,700	100.0	59,676,900	100.0	74,618,600	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 63. Other columns correspond to table 63 in a similar manner.