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The Quality of Our Nation's Waters

Agriculture—A River Runs Through It—The Connections Between Agriculture and Water Quality

National Water-Quality Program
National Water-Quality Assessment Project

Circular 1433

U.S. Department of the Interior
U.S. Geological Survey

Cover: A conservation buffer along a stream, Iowa. Photograph taken by Lynn Betts, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSIA99058, 1999.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2018

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Suggested citation:
Capel, P.D., McCarthy, K.A., Coupe, R.H., Grey, K.M., Amenumey, S.E., Baker, N.T., and Johnson, R.L., 2018, Agriculture—A River runs through it—The connections between agriculture and water quality: U.S. Geological Survey Circular 1433, 201 p., https://doi.org/10.3133/cir1433.

ISSN 2330-5703 (online)

Foreword

Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of the almost 400 million people projected to live in the United States by 2050.

In 1991, Congress established the U.S. Geological Survey National Water-Quality Assessment (NAWQA) to address where, when, why, and how the Nation's water quality has changed, or is likely to change in the future, in response to human activities and natural factors. Since then, NAWQA has been a leading source of scientific data and knowledge used by national, regional, state, and local agencies to develop science-based policies and management strategies to improve and protect water resources used for drinking water, recreation, irrigation, energy development, and ecosystem needs. Plans for the third decade of NAWQA (2013–23) address priority water-quality issues and science needs identified by NAWQA stakeholders, such as the Advisory Committee on Water Information and the National Research Council, and are designed to meet increasing challenges related to population growth, increasing needs for clean water, and changing land-use and weather patterns.

This report is one of a series of publications, *The Quality of Our Nation's Waters*, which describes major findings of the NAWQA Project on water-quality issues of regional and national concern and provides science-based information for assessing and managing the quality of our groundwater resources. Other reports in this series focus on occurrence and distribution of nutrients, pesticides, and volatile organic compounds in streams and groundwater, the effects of contaminants and stream-flow alteration on the condition of aquatic communities in streams, and on the quality of groundwater from private domestic and public supply wells. Each reports builds toward a more comprehensive understanding of the quality of regional and national water resources. All NAWQA reports are available online (https://water.usgs.gov/nawqa/bib/).

We hope this publication will provide you with insights and information to meet your water-resource needs and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters. The information in this report is intended primarily for those interested or involved in resource management and protection, conservation, regulation, and policymaking at the regional and national levels.

Dr. Donald W. Cline
Associate Director for Water
U.S. Geological Survey

Good soil, plentiful sunshine, and sufficient water are needed for successful crop production (Wisconsin). Photograph by Paul Capel, U.S. Geological Survey, 2010.

Prologue – Lessons from Slugs and Beetles

My wife is an avid backyard gardener. Her many flowers are beautiful! For the most part, she understands what her flowers need in order to thrive, but at times, her knowledge of the garden ecosystem becomes limiting. Last year she bought some heirloom zinnia seeds. She looked forward to planting them and watching them grow and bloom. After a week in the soil, they sprouted and grew a couple of inches. One morning, the little leaves were full of smooth round holes and some of the seedlings had died. What was the problem? Insects? Rabbits? Was an insecticide needed? Was fencing needed?

After some investigation, it was determined that the culprits were slugs. The solution to the problem—Epsom salts scattered on the soil.

In another part of the garden, she discovered that some of the leaves on her roses had been skeletonized—all of the green leafy material between the veins had been eaten. Slugs again? Should she get out the Epsom salts? No, slugs generally just eat round holes in the leaves; they do not eat the leaves between the veins in a patterned fashion. This culprit turned out to be Japanese beetles. A little investigation revealed that Japanese beetles can be controlled in the short term by conventional or botanical insecticides, and, perhaps, in the long term by changing plants in the garden or adding a natural, disease-causing bacteria (specific to the grub stage of the Japanese beetle) to the soil.

What are the lessons to be learned from the slugs and beetles? First, everything is connected. Cause and effect relations are the basis of the changes in the world. (Slugs enjoy eating zinnia seedlings, therefore, the zinnia leaves disappear.) Second, these connections are often complex and not always obvious. We need to understand these connections to make informed and useful decisions. (Slugs generally eat round holes in leaves, whereas Japanese beetles mine the green material between the veins of the leaves.) Third, if the connection is unknown or misunderstood, then the attempted solution, no matter how thorough or costly, may have little or no positive effect. (Fencing or insecticides would not keep the slugs from eating zinnias.)

When the cause and effect relations (scientific principles) for the observations in the garden (or in an agricultural field) are correctly understood, the proposed solutions will be better informed and, ultimately, more effective.

Lessons from slugs and beetles are considered in this report as to the connections between agricultural activities and the environment. Water is one of the most important and dynamic connections between agriculture and the broader environment, as well as a vital and highly valued component of our world. Water moves freely between agricultural and non-agricultural areas. Water is often purposely moved into or out of agricultural landscapes to meet the needs of agricultural production. It moves through a variety of natural and constructed flowpaths that are both seen and unseen. Chemicals and soil move with the water. The movement of water, chemicals, and soil out of agricultural landscapes causes numerous concerns and effects on people and the environment. A continual improvement in our understanding of the connections among the agricultural landscape, water flowpaths, chemical and soil movement, and the environment is needed in order to make informed agricultural policy and useful management decisions.

Skeletonized morning glory leaf after a visit from Japanese beetles (Minnesota). Photograph by Paul Capel, U.S. Geological Survey, 2011.

Paul D. Capel

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
liter per day (L/d)	0.2642	gallon per day (gal/d)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
kilogram per hectare (kg/ha)	0.8922	pound per acre (lb/acre)
kilogram per square kilometer (kg/m^2)	5.7099	pound per square mile (lb/mi^2)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per year	1.102	ton per year (ton/yr)
metric ton	1.102	ton
nanogram (ng)	3.527	ounce (oz.)
	Energy	
joule (J)	0.0000002	kilowatt hour (kWh)
	Application rate	
kilograms per hectare per year [(kg/ha)/yr]	0.8921	pounds per acre per year [(lb/acre)/yr]

Conversion Factors—Continued

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

$$°C = (°F - 32) / 1.8.$$

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

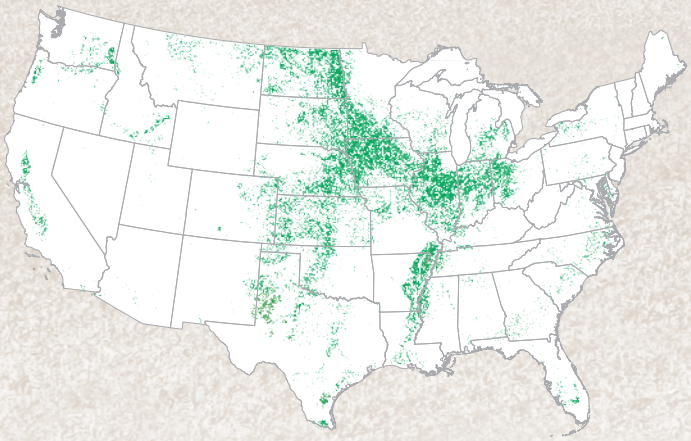
The Agricultural Water and Chemical Use Footprint

Even though greater than 80 percent of the Nation's population lives in urban areas, everyone has a connection to agriculture. Agricultural production in the United States supplies a major portion of the Nation's food, feed, and fiber needs.

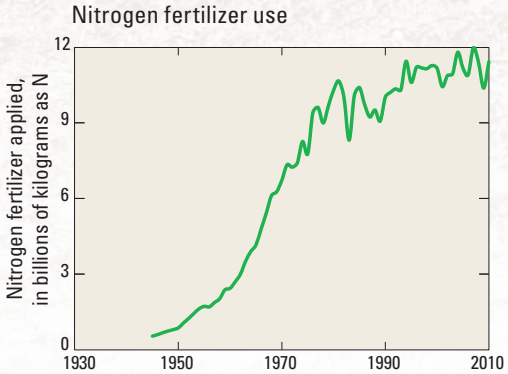
Over the last 100 years, agricultural expansion and intensification has led to adverse effects, including changes in water quantity and quality and the health of stream ecosystems. Agricultural chemicals move into and through every component of the hydrologic system, including air, soil, soil water, streams, wetlands, and groundwater.

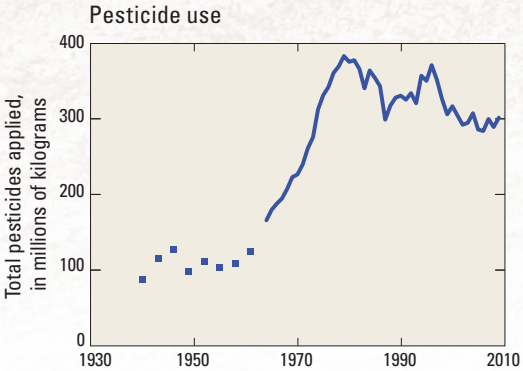
A holistic understanding of water movement coupled with an understanding of how different chemicals behave in different hydrologic settings will help identify effective conservation actions and inform the development of agricultural management policies.

Cropland Areas Across the Nation



The hydrology in many of our agricultural lands has been altered to maximize crop yields. About 490 billion liters of water—almost two-thirds of the total water use in the Nation—is used each day to irrigate crops. Long-term irrigation for crops can cause significant declines in groundwater levels. Artificial drainage—surface ditches and subsurface drains—has been installed on about 25 percent of the cropland. Water can move quickly through these drains and transport agricultural chemicals from the fields to streams.





Considerable increases in fertilizer and pesticide use began in the 1960s. In 2010, about 11 billion kilograms of nitrogen fertilizer and 300 million kilograms of pesticides were used annually to enhance crop production or control pests. Increased levels of nutrients from fertilizers draining into streams can stimulate algal blooms and affect stream health and recreational uses of local streams, downstream reservoirs, and estuaries, and increase treatment costs for drinking water. Pesticides that are transported to streams can pose risks for aquatic life and fish-eating wildlife and drinking-water supplies.

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By Paul D. Capel[1], Kathleen A. McCarthy[1], Richard H. Coupe[1], Katia M. Grey[2], Sheila E. Amenumey[2], Nancy T. Baker[1], and Richard L. Johnson[3]

Overview

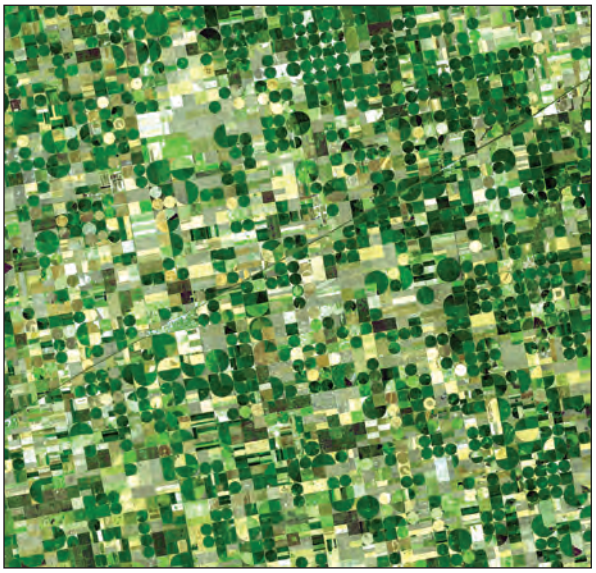
Understanding the movement of water—amounts, timing, and pathways— is fundamental for making optimal agricultural management and policy decisions to minimize the impacts of agriculture on water quality.

Over the last 100 years, expansion of agricultural lands, modification of the landscape, and technological advances in mechanization, chemical use, conventional breeding and, more recently, genetic engineering have resulted in increased agricultural production in the United States, which supplies a major portion of the Nation's food, feed, and fiber. Today, more than 11 billion kilograms of nitrogen fertilizer are applied annually to crops and 490 billion liters of water are withdrawn annually to irrigate crops in the United States. Typically, 5 to 50 percent of applied nitrogen moves from fields to streams through runoff and through groundwater discharge. The cumulative effects of agricultural expansion and intensification have led to adverse effects, including changes in water quantity, water quality, and the health of ecosystems.

Agricultural effects on water quality can occur at local, regional, and national scales. For example, increased levels of nutrients from agricultural fertilizers can stimulate algal blooms and affect the ecology of local streams. Nitrate and some herbicides can move through the soil to groundwater and, eventually, to local streams. Farther downstream, these elevated nutrients can increase costs associated with treating the water so that it is suitable for drinking. Ultimately, chemicals associated with agricultural activities (such as nutrients, pesticides, antimicrobials, and trace elements) and sediment (eroded soil) empty into our estuaries and can harm valuable commercial and recreational fisheries. Elevated nutrient inputs stimulate harmful algal blooms along the Nation's coasts causing negative economic impacts.

A

B



In Wisconsin (*A*), fields are contoured and the crops are planted in strips to help decrease the movement of water and sediment (eroded soil) from the fields to the steam.

In Kansas (*B*), where there is not enough natural rainfall for most crops, the green circles show the widespread prevalence of center pivot irrigation used to enhance agricultural production. Groundwater levels in the High Plains aquifer beneath Kansas and many other areas of the Nation are declining due to withdrawals for irrigation.

[1]U.S. Geological Survey.

[2]University of Minnesota.

[3]Oregon Health and Science University.

The movement (flowpaths) of water is the most important connection between agricultural activities and impacts on the quality of groundwater, streams, rivers, estuaries, and oceans. Understanding the movement of water—amounts, timing, and pathways—is fundamental for making optimal agricultural management and policy decisions toward minimizing the impacts of agriculture on water quality.

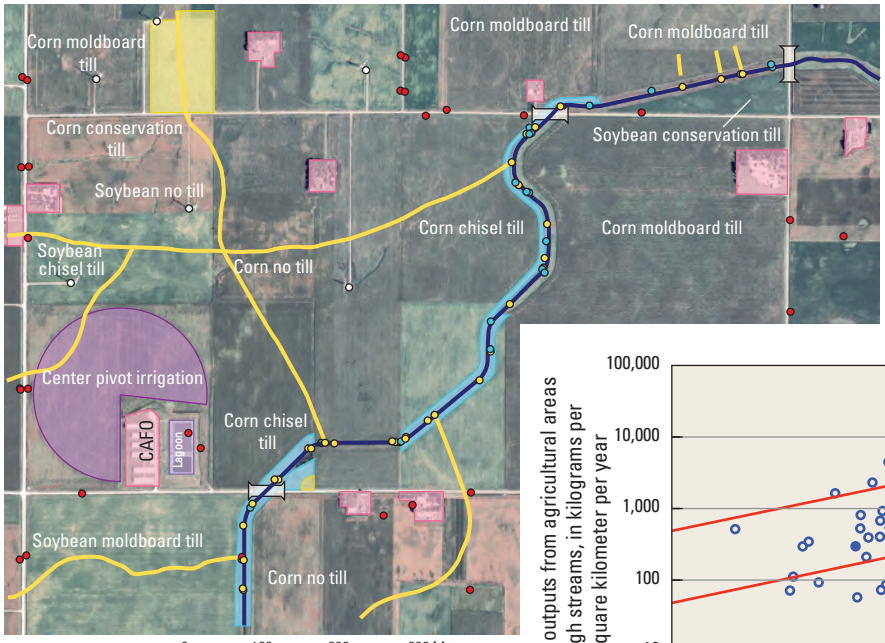
The U.S. Geological Survey conducted a systematic national study in agricultural areas to improve our understanding of field-scale and watershed-scale hydrology and the environmental behavior of individual chemicals. The goals of the study were to understand the connections among agricultural activities, hydrology, and chemical transport—critical information needed to inform management decisions and to help set the expectations for the protection and improvement of water quality, which can result from changes in agricultural management and policy decisions. This study was conducted in seven, hydrologically diverse, agricultural areas across the Nation (California, Indiana, Iowa, Maryland, Mississippi, Nebraska, and Washington).

Decades ago, the landscapes that were naturally too wet for agriculture were drained in the upper Midwest. The landscape was dotted with wetlands and shallow water tables (top left). These areas were drained by digging surface ditches. From Popular Mechanics, March 1922: **Big Ditcher Quickly Turns Swamps into Farms** "*Working steadily with a crew of five men, the machine … can drive a ditch ahead at the rate of about a quarter mile in a working day. …. Work is done on a big scale, dozens of teams, workmen, and tractors being employed. … in short time the marshlands have been changed into highly productive farms.*" New technologies, such as this 76-ton monster wheel excavator (bottom), together with government support for the conversion of wetlands to farmland, opened up vast expanses of fertile land, particularly in the Midwest. (Windsor, 1922). Intensive row crop and animal agriculture now covers the landscape (top right).

Agricultural Landscape Modifications Over the Last Century Have Significantly Altered the Natural Flow of Water and Agricultural Chemicals Entering Streams and Aquifers

Understanding how agricultural chemicals move and are transformed in each of the components of the hydrologic system can provide key insights into which management actions might be most effective in reducing transport of chemicals off the farm. Agricultural chemicals move into and through the various components of the hydrologic system, including air, soil, soil water, streams, wetlands, and groundwater. These chemicals also can be transformed by biological and chemical processes to other chemicals.

The landscape has been modified to allow crops to be grown and thrive in many areas that are naturally too wet, too dry, or have low soil fertility for crops. Agricultural activities, such as irrigation and (or) drainage, can change the availability of water to crops, and the addition of manure and other sources of nutrients can increase soil fertility. Each agricultural activity and landscape modification has an effect on the movement of water and, ultimately, the transport of agricultural chemicals and sediment to the broader environment. The combined effects of all activities and modifications defines the hydrology of the agricultural landscape, and thereby, determines the amount, timing, and specific flowpaths of water, chemicals, and sediment moving through and out of the agricultural landscape.



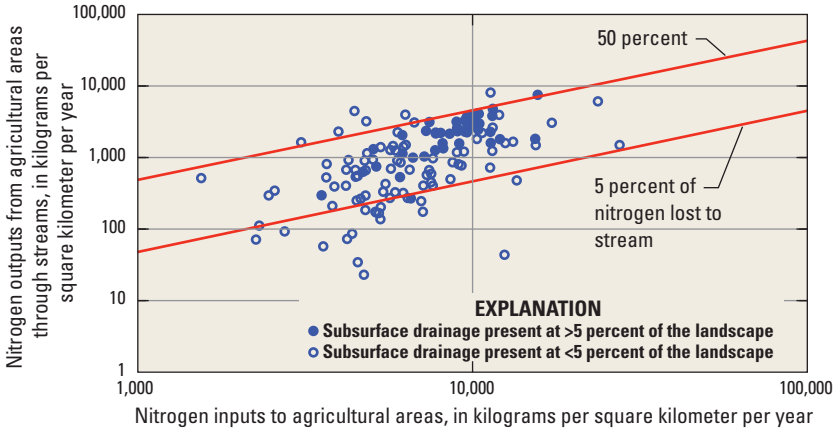
Base image from National Agriculture Imagery Program (NAIP), 2009.

0 100 200 300 Meters
0 200 400 600 800 1,000 Feet

EXPLANATION

- Pasture
- Center pivot irrigation
- Building
- Buffer strip
- Bridge
- Subsurface drain
- Drainage channel
- Drains
  - Vertical surface drain
  - Subsurface drain outfall
  - Surface drain outfall

N



Parts of north-central Iowa have been extensively modified to accommodate crop and animal agriculture including a network of surface and subsurface drainage. The combined effects of these modifications define the hydrology of the agricultural landscape. This area, and other agricultural areas with substantial subsurface drainage in their watersheds, has some of the highest stream concentrations of nitrate in the Nation. Nitrogen, an essential plant nutrient, is applied to agricultural fields in the forms of chemical fertilizers and animal manure. Nitrogen exports in areas with subsurface drained watersheds are slightly more than three times larger than in other agricultural streams (graph modified from Dubrovsky and others, 2010).

Agricultural activities have modified the pathways and amounts of water and chemicals moving through the landscape

Too much soil water

Pre-agricultural landscape

Mississippi

Iowa
Indiana

Wetland forests covered much of the flat landscape. Levees were built to stop the annual flooding from the Mississippi River, forests were cleared, and the land was drained. Streams were straightened and ditches were added to move water quickly and efficiently off the landscape. Currently, cotton, rice, corn, and soybean fields and catfish ponds cover the landscape.

Maryland

The topography, soils, and climate of the Delmarva Peninsula make it well suited to agriculture. Forests were cleared mid-17th century to make way for crops and animals—currently, corn, soybean, dairy, and poultry. Forested buffers along streams and scattered wetlands and farm ponds are common in the area.

Nebraska

California

Washington

The landscape receives about 18 centimeters (cm) of precipitation each year. Prior to irrigation, the land was covered with small desert shrubs. Sunnyside Canal, completed in 1980, delivers snowmelt water from the Cascade Mountains (110 cm) for irrigation to support dairies and crops (alfalfa, hops, vegetables, orchards).

Too little soil water

Areas included in this study are shown on the continuum of too much to too little soil water.

Most historical and current water-quantity and water-quality impacts from agriculture are the result of the modification of the natural water flowpaths and (or) the use of chemicals.

Agricultural landscape

Water-quality effects

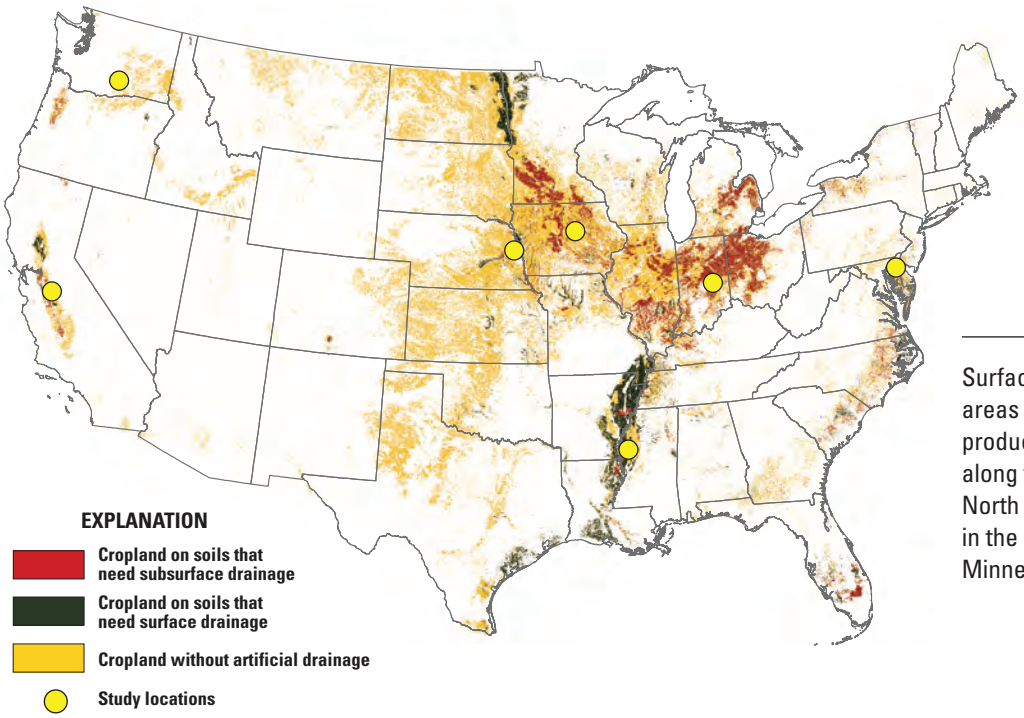
Groundwater pumping for irrigation has lowered the water table and dried up some rivers. Sediment, nutrients, and pesticides are exported from agricultural fields to the Mississippi River.

Excess nitrogen from fertilizer and manure has contaminated the groundwater and affected drinking water. The contaminated groundwater seeps into local streams and rivers and contributes to the eutrophication of Chesapeake Bay.

Prior to the 1990s, excess irrigation runoff transported large amounts of sediment and nutrients to streams. In the 1990s, changes in irrigation methods reduced the amount of runoff, decreasing the amount of sediment transported to streams. As the streams became less turbid, increased light penetration stimulated excessive aquatic plant growth in the clear, nutrient-rich stream water.

Artificial Drainage—For where there is too much water

About 25 percent of the cropland in the country has artificial drainage—surface (ditches) and subsurface (tiles). Prior to European settlement, there were about 1 million square kilometers (km^2) of wetlands in the conterminous United States. By the mid-1980s, less than half of this wetland area remained; most of the drained areas have been converted to agricultural use. Generally, the drained water is moved quickly—hours to weeks—through the surface layers of soil, into the local drainage network, and out to the stream. Artificial drainage quickly moves water out of the soil to protect plant roots from excess water and to allow farm machinery to operate in the fields. Agricultural chemicals, pesticides, and nitrate can be transported with the drained water. Nitrogen export in streams with substantial subsurface drainage in their watersheds is slightly more than three times larger than in other agricultural streams in the Nation.



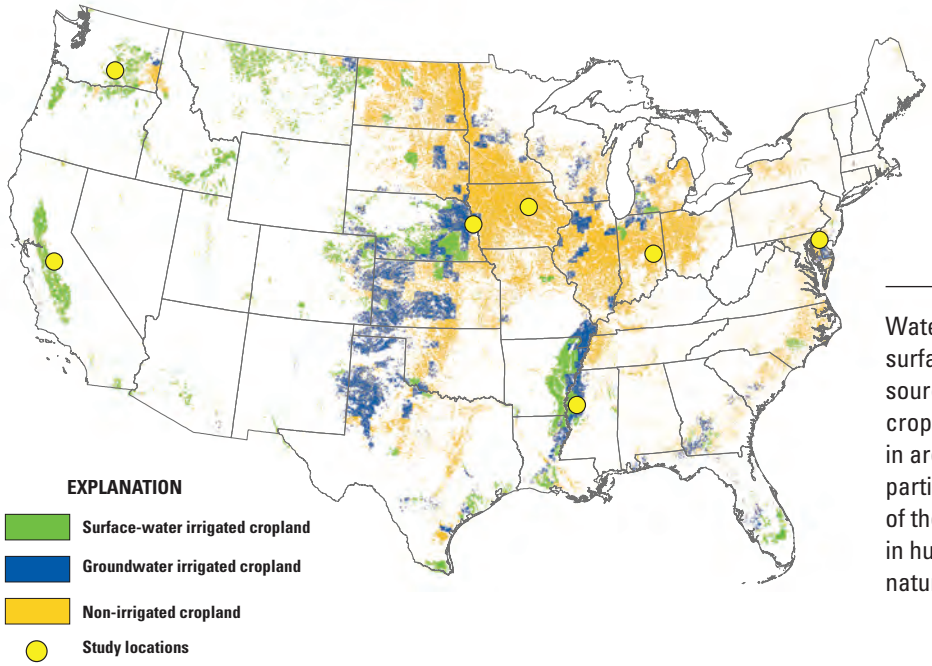
Surface and subsurface drainage areas have turned wetlands into productive cropland, particularly along the East coast in Maryland, North Carolina, South Carolina, in the Midwest from Ohio to Minnesota, and in California.

Temporary ponds form on the landscape, like this field in Iowa, when rainfall intensity exceeds the soil's ability to infiltrate water. One method that is used to minimize the damage to the crops by ponded water is the installation of surface inlets to the subsurface drainage. An orange inlet can be seen near the left edge of the pond. The surface inlets, open conduits to the subsurface drains, quickly move water along with sediment and chemicals from the pond to the stream.

Irrigation—For where there is too little water

Irrigation is used to meet agricultural needs in naturally arid areas and in humid areas where precipitation may not come at the proper time of year. Irrigation for agriculture constitutes 62 percent of the total water use in the Nation (excluding water used for thermoelectric power). Irrigation water can be derived from groundwater or surface water. The selection of the source of irrigation water largely depends on the availability of the water resource, cost of moving the water, legal ownership of the water, and its degree of salinity. Excess irrigation water can transport agricultural chemicals and sediment directly to streams. Excess irrigation water also can increase water recharge and the movement of agricultural chemicals to groundwater. In parts of the arid West, irrigation has mobilized naturally occurring trace elements and increased salinity in streams and shallow groundwater. For example, irrigation recharge along the eastern San Joaquin Valley in California has mobilized naturally occurring uranium to levels that now exceed the drinking-water standard.

Artificial Water Use and Cropland



Water, derived from both surface-water and groundwater sources, is used to irrigate crops and water livestock in areas across the Nation, particularly in the arid parts of the West. Irrigation is used in humid areas to supplement natural rainfall.

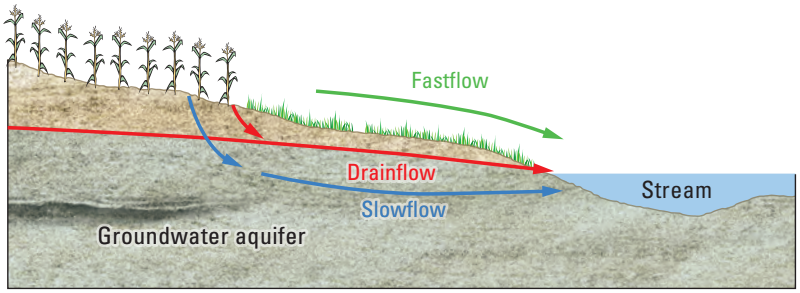
A center-pivot irrigator sits idle in Wisconsin during winter. Although this area receives adequate rainfall, supplemental irrigation is used to maintain good levels of soil moisture in the quickly draining sandy soils.

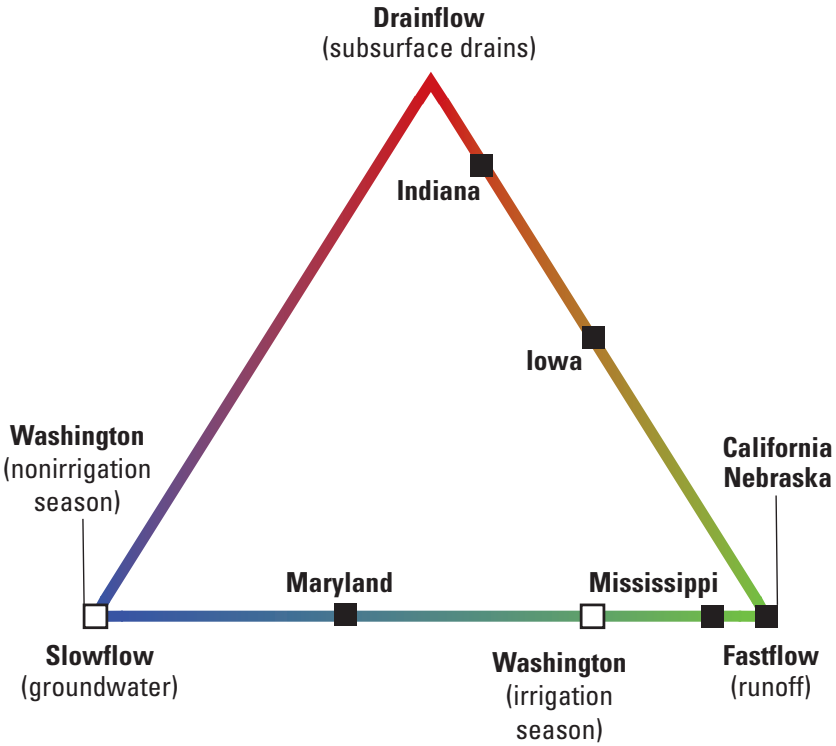
Tracking How Water Moves Through Agricultural Landscapes Provides Insights on the Movement of Agricultural Chemicals

The movement of water in many agricultural areas has been altered to increase crop production. These hydrological alterations also can influence the movement of agricultural chemicals to streams and groundwater. The water flowpaths, as well as the timing and intensity of precipitation and (or) irrigation, are important in determining the timing and magnitude of the movement of chemicals to streams and groundwater.

Water reaches a stream through a combination of fastflow, drainflow, and slowflow pathways. Fast flowpaths (fastflow), such as surface runoff, can be high energy and occur over timeframes of hours to days. Slow flowpaths (slowflow), such as movement through groundwater to streams, occur over timeframes of months to decades. Drainage flowpaths (drainflow) are engineered movement of water through subsurface drains.

Water reaches a stream through a combination of fastflow, drainflow, and slowflow pathways. In many agricultural settings, the movement of water has been altered to enhance crop production. These changes to the hydrologic system also can influence the movement of agricultural chemicals to groundwater and streams.





The corners of the triangle represent examples of streams that have a single important flowpath. The edges of the triangle represent streams that have a mixture of two flowpaths. The interior of the triangle represents streams that have a mixture of all three flowpaths. The squares on the triangle denote the flowpaths observed in the study area shown on page 4.

Fastflow—water that moves off the landscape to the stream in **hours to days** following rainfall or irrigation. This water moves through surface runoff, overland flow, and other pathways.

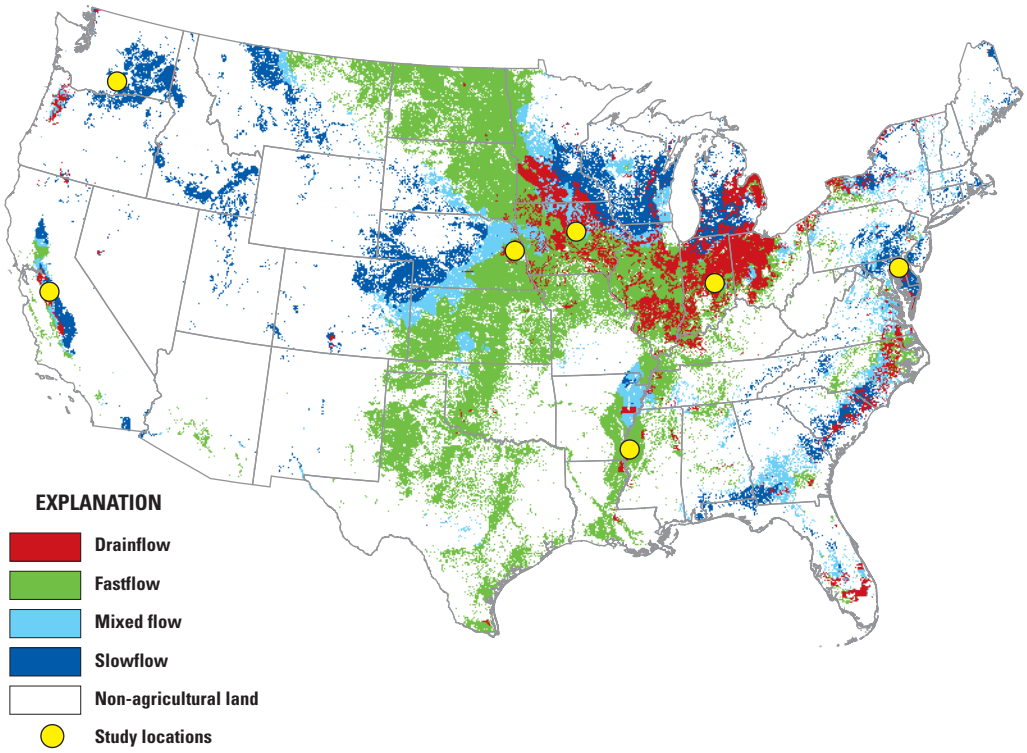
Drainflow—water that moves off the landscape through artificial subsurface drains in **hours to weeks** following rainfall or irrigation. The subsurface drains quickly and moves out of the root zone to protect the crop roots and to allow machines to enter the fields.

Slowflow—water that takes **months to decades** to move from the landscape to the stream. This water can infiltrate into the soil, recharge groundwater, and eventually discharge to the stream. Slowflow water also can be stored in wetlands before it reaches the stream.

Excess rainfall and irrigation water move from the landscape to streams through a combination of flowpaths—fastflow, slowflow, and (or) drainflow (artificial subsurface drainage).

Water in a stream is a mixture of water from various sources that flow through the landscape and streams in small watersheds can be categorized by their important flowpath(s). A national assessment of watershed properties, probable locations of subsurface drainage, and hydrologic studies of gaged streams provides insights about which flowpaths are important in various areas of the Nation. However, care must be taken when using a large-scale map on small scales because all flowpaths are local. The flowpaths leaving even two adjacent fields could be markedly different due to topography, soils, land management, and (or) the presence/absence of subsurface drainage.

Flowpaths on Agricultural Lands

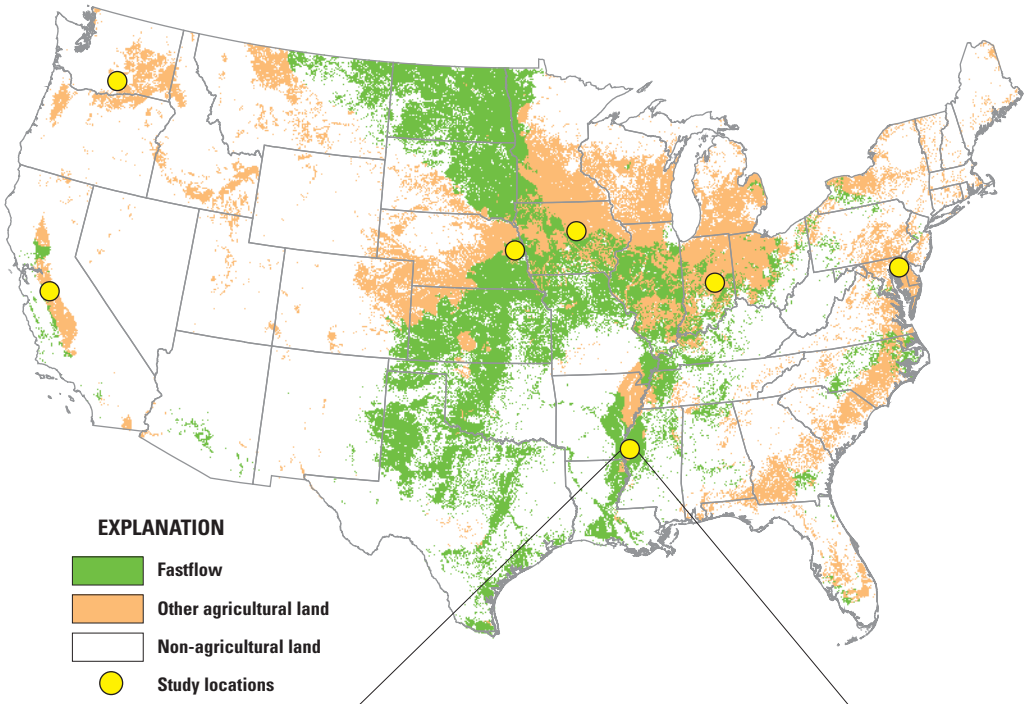


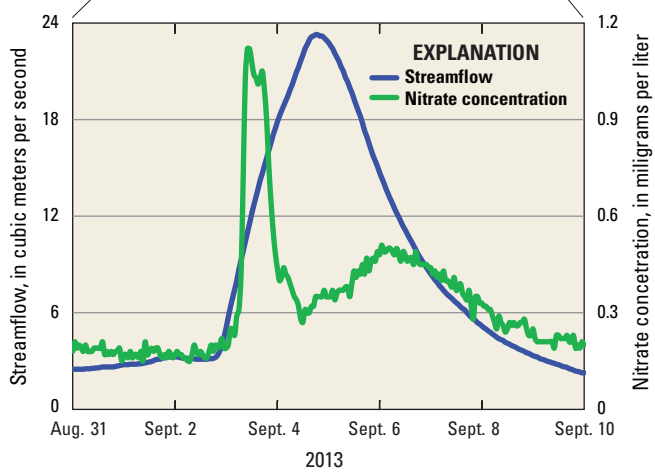
Fastflow

In some watersheds, especially those with steep slopes and (or) clayey soils, surface runoff is an important flowpath. The streamflow in these watersheds responds quickly to rain events, usually within minutes to hours. Agricultural chemicals can be transported to the stream with the surface runoff, but fastflow is especially important for transporting sediment and sediment-associated chemicals, such as total phosphorus, pesticides, and some trace elements.

Agricultural Lands Where Fastflow is Important

Episodic Delivery of Chemicals and Sediment to Streams—Hours to Days





Fastflow transport of water and nitrate in the Bogue Phalia, Mississippi

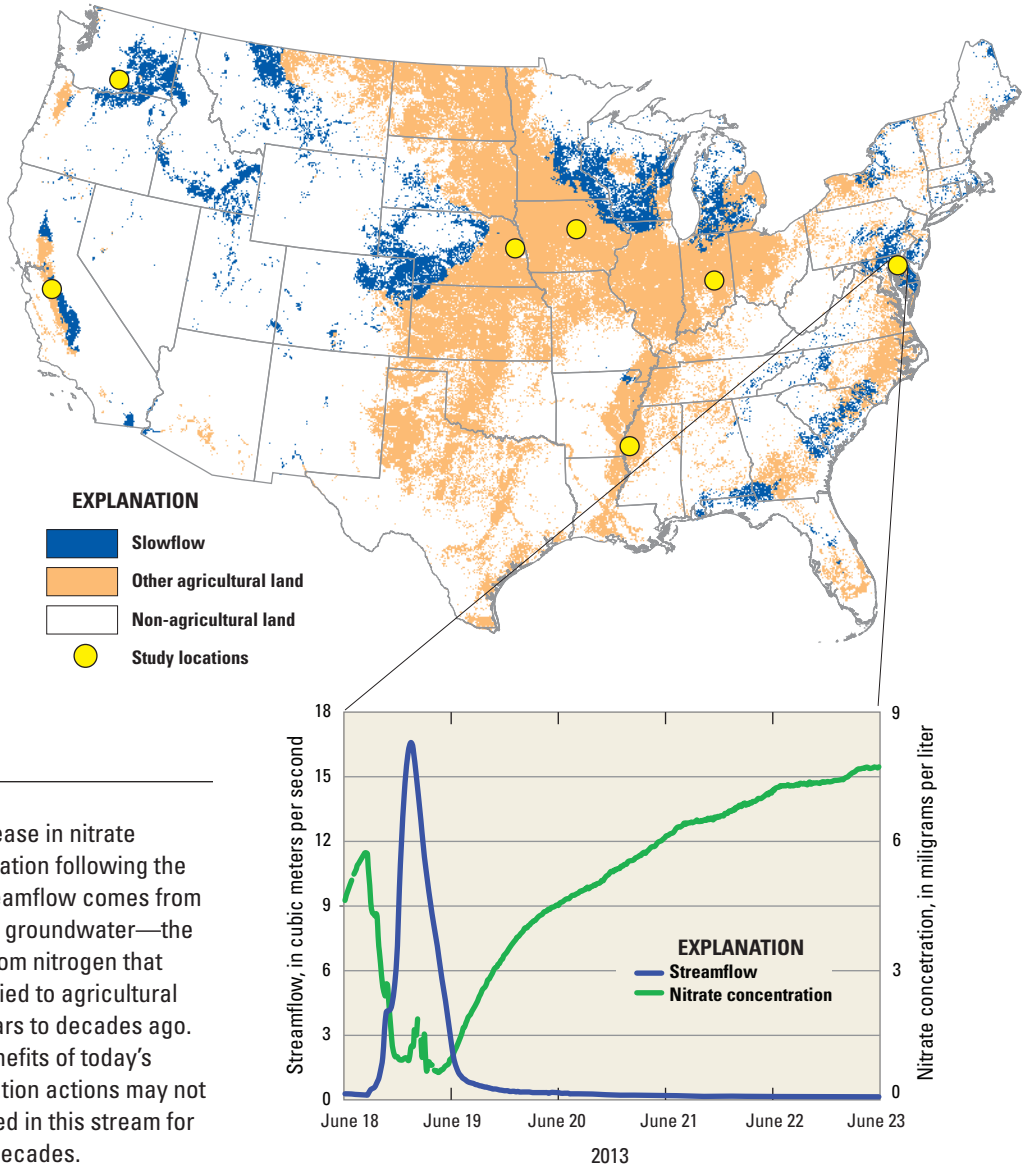
Fastflow is an important pathway for the delivery of nitrate to this stream. Many conservation management practices, such as buffer strips and conservation tillage, are effective in preventing sediment and sediment-associated chemicals from reaching the stream. However, these practices are less effective at controlling dissolved chemicals such as nitrate.

Slowflow

In watersheds with gentle slopes and permeable soils, groundwater is generally a major contributor to streamflow. Rain water and agricultural chemicals dissolved in the water infiltrate through the soil, recharge groundwater, and eventually discharge to the stream. It can take months to decades for the water and chemicals that infiltrate the soil to eventually discharge to a stream. This can cause long lag times between when the chemical is applied at the land surface and when it actually appears in the stream. Nitrate, herbicides, and herbicide transformation products are often important water-quality concerns in streams that receive water from slow flowpaths.

Agricultural Lands Where Slowflow is Important

Steady Delivery of Dissolved Chemicals to Streams—Months to Decades



The increase in nitrate concentration following the peak streamflow comes from slowflow groundwater—the legacy from nitrogen that was applied to agricultural fields years to decades ago. Thus, benefits of today's conservation actions may not be realized in this stream for several decades.

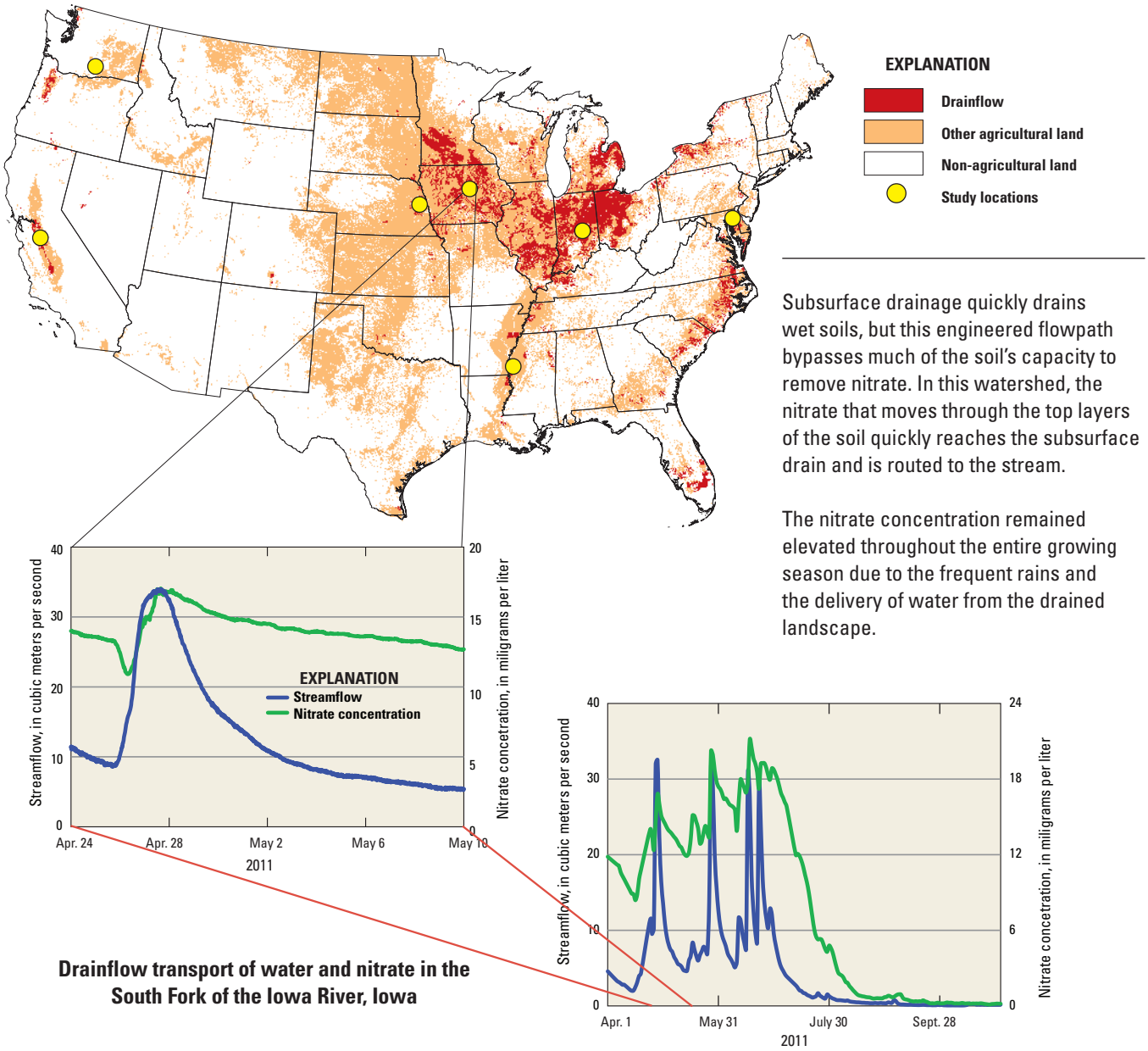
Slowflow transport of water and nitrate in Chesterville Branch, Maryland

Subsurface Drainflow

The installation of subsurface drains creates an artificial water flowpath engineered to quickly move water out of the soil and into the stream. The drains, located below the root zone, control the groundwater level so it is at or below the level of the drains. Water flowing in the subsurface drains is generally fastflow from recent excess rainfall and (or) excess irrigation and slowflow that is being skimmed off the top of the groundwater. The flow in the drains can respond to rainfall or irrigation within hours. Chemicals that readily dissolve in water can move through the soil root zone into the drains and directly to the stream. The chemicals moving through subsurface drains bypass many natural removal processes of the soil. Nitrate, herbicides, and herbicide transformation products are often observed in streams that receive water from subsurface flowpaths.

Agricultural Lands Where Drainflow is Important

Episodic and Steady Delivery of Dissolved Chemicals to Streams—Hours to Weeks



Subsurface drainage quickly drains wet soils, but this engineered flowpath bypasses much of the soil's capacity to remove nitrate. In this watershed, the nitrate that moves through the top layers of the soil quickly reaches the subsurface drain and is routed to the stream.

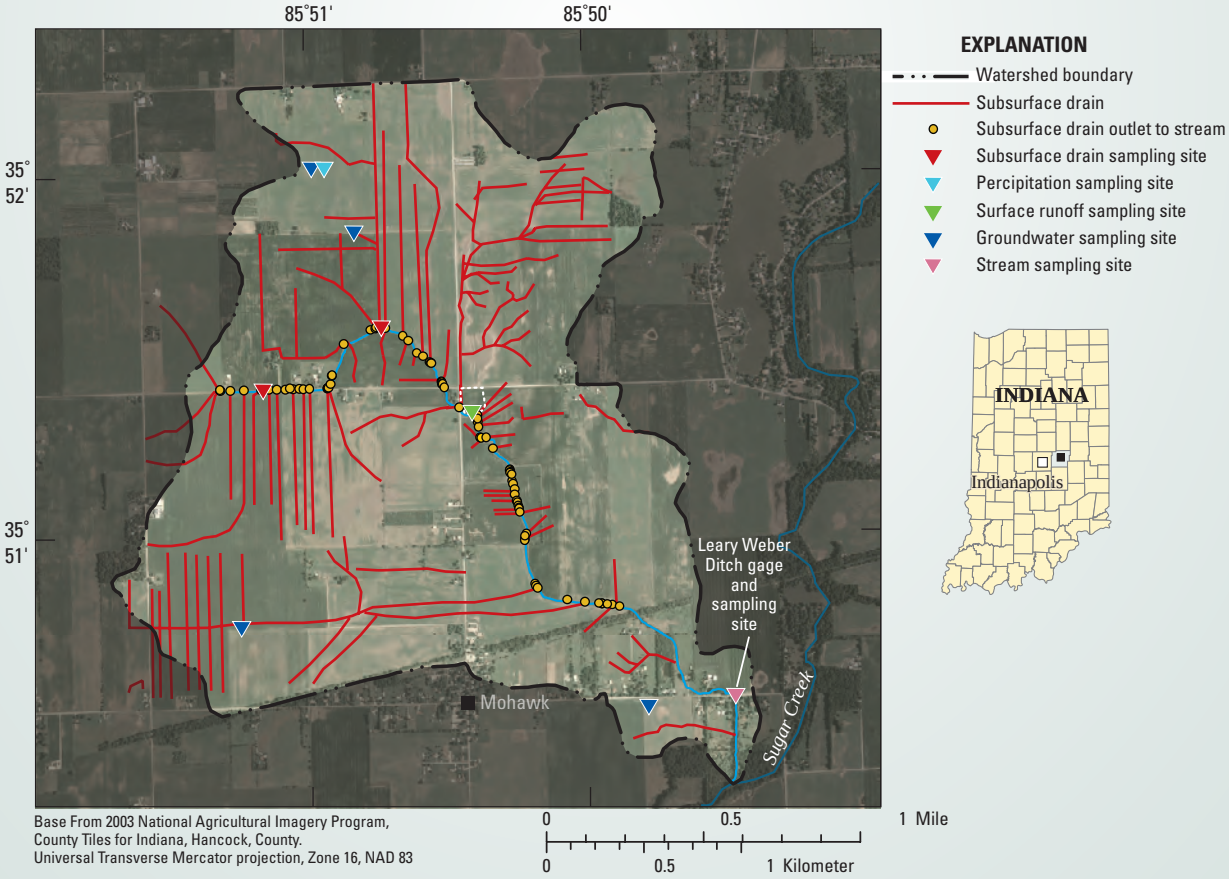
The nitrate concentration remained elevated throughout the entire growing season due to the frequent rains and the delivery of water from the drained landscape.

Drainflow transport of water and nitrate in the South Fork of the Iowa River, Iowa

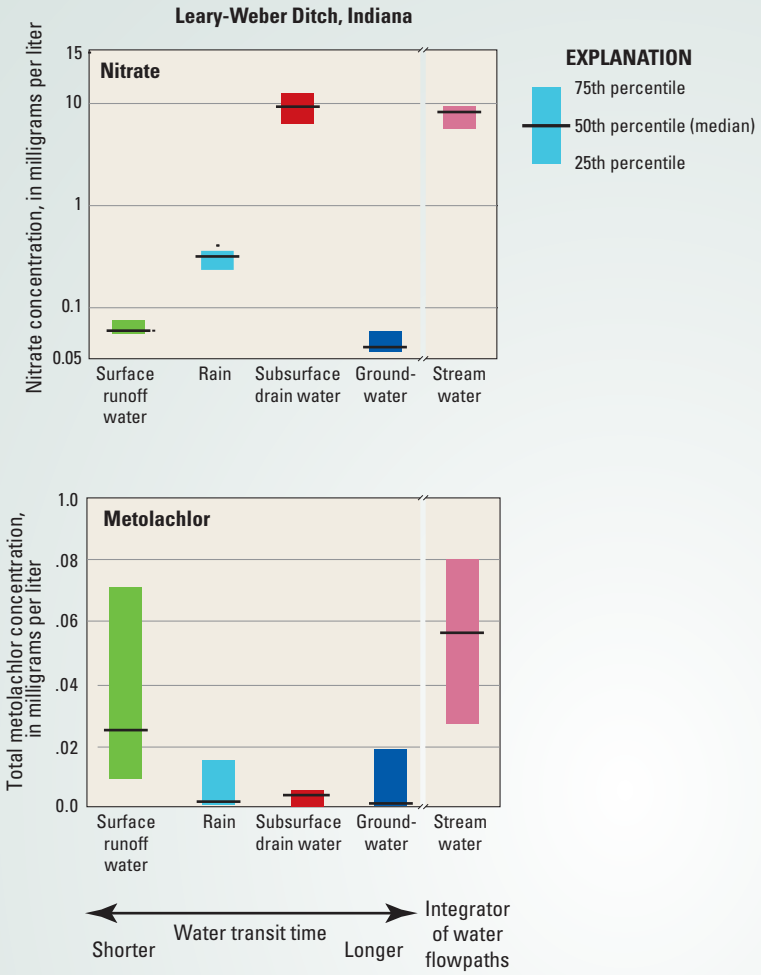
Nitrate and Metolachlor in Leary-Weber Ditch, Indiana

Numerous surface and subsurface drains quickly move excess water from poorly drained soils to protect plant roots and to allow farm machinery to access fields in the Leary-Weber Ditch watershed in central Indiana. This quick and efficient drainage of the watershed creates a short circuit. Water and agricultural chemicals bypass the natural transformation processes and are quickly transported to the Leary-Weber Ditch, and eventually to the Ohio River and Gulf of Mexico. Two commonly used agricultural chemicals (nitrate and metolachlor) were detected in every component of the hydrologic system in Leary-Weber Ditch; however, these agricultural chemicals are transported to the stream through different flowpaths. The difference in the important flowpath for the two chemicals is partly because of the different times of application of the chemicals relative to rainfall and their different spatial patterns of application. The water from all these components (rain, surface runoff water, subsurface drain water, and groundwater) is integrated into the stream, but with different transit times, from hours to years. An improved understanding of how these chemicals are transported by different flowpaths to a stream can help water resource managers select and target appropriate conservation actions.

Water enters a surface ditch from a subsurface drain outlet.



Base From 2003 National Agricultural Imagery Program, County Tiles for Indiana, Hancock, County. Universal Transverse Mercator projection, Zone 16, NAD 83



Nitrate was detected in relatively high concentrations in the subsurface drain water and stream water. Nitrate also was present, although at much lower concentrations, in rain, groundwater, and surface runoff. These results show that the movement of nitrate into this stream is more likely through the subsurface drains than through groundwater or surface runoff.

The highest concentrations of total metolachlor were detected in the stream and the surface runoff water. In deep soils and groundwater, however, the long-lived metolachlor transformation products were detected at higher concentrations than the more quickly transformed metolachlor. Over the course of a year, surface runoff is the important flowpath for metolachlor to reach the stream, whereas groundwater discharge is the important flowpath for metolachlor transformation products to reach the stream.

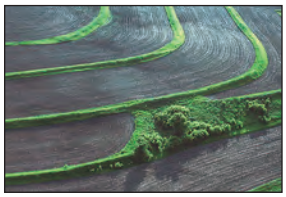
The difference in the important flowpath for the two chemicals is, in part, because of the different times of application of the chemicals relative to rainfall and their different spatial patterns of application.

The agricultural landscape of central Indiana shown from ground level and from the air.

Setting Realistic Expectations for Water-Quality Improvements

Expectations for water-quality improvements due to the implementation of agricultural activities must consider the properties of the chemical and sediment and especially the hydrologic flowpaths that transport the chemical to the impacted water body.

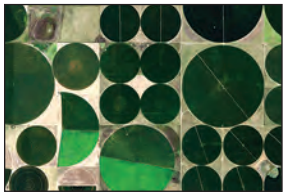
Examples of Agricultural Activities Used for Protection or Improvement of Water Quality



Trapping practices
- Terraces, grassed waterways
- Buffer/filter strips
- Brims at edge of stream
- Cover crops
- Strip cropping

Tillage practices
- Conservation tillage
- No-till tillage
- Contoured plowing

Drainage practices
- Controlled subsurface drainage
- Biofilters on subsurface drains
- Removal of subsurface drains
- Removal of surface inlets to subsurface drains



Irrigation practices
- General decrease in volume and energy of irrigation water

Chemical use practices
- Decrease in chemical use
- Use of chemicals with short environmental half-lives

Set-aside land for conservation
- Conservation reserve programs (Federal and state; for example, USDA CRP)
- Constructed wetlands

The effectiveness of an agricultural activity depends on the local hydrologic flowpaths within a specific field and the environmental behavior of the specific chemical or sediment.

Trapping and tillage practices are primarily designed and implemented to minimize soil loss and prevent runoff of the sediment into the stream by fastflow. These practices are effective because they slow down the water moving across the fields by fastflow and increase the volume of recharge. However, trapping and tillage practices have little effect on the removal of water-associated chemicals moving with fastflow, and can potentially exacerbate the movement of water-associated chemicals to the subsurface by increasing the rate of recharge through enhanced drainflow and slowflow. Because trapping and tillage practices can increase recharge, they can increase the movement of water-associated chemicals into the subsurface. Because water-associated chemicals in the subsurface are no longer influenced by activities at the land surface, only natural transformation processes can decrease their concentrations until they are eventually discharged to a stream.

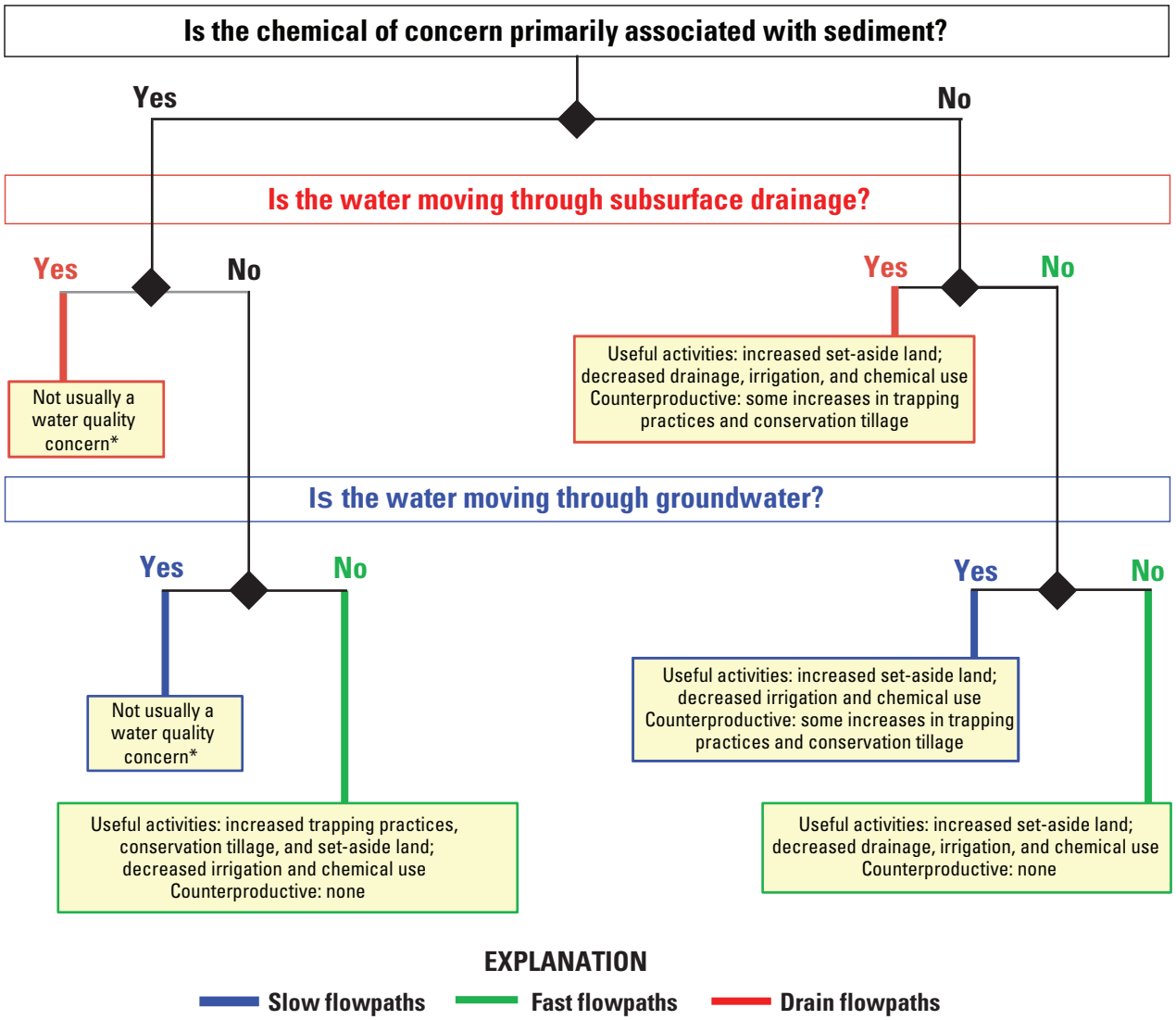
Connecting Water Flowpaths and Chemical Behavior Can Inform Agricultural Management Decisions

Understanding the connections among agricultural activities, water flowpaths, and behavior of specific chemicals and sediment can be combined into a framework to guide policy and management decisions to reduce current and prevent future impacts on water quality. This framework is built on a generalization of stream hydrology—water, whether from natural rainfall or irrigation, moves to a stream by a combination of slowflow, fastflow, and drainflow and each of these flowpaths are associated with a range of timescales. The framework generalizes the behavior of chemicals and sediment—all chemicals and sediment are distributed on a continuum between those completely associated with water and those completely associated with sediment. Finally, each agricultural activity is assumed to have its expected effect on the movement of water and chemicals across the landscape, supported by observations in the environment and quantified in models. This framework, shown as a decision tree, is a gross simplification and it is not intended to be used as a primary decision-making tool on a site-specific basis. Additional detailed knowledge of the local environment, climate, and agricultural production is required to make design decisions for the implementation of an agricultural activity for a particular location.

The first question in the decision tree concerns the environmental behavior of the chemical of concern: Is the chemical of concern primarily associated with sediment? The second question addresses the presence of permanent or semi-permanent agricultural modifications to the landscape that are already in place: Is the water moving through subsurface drainage? The final question regards the nature of the hydrologic setting: Is the water moving through groundwater? The answers to these three questions can guide the selection and expectation of the effectiveness of implementing an agricultural activity.

Although valuable knowledge can be gained from a general understanding of how water and chemicals move in an agricultural landscape as presented in this conceptual framework, local knowledge of hydrology and chemistry are required to optimize effective conservation actions on a field-by-field and chemical-by-chemical basis.

A Simple Decision Tree Connects Water Flowpaths, Chemical Behavior, and the Effectiveness of Agricultural Activities



EXPLANATION

Slow flowpaths **Fast flowpaths** **Drain flowpaths**

The decision tree can assist with identification of which agricultural activity(s) (see "Understanding the connections among hydrologic settings and chemical behaviors can help set realistic expectations for water-quality improvements" in Chapter 9") could be effective in protecting or improving stream-water quality and which agricultural activity(s) could be counterproductive. * Denotes that these chemicals do not usually cause a water-quality concern for the fraction of water moving through subsurface flowpaths (for example, moving through soil to groundwater or to subsurface drains), but they can cause a concern for the water moving through flowpaths across the land surface.

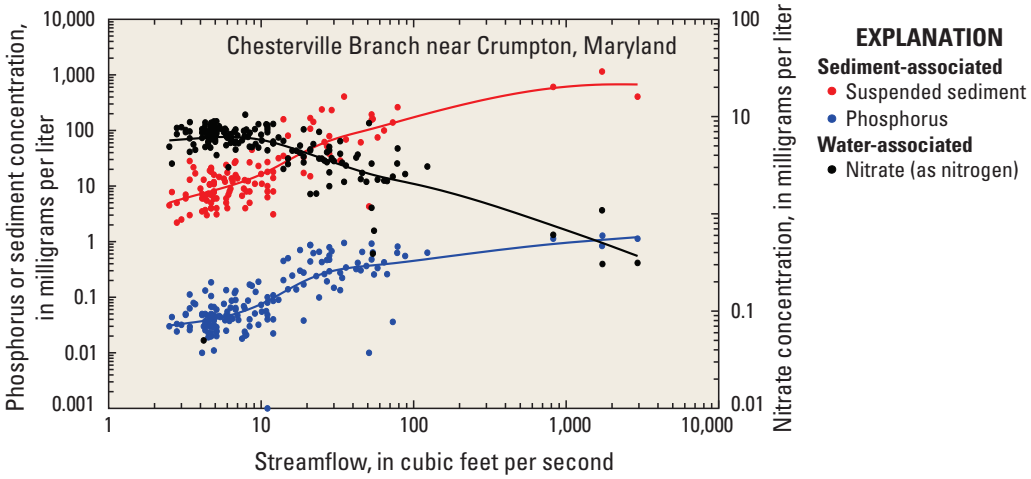
Example—Which Agricultural Activity(s) is Most Effective for Reducing Nitrate in Slowflow, Chesterville Branch, Maryland?

Groundwater is a major contributor to streamflow in the Chesterville Branch located on the Delmarva Peninsula in Maryland. This watershed contains gentle slopes and permeable soils, which allow rain water to easily infiltrate the soil and recharge the groundwater—key characteristics of a slowflow area. Chemicals that are largely associated with water, such as nitrate from fertilizers and manure, infiltrate into the soils with precipitation and move slowly to groundwater. It takes, on average, about 50 years for this water to travel from land surface through groundwater and to ultimately discharge to Chesterville Branch. On an annual basis, about half the streamflow in Chesterfield Branch comes from groundwater, so it is an important source of water and nitrate to the stream, especially during low-flow periods.

A coupled understanding of water movement and how different chemicals are transformed in different hydrologic settings can help identify the most effective management practices and inform conservation policies. The heavy black line on the decision tree follows the chemical behavior and hydrologic setting—nitrate is strongly associated with water, there is minimal subsurface drainage in the watershed, and groundwater is an important water flowpath to the stream. The use of most trapping and tillage practices that are designed to reduce soil erosion could be counter-productive, because they generally increase groundwater infiltration and can increase the movement of nitrate to groundwater. Cover crops can be effective at storing nitrogen in the plants and soil, but the stored nitrogen has the potential to eventually leach to groundwater. In this slowflow area of Chesterville Branch, one of the most effective activities is the reduction of fertilizer use. Optimizing the amount of irrigation, in addition to the fertilizer, could decrease the amount of nitrate that reaches the groundwater system.

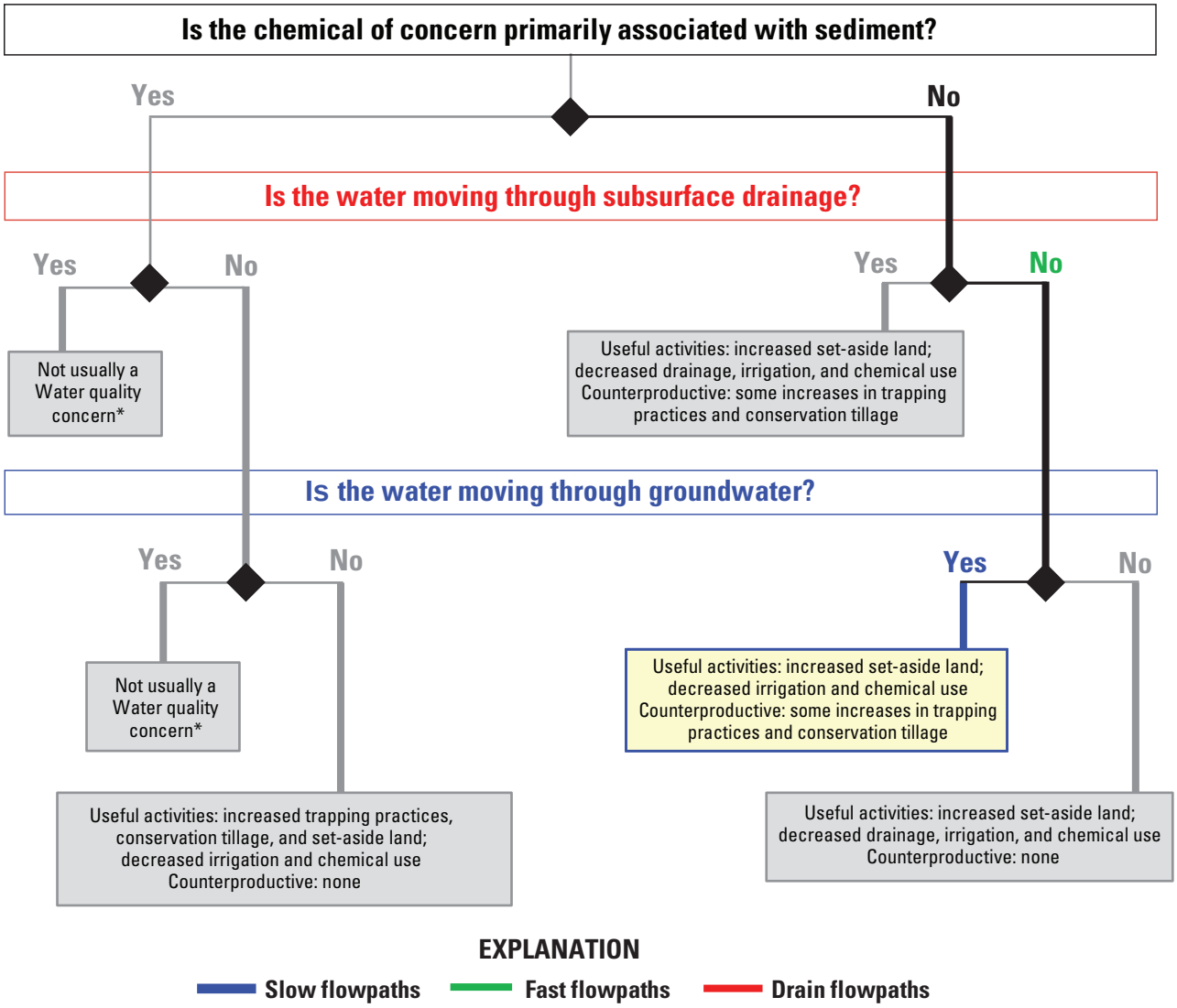
In slowflow areas, such as the Chesterfield Branch watershed, it can take years for a chemical like nitrate to move from the land to the groundwater and ultimately to the stream. Groundwater nitrate inputs in this stream currently are representative of fertilizer applied to crops years or decades ago, thus benefits of today's conservation actions may not be realized in this stream for several decades.

The agricultural landscape of Maryland's Eastern Shore shown from ground level and from the air.



Data for water- and sediment-associated chemicals show the complexities of real life and reinforce the need to understand the connections between hydrologic flowpaths and chemical transport to inform agricultural management decisions. In Chesterville Branch, different flowpaths are primarily responsible for the transport of water-associated and sediment-associated chemicals. This stream continually receives slowflow (groundwater), but it also receives fastflow after periods of rain. The fastflow water contains greater concentrations of sediment and sediment-associated chemicals, like phosphorus, than does groundwater. Therefore, the concentrations of suspended sediment and phosphorus increase with higher streamflow (more fastflow). The nitrate concentration in the stream decreases with increasing streamflow because groundwater with a higher nitrate concentration is being diluted by fastflow, which has a lower concentration. (From Ator and Denver, 2015.)

Nitrate Movement in Slowflow Areas—Chesterville Branch, Maryland



In slowflow areas, it can take decades for nitrogen fertilizer to move from the land to the groundwater and to the stream—groundwater nitrate inputs to the stream today reflect fertilizer and manure inputs decades ago.

Example—Which Agricultural Activity(s) is Most Effective for Reducing Sediment in Fastflow from Excess Irrigation in Granger Drain, Washington?

Excess irrigation runoff is a major contributor to streamflow during the growing season to the Granger Drain in central Washington. The naturally arid climate requires irrigation to maintain agricultural productivity. Irrigation water is relatively abundant from the snowmelt water from the Cascade Mountains. Excess irrigation runoff transports large amounts of sediment, as well as agricultural chemicals associated with sediment such as total phosphorus. The transported sediment creates turbidity in the stream, which can adversely affect aquatic organisms.

Prior to the late 1990s, much of the sediment came from fields that received furrow irrigation, an inefficient method of irrigation that can cause large amounts of soil erosion. After the late 1990s, irrigation practices shifted from furrow to sprinkler and drip methods. This widespread change resulted in dramatic improvements in water quality—sediment loads were reduced by more than 90 percent in some locations.

Sediment-laden waters enter the Yakima River from Granger Drain, Washington. Photograph by U.S. Geological Survey, 1991.

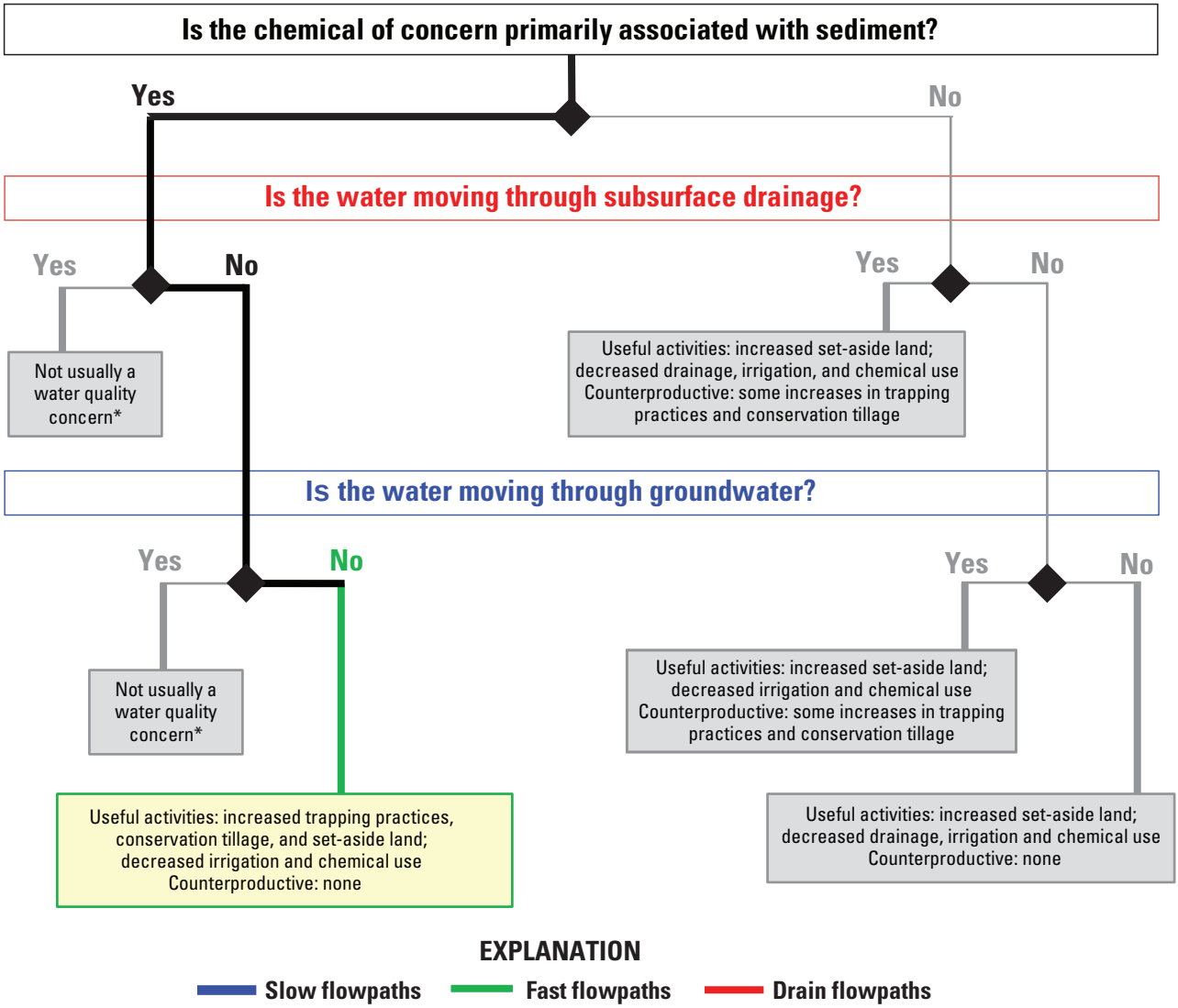
The agricultural landscape of central Washington shown from ground level and from the air. Sunnyside Canal (top) provides the water that irrigates the Granger Drain watershed.

The heavy black line on the decision tree follows the behavior of sediment and sediment-associated chemicals in the excess irrigation water (fastflow) from the fields of the central Washington to the streams. Since the early days of farming, the streams and rivers of central Washington have been affected by sediment from irrigation runoff. Even though the slowflow groundwater is an important source of water to Granger Drain, the sediment does not move through the soil layers to subsurface drains (drainflow) or groundwater (slowflow).

The use of less irrigation water and efficient irrigation methods were effective in controlling sediment in runoff. More recently, other sediment control methods, such as the application of polyacrylamide (PAM) and even more efficient methods of irrigation have been implemented.

In fastflow environments, such as the excess irrigation water in Granger Drain, the benefits of conservation actions—improvement in stream-water quality—may be realized within months or a few years. In this stream, turbidity and suspended sediment, total phosphorus, and DDT concentrations substantially decreased within a few years. Granger Drain became clearer as the amount of sediment erosion was reduced. Aquatic plant growth increased downstream in the clear water due to excess nutrients. This changed the stream ecology and created a different impact on water quality that may require additional modification of current agricultural practices, such as reducing fertilizer application rates to reduce nutrient loading from excess irrigation water.

Sediment Movement in Fastflow From Excess Irrigation—Grainger Drain, Washington



The effectiveness of an agricultural activity depends on the local hydrologic flowpaths in a specific field and the environmental behavior of the specific chemical or sediment.

Chapter 1 —NAWQA Studies on Agriculture and Water Quality

The U.S. Geological Survey (USGS) has established various long-term monitoring programs to assess the quality of our Nation's water. A consistent study design and uniform methods of data collection and analysis are used in each program to ensure that water-quality data in a specific locality, watershed, river **basin**[4], or aquifer can be directly compared with data collected in other geographic regions and at different time periods. A unique feature of these studies is the ability to monitor the movement of water and chemicals in multiple components of the hydrologic system at multiple scales.

Since 1991, the USGS National Water-Quality Assessment (NAWQA) Project has implemented interdisciplinary assessments in 51 of the Nation's most important river watersheds and aquifers, which represent between 60 and 70 percent of total water use in the Nation (fig. 1.1; U.S. Geological Survey, 2012). The mission of the NAWQA is to assess the status and trends of national water quality and to improve our understanding of the various factors that affect water quality. Information from NAWQA assessments help us understand how water quality varies over space and time, and how it is affected by human activities and natural factors across the Nation. NAWQA findings thereby describe the general health of water resources, and help identify current and emerging water issues while providing information that is essential for developing practical management strategies for protecting and restoring water quality. The NAWQA study areas are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination. By combining information on water chemistry, landscape characteristics, stream habitat, and aquatic life, NAWQA provides science-based insights that can be used to set priorities among various current and emerging issues related to water quality across the Nation.

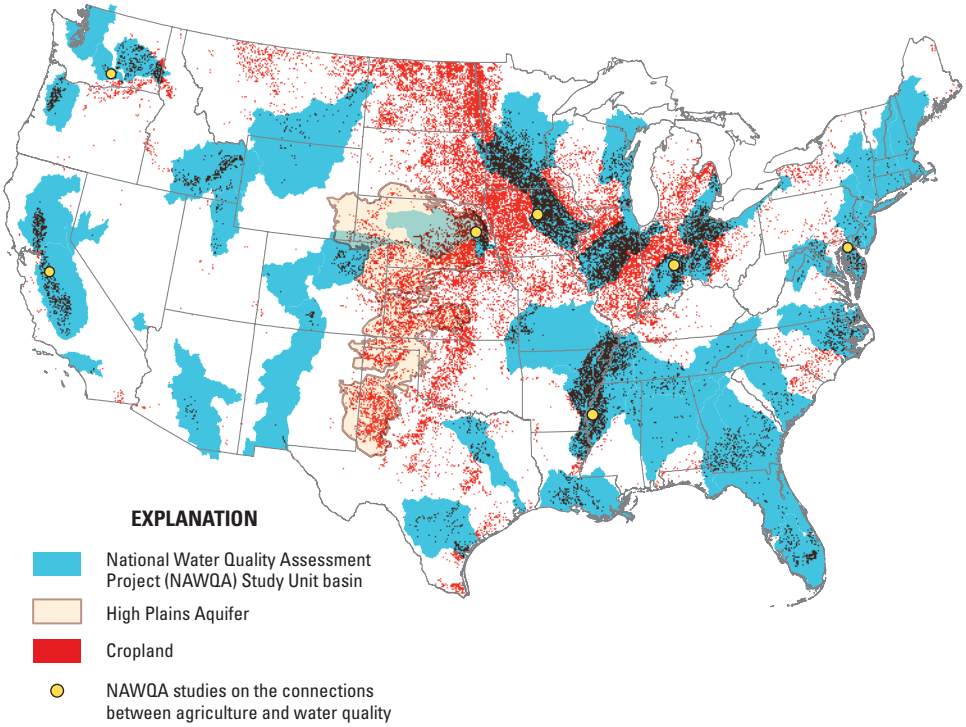


Figure 1.1. Study areas in the U.S. Geological Survey National Water-Quality Assessment Project (study units, major river basins, and High Plains aquifer) compared to areas of cropland in the conterminous United States.

[4]**Bold** words indicate glossary terms. See "Glossary of Terms" at back of report.

The NAWQA Project completed a series of topical studies that were intended to improve understanding of how natural features and human activities affect water quality. The specific focus of these studies was to establish links between sources of chemicals, the transport of those chemicals through the hydrologic system, and the potential effects of chemicals on humans and aquatic **ecosystems**. This report focuses on the connections between agriculture and water quality in agricultural watersheds; however, the report also features findings from other NAWQA studies that examined the effects of agricultural activities on the quality of surface-water and groundwater.

Connections Between Agriculture and Water Quality

The primary questions of the study were: "How do environmental processes and agricultural activities interact to affect the transport and fate of agricultural chemicals in the hydrologic system?" and "What are their effects on water quality and the implications for management of water resources?" These questions were addressed by studying multiple components of the hydrological system in agricultural areas to improve the understanding of how agricultural chemicals are transported into and through streams and groundwater.

In this whole-system approach, five components of the hydrologic system (atmosphere, surface water, land surface/**root zone**, unsaturated zone, and groundwater) and the interfaces and **flowpaths** that connect these components were addressed by using a combination of field observations and model simulations to provide information on the sources, transport, and fate of water and agricultural chemicals. These data were coupled with field-scale information on agricultural activities (crops, irrigation, drainage, management practices, and chemical use) and large-scale (larger than field scale; for example, watershed scale) spatial information available from national data bases (soils, weather, chemical use, and cropping patterns) to provide information across a range of spatial scales. The study areas represent major agricultural settings, such as irrigated diverse cropping in the West and corn and soybean row cropping in the Midwest, Mid-Atlantic, and Southeast, and, therefore, findings are relevant throughout much of the Nation.

Design of the Study.—This study design led to an improved understanding of the many factors that can affect the movement of water and chemicals in different agricultural settings. The study integrated the collection and analysis of field data with numerical modeling to evaluate the sources, transport, and fate of water and selected agricultural chemicals in a variety of nationally important agricultural settings. Agricultural settings were the superposition of hydrologic settings and agricultural systems. The hydrologic setting was the combination of surface and subsurface hydrologic systems, characterized by specific topography, geology, soils, and climate. The agricultural systems were defined by the classification of cropland; this definition suggests that the distribution of crops can be used to characterize regional agricultural patterns (Gilliom and Thelin, 1997).

A unique feature of these studies was the simultaneous assessment of agricultural chemicals throughout the hydrologic system at many scales. In a small watershed within each study area, data were collected on precipitation and weather; on **streamflow**; on water quality in streams, runoff, subsurface drains and shallow groundwater; and on streambed sediments and agricultural soils. Streamflow and water quality also were assessed in the larger river network of the study area. A network of wells was sampled to characterize the age, movement, and quality of shallow groundwater. In each study area, wells along a 1- to 3-kilometer (km)-long flow system were used to characterize chemical transport and transformation rates in the shallow groundwater that recharged within about the last 50 years. The design applied to the study area near Indianapolis, Indiana, is shown in figure 1.2. The 7.2-km^2 drainage area of the Leary-Weber Ditch was nested within the Sugar Creek watershed, a 240-km^2 agricultural watershed nested within the larger, more heterogeneous White River watershed (more than 29,000 km^2).

This study compared and contrasted the environmental processes that control the fate and transport of water, agricultural chemicals, and sediment within and among the various components of the hydrologic system using consistent methodologies and analyses. Environmental observations were made and mathematical models applied at a range of scales from the field (less than 1 km^2) to large watersheds and aquifer systems (greater than 10,000 km^2). Particular attention was given to the small watershed scale (about 3–15 km^2). The data necessary to calculate water and chemical mass budgets were collected. It was recognized that calculations of precise mass budgets for agricultural chemicals generally were not possible at this scale, but the approach provided a useful paradigm for the field and modeling study designs. Results gained by using this approach can add to the knowledge of environmental transport and fate processes, and to the ability to extrapolate findings to unstudied areas and at different scales.

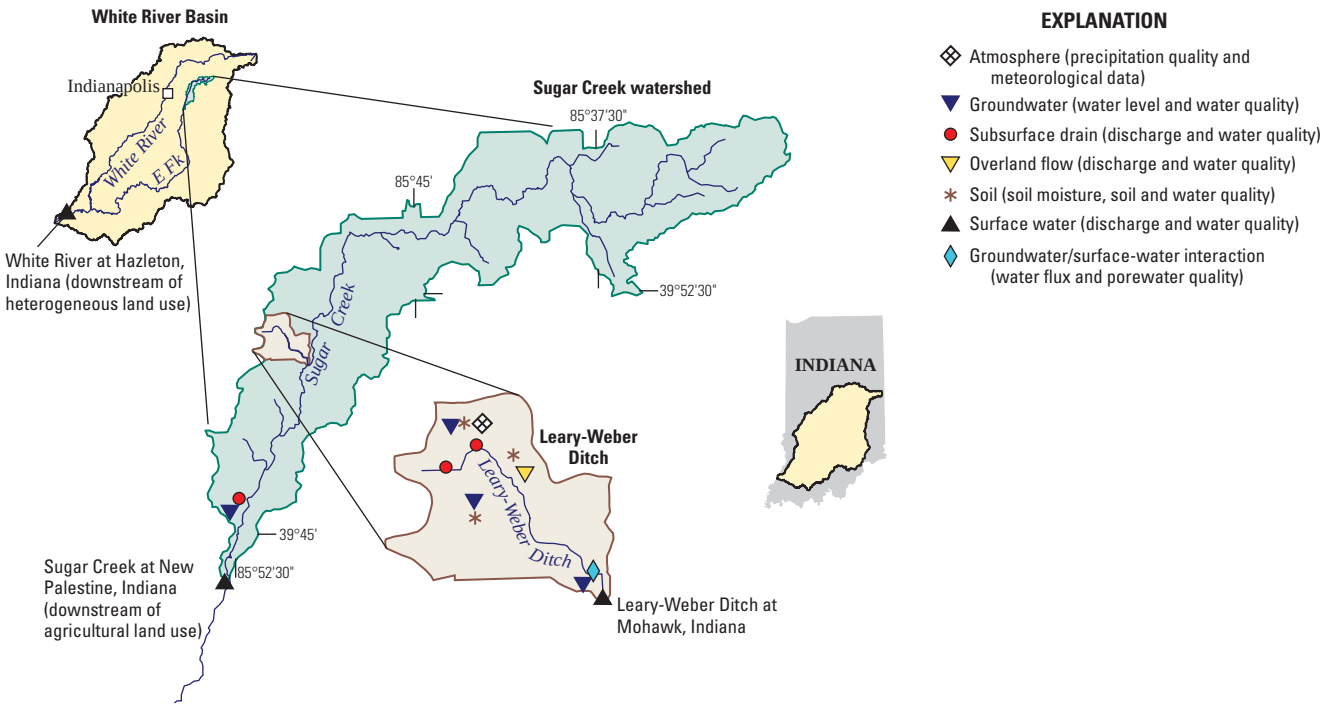


Figure 1.2. Design of the NAWQA studies on the connections between agriculture and water quality applied to the study area near Indianapolis, Indiana, showing locations of various data collection activities.

Characteristics of Study Areas.—The study areas represent a range of agricultural settings—with varying crop types and agricultural practices related to **tillage**, irrigation, **artificial drainage**, and chemical use (fig. 1.3, table 1.1). A number of land-surface, subsurface, and climatic characteristics affect the fate and transport of water and chemicals. For agricultural areas, these characteristics include watershed area, soil properties, crop types, irrigation practices, drainage enhancements, streamflow characteristics, and whether the local subsurface flow system exchanges water with the deeper, regional groundwater system (deeper than the shallow groundwater system). These characteristics vary considerably among the study areas, which provided an opportunity to compare and contrast these diverse settings. A summary of each study area, including the history, climate, agricultural crops and animals, and recent water-quality studies are presented at the beginning of each of the chapters. The results from other NAWQA studies are also highlighted to extend the geographical coverage.

The study areas in California and Washington are characterized by semiarid to arid climates and more than 95 percent of crops in these areas are irrigated. The sources of irrigation water in these two areas, however, differ substantially. Most irrigation water in the California study area is pumped from deep groundwater, whereas in the Washington study area an extensive network of water delivery canals distributes surface water from the Yakima River. Agriculture is comprised of predominantly orchards, vineyards, row crops, and dairies in both study areas.

The study areas in Nebraska, Iowa, Indiana, and Maryland are characterized by humid climates, each receiving 70–100 cm of precipitation each year. These four study areas are dominated by corn and soybean row cropping, but differ in ways that affects the movement of agricultural chemicals. Specifically, irrigation is used to augment water needs in the Nebraska study area, where 30 percent of the farmland is irrigated from deep wells. Subsurface drains, used to move excess water from the root zone, are widely used in the Iowa and Indiana study areas, where topography is flat and soils were relatively high in clay content and impermeable. In contrast, soils in the Maryland study area are permeable and well drained, and precipitation and natural soil drainage are adequate for agricultural activities.

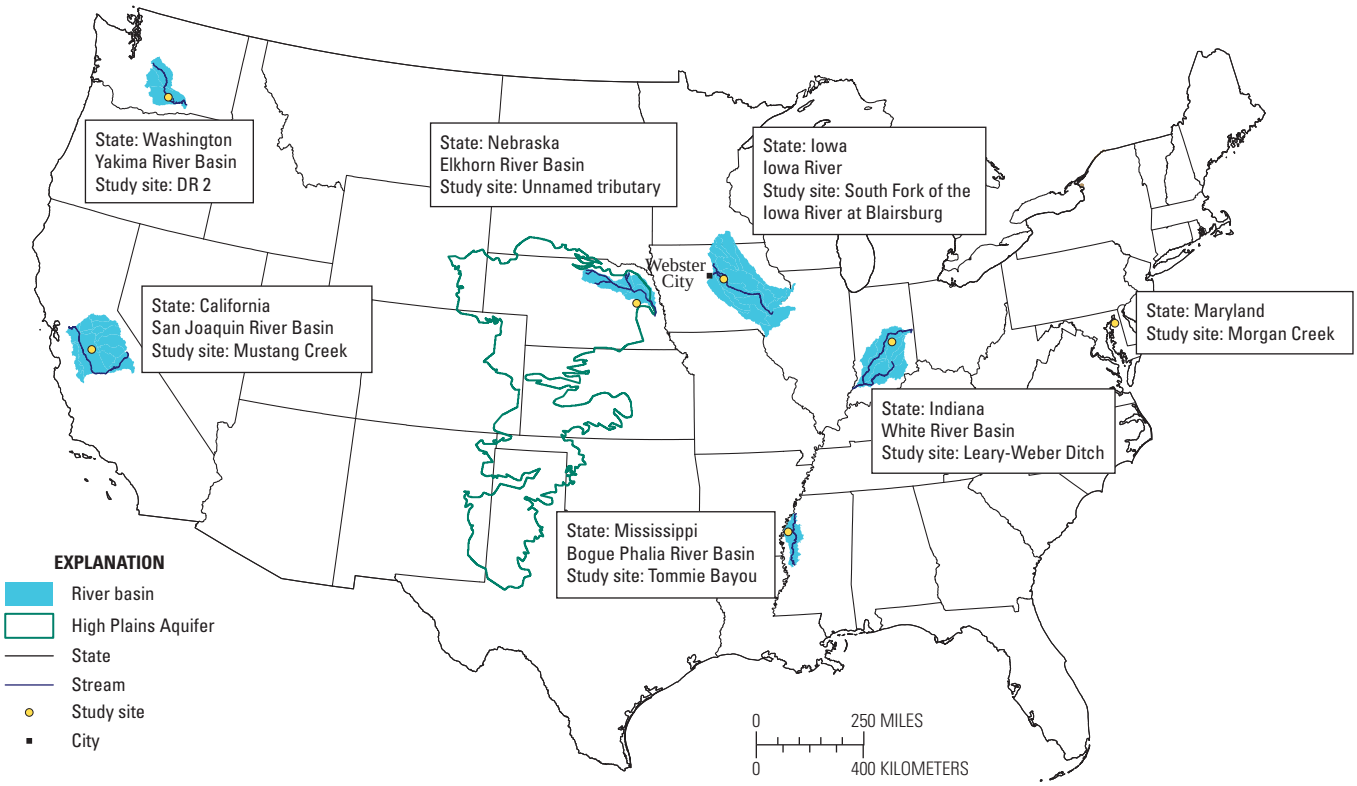


Figure 1.3. Locations of the NAWQA studies on connections between agriculture and water quality in the conterminous United States.

The study area in Mississippi is characterized as a subtropical climate that receives 130–150 cm of precipitation each year—much of it in torrential downpours. Approximately one-half of the cropland is planted in soybean, with the remaining land planted in rice, cotton, and a variety of other crops including corn, peanuts, pecans, sugar cane, and sweet potatoes. Because of the uneven seasonal distribution of rain, irrigation is often necessary to meet crop needs.

NAWQA Studies on Agriculture and Water-Quality in Context.—The NAWQA Project is one of numerous ongoing studies of the effects of agriculture on water quality. Water-quality studies are being conducted by academia, Federal, State, and local government agencies, watershed and drainage districts, corporations, advocacy groups, and farmers. The results of these diverse studies are reported in scientific journals, agency reports (for example, U.S. Department of Agriculture, National Agricultural Library, 2012a, 2012b; U.S. Environmental Protection Agency, 2012e), books, and other resources. Multiple agencies within the U.S. Department of Agriculture (USDA) have cooperated on the Conservation Effects Assessment Project "to quantify the environmental effects of conservation practices and programs and develop the science base for managing the agricultural landscape for environmental quality" (U.S. Department of Agriculture, Natural Resources Conservation Service, 2012a). Each of these various studies focuses on a particular location or aspect of measuring or preventing water-quality effects from agriculture and (or) informing the decisions of policy-makers and agricultural managers. This NAWQA study focused on the effect of water flowpaths that define the connection between agricultural activities and water quality.

Hydrology is Key.—An accounting of local hydrology—the amount of water that enters the watershed, moves within the watershed, and leaves the watershed—forms the foundation for understanding the movement of agricultural chemicals in each of the study areas. In the following chapters of this report, the connections between agricultural activities and water quality are made by way of the movement of water through and between the various components of the hydrologic system (water flowpaths).

Knowledge about the predominant water flowpaths and understanding their characteristic transport times can guide selection of the most effective management practices in improving water quality for particular agricultural settings. For example, buffer zones around streams can be effective in improving water quality where **overland flow** is important, but would be less effective where much water in a watershed travels to the stream through subsurface drains

Table 1.1. Locations and characteristics of study areas from the NAWQA studies on connections between agriculture and water quality.

Location	Major crops and animal production	Primary agricultural management practices	Hydrogeologic setting	Major water-quality issues
Washington Yakima River Granger Drain DR2	Orchards, vineyards, corn, hay, mixed row crops, dairy, cattle feedlots	Sprinkler and gravity irrigation; conventional tillage and no-till; subsurface drains, surface ditches	Arid; deep loess soils underlain by basalt	Pesticides and nutrients, water temperature, sediment, and fecal bacteria
California San Joaquin River Lower Merced River Mustang Creek	Orchards, vineyards, mixed row crops, dairy	Spray, furrow, flood, and drip irrigation; conventional tillage and no-till	Arid; permeable sands with relatively shallow water tables and poorly drained soils with deeper water tables	Nitrate in groundwater, insecticides in streams with toxicity to aquatic invertebrates
Nebraska Elkhorn River Maple Creek Unnamed tributary	Corn, soybean, alfalfa, hay, and wheat; beef cattle, some dairy and hogs	Mostly dryland; central pivot irrigation; conventional/ conservation tillage, no-till increasing	Semiarid; permeable surface and subsurface	Herbicides and nutrients in streams and groundwater, including drinking-water wells; sediment in streams
Indiana White River Sugar Creek Leary-Weber Ditch	Corn and soybean	No irrigation; conventional and reduced tillage; tile subsurface drains, surface ditches	Humid; poorly drained soils	Herbicides, nutrients, accelerated transport of pesticides and nutrients to streams by way of subsurface drains
Maryland Morgan Creek	Corn and soybean; some dairy	Some central pivot irrigation; conventional tillage and no-till	Humid; moderately to well drained soils; permeable aquifer composed of sand and gravel	Herbicides and nutrients in streams and groundwater, long-term storage of nitrate in groundwater
Iowa Iowa River South Fork at NP[1] South Fork at BB[2]	Corn and soybean; extensive hog confined feeding operations	Conventional and conservation tillage; subsurface drains, surface ditches	Humid; poorly to moderately drained soils from glacial till	Herbicides, nutrients, accelerated transport of pesticides and nutrients to streams by way of subsurface drains
Mississippi Bogue Phalia Tommie Bayou Clear Creek	Cotton, rice, soybean, corn; catfish, few other animals	Flood, pivot, spray, and furrow irrigation	Subtropical; poorly drained alluvial soils	Residual organochlorine insecticides and currently used pesticides, fine sediment, and low dissolved oxygen in streams

[1]South Fork of the Iowa River near New Providence, Iowa.

[2]South Fork of the Iowa River near Blarisburg, Iowa.

or by deep groundwater flowpaths. Knowledge concerning which water flowpaths predominate in particular settings also helps managers develop appropriate monitoring plans. In situations where most water in a watershed is transported along deep groundwater flowpaths, responses to management changes may not be apparent in stream-water quality for years. In contrast, responses in stream quality may be apparent almost immediately in areas with short flowpaths, such as watersheds with extensive overland flow and (or) subsurface-drainage systems.

Agriculture in North-Central Iowa

The French were the first Europeans to visit the present State of Iowa in the late 1600s. Zebulon Pike in 1805 explored parts of Iowa to survey locations for forts and trading posts. These Iowa explorers, traveling by river, would have been surrounded by dense hardwood forests. Away from the river in drier upland areas, oak savannas bordered the tallgrass prairie that encompassed most of the landscape. In the dry autumn, the prairie ecosystem was prone to routine wild fires, which kept trees from invading the open land and recycled nutrients to the soil. The topography was flat or gently rolling hills with thousands of small depressions dotting the landscape. These topographic depressions, left behind during the last glacial period about 14,000 years before the present era (Steinwand and Fenton, 1995), contained isolated wetlands. The soil beneath the prairie and wetlands was deep and rich in organic matter.

The cast-iron plows the settlers had brought with them from the East were designed for the light, sandy New England soil. The rich, Midwest soil clung to the plow so that every few steps it was necessary to scrape off the soil, making plowing a slow and laborious task. Many pioneers were discouraged and considered moving on, or heading back East. By the mid-1800s, with the help of John Deere's new steel plow ("self-polishers") with its highly polished and properly shaped moldboard that scoured itself as it turned the furrow slice, the rich lands of Iowa were plowed and cultivated for agriculture (Drache, 2001). Farmers plowed the prairies and planted mostly corn, wheat, oats, and hay for livestock feed. By the 1900s, settlers had converted nearly the entire prairie to farmland. The wetlands that remained quickly disappeared because of the practice of drainage through ditch digging, trenching, and installation of subsurface drains. The economy of north-central Iowa was driven by agriculture and the other industries that supported agriculture. Webster City (fig. 1.3) was home to a factory that would produce much of the clay pipe used for subsurface drains. The net effect of European settlement in Iowa was, thus, a change from a prairie ecosystem that supported a diverse flora and fauna to uniform blocks of monoculture farmland. "Incredibly, this astounding transformation from a natural landscape of wild places teeming with wild creatures to a checkerboard of manicured fields, cities, and roads, took place in barely 60 to 70 years, less than a lifetime" (Flickinger, 2010).

Recent trends in agriculture in north-central Iowa have included an increase in the number of large concentrated animal feeding operations (CAFOs) established for swine and poultry, a substantial increase in the amount of **subsurface drainage**, and an increase in the area planted in corn that is used for biofuel. CAFOs, each one potentially housing thousands of pigs, have transformed animal agriculture from relatively small numbers of animals housed at many farm sites to large numbers of animals housed at a much smaller number of locations. Recent studies by the USGS and USDA on the effects of agriculture on water quality in north-central Iowa have focused on nutrient transport in streams and subsurface drains (Tomer and others, 2010), sediment yield (Merten and others, 2016), occurrence of glyphosate (Chang and others, 2011; Coupe and others, 2011), trends in pesticide concentrations (Sullivan and others, 2009), trends in herbicide **transformation products** (Kalkhoff and others, 2012), and the occurrence of phytoestrogens and mycotoxins (Kolpin and others, 2010).

The landscape of north-central Iowa. (*A*) An isolated wetland typical of the time before agriculture, (*B*) typical cropped fields, and (*C*) the view from the air (23 square kilometers). Photograph *A* by Lynn Betts, U.S. Department of Agriculture, Natural Resources Conservation Services photo gallery, NRCSIA99470, 1999; photograph *B* by Paul Capel, U.S. Geological Survey, 2008; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010.

Chapter 2—Overview of Agriculture and Water Quality

Why are there Water-Quality Effects from Agriculture?

Agriculture in the United States supplies a large part of the Nation's food, feed, and fiber needs. Hundreds of different crops and agricultural products are grown each year in the United States to meet the needs and expectations of society. In response to both societal demands and market forces, agriculture has expanded, diversified, modified the landscape, and intensified. Crop and animal yields have increased through advances in mechanization, genetics, breeding, biotechnology, and chemicals. For commercial success, each agricultural crop and animal requires its own set of agricultural activities—procedures that fulfill the requirements of the production of crops or animals. Many of these activities include the application of chemicals to the land—fertilizers and soil amendments for crop growth and soil health, herbicides for weed control, and insecticides for insect control.

There is considerable public concern—as well as scientific evidence—that many agricultural activities adversely affect the quality of water, air, and soil, and the overall health of the environment. These effects and concerns are the result of complex interactions among agricultural activities, natural processes, societal needs, and market forces—interactions that must be understood on a fundamental scientific basis in order to design agricultural policies and management approaches that can successfully address the sustainability of both agriculture and the environment. Many of the environmental concerns originate from the off-site movement of water, agricultural chemicals, and eroded soil through water and air. The identification and characterization of transport pathways into, through, and away from agricultural areas are essential for understanding connections between agricultural activities and their effects on water flowpaths and water quality.

As the National Water Quality Assessment (NAWQA) Project began its second decade of assessment in 2002, one of the highest priorities identified by scientists and stakeholders was to improve our understanding of the sources and transport of agricultural chemicals in the hydrologic system. This priority was addressed by a set of coordinated and systematic studies in agricultural settings of the Nation that represent a wide range in the diversity of both agricultural products and activities, and in natural settings with their associated hydrologic systems. Findings from these studies, combined with selected findings from other NAWQA studies and extensive contributions from numerous other programs, agencies, and organizations, demonstrate and explain the connections between agriculture and water quality—and how essential it is to understand these connections for effective management.

Even though greater than 80 percent of the Nation's population lives in urban areas (Mackun and Wilson, 2011), everyone has a connection to agriculture. Despite the ever-increasing expectations for high-quality, abundant, diverse, and inexpensive food, many people have little direct contact with (or understanding of) the agricultural activities that provide these products. For many Americans, their closest contact with agriculture consists of shopping at the supermarket for food and the department store for clothing.

To meet the needs and expectations of society, American agriculture is highly diverse (fig. 2.1). Hundreds of different crops and agricultural products are grown. Each crop and animal requires its own unique set of agricultural activities and resources—including space, soil, water, nutrients (plants), food (animals), protection (from pests and weather), and disposal of the wastes—for commercial success. Agricultural activities are defined herein as all farming procedures that lead to the production of crops or animals (see "Specific Terms Used in this Report"). These activities include the growing and harvesting of crops and animals, modifications of the landscape, application of chemicals, and disposal of wastes. For annual crops, the soil is prepared, and crops are planted, maintained, and harvested. For perennial crops, such as orchards and vineyards, the plants are pruned and maintained according to their seasonal needs. Most crops are fertilized or protected with pesticides, and water is added to or removed from the landscape as needed. Animals are housed or fenced, fed, watered, and harvested; their manure is stored and used on the landscape. Agricultural activities generally fulfill one or more of the crop or animal requirements in an economically sustainable fashion (table 2.1), or they are implemented to help minimize the adverse effects of agricultural activities on water flowpaths, water quality, and (or) the environment.

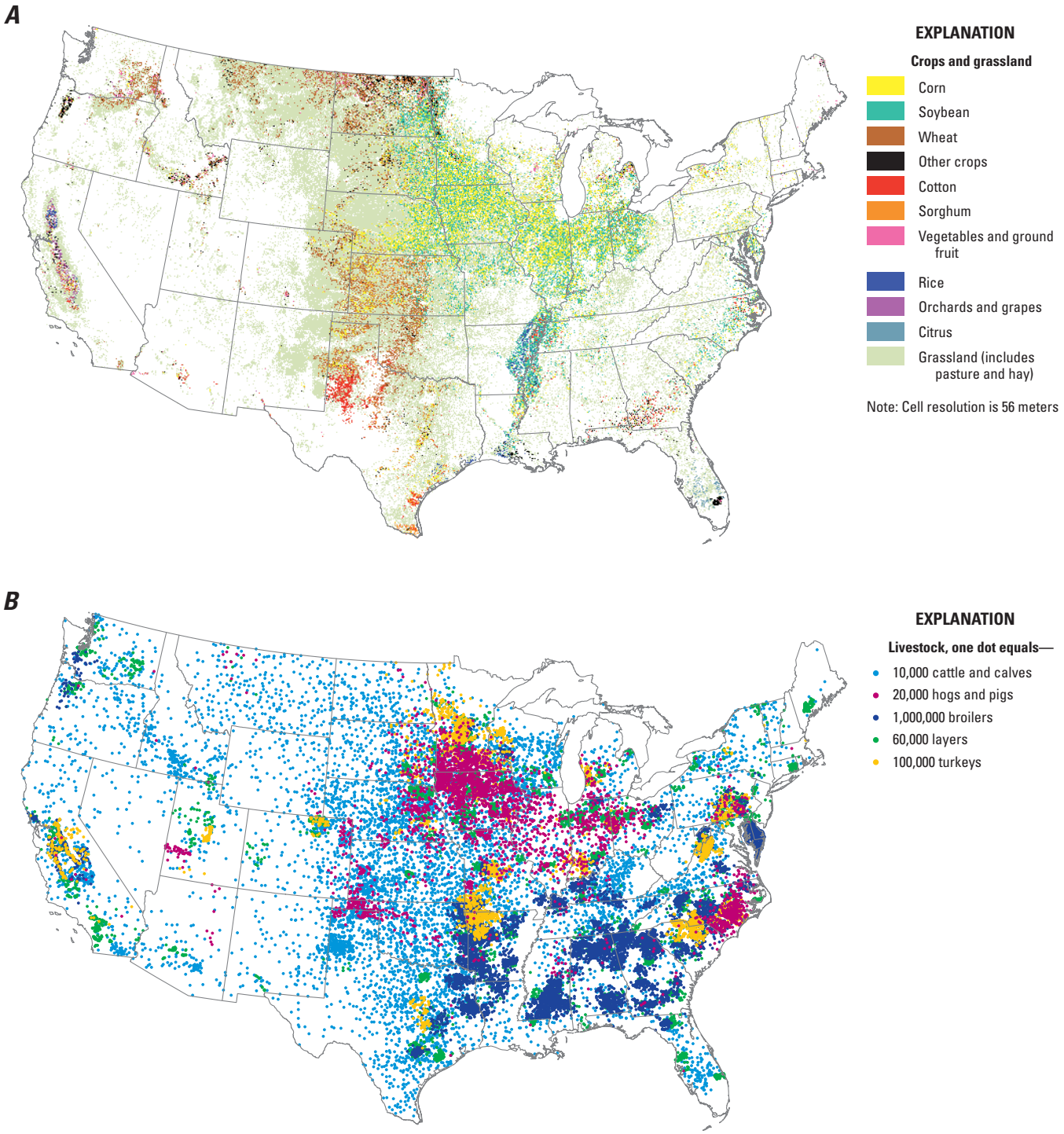


Figure 2.1. Diversity of (*A*) crops and (*B*) livestock in the conterminous United States (U.S. Department of Agriculture, 2009).

Table 2.1. Agricultural activities fulfilling crop and animal requirements and their environmental concerns.

[**Abbreviations:** ET, evapotranspiration; BOD, biochemical oxygen demand; DDT, 1,1,1-trichloro-2,2-di(4-chlorophenyl)ethane; –, not applicable]

Requirement	Agricultural activity for crops	Potential movement	Agricultural activity for animals	Potential movement
Nutrients/food	Fertilizer, manure, and lime applications	Nitrate, nitrite, ammonia, nitrogen oxides, organic nitrogen, phosphorus	Feed: derived from plant primary production	Manure, methane
Sufficient water	Irrigation	Increased water in streams, increased infiltration, increased ET, mobility of dissolved ions (increased salinity), groundwater depletion, streamflow depletion	Farm ponds, building plumbing, free range to streams and ponds	Pathogens, BOD, phosphorus, sediment
Protection from weeds	Herbicide application	Metolachlor, glyphosate, atrazine, many other specific compounds	–	–
Protection from insects	Insecticide application	Carbaryl, permethrin, DDT, many other specific compounds	Insecticides	Lindane, DDT, many other specific compounds
Protection from disease	Fungicide application	Benomyl, captan, thiabendazole, many other specific compounds	Antibiotics	Tetracycline, many other specific compounds
Protection from excess water	Surface drainage, subsurface drainage, vertical drains	Increased discharge, nitrate, nitrite, ammonia, organic nitrogen, phosphorus, pathogens, organic carbon (BOD), sediment, metolachlor, permethrin, DDT, many other specific compounds	–	–
Waste disposal	–	–	Lagoons, manure spreading	Odors, nitrate, nitrite, ammonia, nitrogen oxides, organic nitrogen, phosphorus, pathogens, organic carbon (BOD)
Enhanced yield	Prophylactic application of fungicides	Propiconazole, azoxystrobin, chlorothalonil	Hormones, prophylactic use of antibiotics	Tetracycline, many other specific compounds
Protection from wind damage and erosion	Hedge rows, wind rows	Decreased leakage of soil and chemicals	–	–
Protection of soil from water erosion	Terraces, contour farming, grassed waterways	Decreased leakage of soil and chemicals	–	–
Protection of environment from soil erosion	Buffer strips, sedimentation basins, constructed wetlands	Decreased leakage of soil and chemicals	–	–

Specific Terms Used in This Report

Agricultural activities are all farming procedures that lead to the production of crops or animals. These activities include the growing and harvesting of crops and animals, modifications of the landscape, application of chemicals, and disposal of wastes. Every agricultural activity has the purpose of fulfilling one or more of the crop or animal requirements in an economically sustainable fashion. Agricultural activities also are implemented in many cases to minimize any effects of agricultural activities on the broader environment.

Agricultural chemicals are associated with both plant and animal agriculture. Many chemicals, such as fertilizers, lime, pesticides, hormones, and **antimicrobials** are purposely used because they directly benefit crops or animals**.** Both manufactured chemicals and manure can be used as fertilizers. Some chemicals are produced by the crops or animals as waste by-products. Other chemicals are natural occurring and mobilized by agricultural activities. Although eroded soil particles (sediment), microorganisms, and manure are not chemicals, they are discussed in this report because they share many of the same sources and environmental transport processes, and can cause adverse effects on water quality.

Agricultural modifications are any agricultural activities that change the landscape, and, therefore, usually change the manner in which water moves across the landscape. The goals of agricultural modifications generally are to increase crop yield, minimize soil loss, maintain soil fertility, protect crops and animals, and (or) minimize adverse effects on the broader environment. Some modifications—such as irrigation, drainage, **reservoirs**, and **constructed wetlands**—have become a permanent part of the landscape and have substantially changed it. Other types of modifications, such as tillage, crop type, and choice of land cover, are frequently revised, and only temporarily change the movement of water on the landscape.

Environmental concerns are the potential effects that agricultural activities can have on ecosystems and people. A few broad environmental categories are of general societal importance, but there can be many specific concerns within each of these broad categories. In specific areas, at specific times, some concerns are realized by actual adverse environmental effects.

Field describes any area where agricultural activities take place. This area could be a cropped field, orchard, vineyard, pasture, grazed land, or animal feeding operation.

Sustainability means meeting the needs of the present without compromising the ability of future generations to meet their own needs.

Each agriculture type has a unique set of agricultural activities. The production of corn is different from the production of grapes. The production of cotton is different from the production of asparagus. The production of sheep is different from the production of eggs. For example, cattle farming covers a broad range of agricultural settings (fig. 2.2). Near one end of this range are low-density operations like grazing and ranching. Small dairies, where cattle are raised in combination with row crops, have about the same animal density as grazing operations, but these two types of activities function and dispose of their wastes differently. At the other end of the range are concentrated (high density) animal operations—large dairies and beef feedlots—where feed, medications, diseases, and waste are managed on a much larger scale. Each agriculture type connects to and affects water quality differently.

The early European settlers quickly developed commercial agriculture to supply urban areas and provide exports. Agriculture expanded to meet the needs and expectations of society through an expansion of agricultural lands, modification of the landscape, and technological advances in mechanization, chemical use, conventional breeding and, more recently, genetic engineering that resulted in increased production (fig. 2.3). Although each of the methods listed above has resulted in increased production (Chapter 3), the cumulative effect of this agricultural expansion and intensification has led to adverse effects, including changes in water quantity, water quality, and the health of ecosystems. Some of these effects, such as the sedimentation of rivers and other surface waters downstream of agricultural areas, are obvious and appear immediately after a heavy rain. Other adverse effects, such as the deterioration

Figure 2.2. Each agriculture type has a unique set of agricultural activities. Cattle densities vary for different types of agricultural settings in the United States. (*A*) Crops only (grapes, California); (*B*) grazing (Colorado); (*C*) small dairy (Iowa); (*D*) confined animal feeding operation (Washington) (Capel and Hopple, 2018). Photographs *A*, *C*, and *D* by Paul Capel, U.S. Geological Survey, 2010. Photograph *B* by Jeff Vanuga, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSCO02015, 2002.

Operation	Head per square kilometer
Crop only	0
Beef – grazing	30
Dairy – small	60
Dairy – large	200
Beef – confined feeding (outdoor)	50,000
Beef – confined feeding (indoor)	200,000

of coastal ecosystems caused by the discharge of fertilizer-derived nutrients at rates exceeding the capacity of these ecosystems to absorb them, may go unnoticed for decades. The changes in the ecosystems of Chesapeake Bay and the Gulf of Mexico are examples of these latter types of effects.

As part of the management of agricultural systems, there are material inputs and outputs on a reoccurring basis (daily to annually). Material inputs include water, nutrients, feed, pesticides, and chemicals for enhanced crop and animal growth. Material outputs include harvested products—crops, meat, milk, and eggs. Water for crops comes either from precipitation or irrigation. Water is provided to animals either indoors (through plumbing) or outdoors (from farm ponds, water troughs, natural streams, and other sources). Nutrients are applied to crops through fertilizers or manure, supplementing the nutrients available in the soil. Food is provided to animals as feed (from crops). A by-product of life and growth is the generation of waste. Plant waste (crop residue) generally is returned to the soil after the plant's death or senescence. Subsequent microbial decomposition returns the plant's chemical building blocks (elements) to the soil. Waste from animal agriculture (manure) is often spread on the land as a soil amendment, a source of nutrients for crops, and (or) as a disposal method (MacDonald and others, 2009).

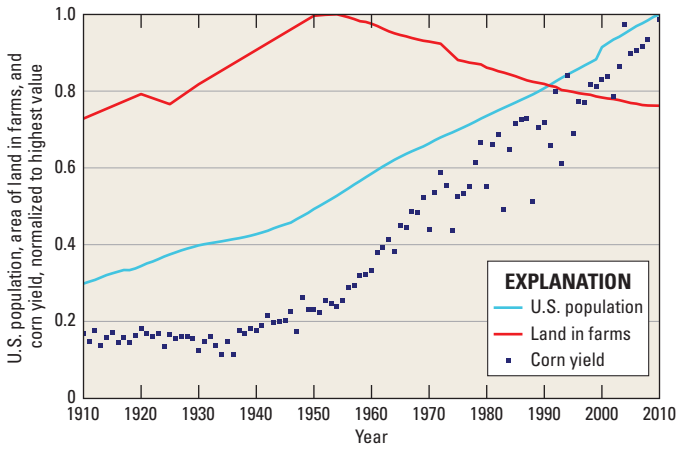


Figure 2.3. Changes in population, land in farms, and yield of corn (for grain) in the United States, 1910–2010. Data are presented as normalized values where the maximum value is equal to 1.0. Maximum U.S. population—309 million (2010). Maximum area of land in farms—488 million hectares (1952–54). Maximum corn yield—10,340 kilograms per hectare (2009) (Grey and others, 2012).

Additionally, many types of inputs are used to protect the product of interest. Herbicides protect crops against competing weeds, insecticides protect crops and animals against insects, fungicides protect crops and animals against fungi, and antimicrobials protect animals against bacterial diseases. Other chemicals, such as lime, are used to improve soil conditions. Finally, some chemical inputs are designed to enhance growth. For crops, nitrogen is sometimes applied in excess of the basic plant requirements to enhance resilience against poor weather conditions. For animals, hormones are used to yield faster growth and larger animals.

About 54 percent of the land in the conterminous United States is used for agriculture. About 13 percent is cropland and 41 percent is pasture and grasslands used for grazing (Baker and Capel, 2011). Land with sufficient soil and water is used for growing crops, whereas more arid grasslands and scrublands are more commonly used for grazing. Much of the animal agriculture, outside of the arid areas, is interspersed within the areas of crop agriculture (fig. 2.1). At each location where agriculture activities began, there was an initial one-time transition from a natural landscape to an agricultural landscape.

Before agricultural use of the land began, the landscape had a natural vegetative cover and natural water flowpaths (movement of water). Water moved through natural landscapes in expected ways—referred to as the "water cycle"—controlled primarily by the local vegetation, soils, topography, and the geologic framework. The most important input of water is precipitation. The major flowpaths for the removal of water include return to the atmosphere by way of evaporation and **evapotranspiration** (through plant respiration), runoff across the landscape to streams and other surface-water bodies, and **recharge** through the soil to groundwater and, eventually, discharge to streams, lakes, and coastal areas. The relative importance of water flowpaths is dependent on the specific location on the landscape and season of the year.

Modifications of the landscape for agriculture often resulted in substantial changes in the water flowpaths, rates of water movement, and its abundance on the natural landscape. The goals of the agricultural landscape modifications are to increase crop yield, minimize soil loss, maintain soil fertility, protect crops and animals, and (or) minimize adverse effects to the broader environment. (The term "modification" is defined here as any agricultural activity that changes the landscape, and, therefore, usually changes the manner in which water moves across the landscape.) Some modifications—such as irrigation, drainage, and the construction of reservoirs and **wetlands**—have become a permanent part of the landscape and have substantially changed water movement and agricultural abundance. Other types of modifications or practices, such as tillage, crop type, and choice of land cover, are frequently revised, and only temporarily change water movement on the landscape.

Each orchard, field, pasture, range, and animal feeding operation has unique landscape characteristics and unique water flowpaths. Each water flowpath has a beginning and an end, persists for a specific period, with variable intensity (flow rate) over time. The resulting water flowpaths from any specific agricultural location are the sum of the multiple modifications that have been made to the landscape, superimposed over the features of the original hydrologic system. Modified flowpaths can contain water that has moved from fields, such water can also move sediment (eroded soil) and agricultural chemicals from fields and farms into the environment, where these materials can interact with people and ecosystems, and are a possible source of concern. (Wind also can move soil and agricultural chemicals into the broader environment through the air.)

The generalized connection among agricultural activities and water-quality effects can be thought of as a series of cause and effect events. Crops and animals have requirements for growth; therefore, agricultural activities are conducted to meet these requirements. The water, chemicals, and sediment that move from the agricultural areas can have adverse effects on water quality, water quantity, and other aspects of the environment. The specific environmental effects aggregate and result in broad societal concerns about the environmental effects of agriculture (table 2.2).

The practice of irrigation allows agricultural land use in arid areas (Washington). Photograph by Paul Capel, U.S. Geological Survey, 2010.

Runoff from an almond orchard after a heavy rain (California). Photograph by Joseph Domagalski, U.S. Geological Survey, 2004.

Table 2.2. Environmental concerns from agriculture are grouped in a few broad categories of societal concerns.

[Within each of these broad categories, there are many specific concerns. See "Human and Ecosystem Health Effects of Agricultural Chemicals," for a detailed summary of one of these broad categories]

Broad concerns	Specific examples
Economic sustainability	
	Increased treatment for drinking water required
	Loss of infrastructure
	Increased cost of navigation, dredging
	Loss of water storage (reservoir infilling)
Agricultural sustainability	
	Loss of water for irrigation (because of poor quality)
	Loss of soil
	Loss of soil fertility
	Loss of crop
	Loss of livestock (sickness/death)
	Loss of aquatic harvest
	Weed resistance to herbicides
Aesthetics and recreation	
	Aesthetics
	Fishing
	Swimming
	Odor
Health (human and ecosystem)	
	Loss of habitat, loss of species
	Change in ecosystem
	Human–sickness/death
	Animals–sickness/death
	Cancer
	Developmental/reproduction problems
	Antimicrobial resistance
Climate change	

Human and Ecosystem Health Effects of Agricultural Chemicals

Agricultural chemicals applied to the land can be carried through precipitation- or irrigation-derived flowpaths—either in dissolved form or bound to sediment particles—to the broader environment. The chemicals may be transformed into other compounds by natural chemical and (or) biological processes, or become concentrated in the water, sediment, and (or) tissues of organisms living within the water. Relatively persistent chemicals may be further concentrated in the bodies of predators that feed on contaminated organisms living in the water—a process known as biomagnification. In long-lived organisms, such as many mammals, fish, and birds, persistent chemicals pose a greater risk of negative health effects over a long life span as more of the chemical accumulates in the body tissues of the organism.

The range of deleterious health effects caused by agricultural chemicals is large, and varies with the species, sex, and developmental stage of the organism in question. Factors such as dose, length of exposure, type of substance, and the physiological response of the organism to the chemical are all important in determining the extent of damage. As a result, not all exposures to potentially hazardous chemicals will cause harm. Because of similarities in biological systems across species, chemicals that are harmful to one type of organism are often harmful to other closely related organisms. By contrast, a particular biological species' unique (or nearly unique) sensitivity to a particular chemical is often the reason for its use as a pesticide.

All living organisms have systems designed to eliminate wastes and foreign substances. Many chemicals that are harmful to organisms have properties that cause them to bypass an organism's detection or detoxification processes. Some chemicals may act to block normal cell function, or spread across membranes into adjacent cells, organs, and the circulatory system. Exposure to high concentrations of hazardous chemicals may cause a disruption in oxygen or nutrient uptake, birth defects, learning disabilities, early onset of puberty, hormonal imbalances, reproductive failure, lowered immunity against infections and a variety of other problems (table 2.3). Furthermore, some chemicals can bind directly to DNA, causing mutations that may predispose an individual to cancer. Mutations in reproductive cells can be passed on to future generations where they may perpetuate negative health effects. One example of variable health effects ranging across different groups of organisms is the organochlorine insecticide DDT. Originally thought to be non-toxic to humans, DDT was used extensively as an insecticide after World War II (U.S. Environmental Protection Agency, 2012d). By 1972, because of its biomagnification in predatory birds feeding on contaminated fish—and the health disruptions that resulted—DDT was banned in the United States. A notable effect of DDT was thinning eggshells and reduced numbers of offspring in bald eagle populations. DDT also causes reproductive failure in other species, such as fish and mammals. Additionally, impairment of the nervous, immune, and endocrine systems has been linked to DDT, as well as mutations that could lead to cancer (table 2.3).

Table 2.3. Selected agricultural chemicals and their health effects for a range of biological species.

[From Capel and Hopple (2018). Health effects can be acute or chronic, damaging one or more systems within the organism, or the whole organism. **Type of toxicity:** A, acute toxicity (refers to the adverse effects of a substance that result either from a single exposure or from multiple exposures in a short space of time); C, chronic toxicity (refers to the adverse effects of a substance that result from long-term exposure). **Shading:** Green denotes a relatively low effect; blue denotes a relatively moderate effect; pink denotes a relatively high effect. **Biological species:** B, bird; F, fish; H, human; I, insect; R, rat. **Immune system:** A complex and integrated body system of organs, tissues, cells, and cell products such as antibodies that differentiate the body's cells from foreign objects and protect the organism from potentially pathogenic organisms or substances. **Endocrine system:** Composed of a group of cells and glands that make, store, and secrete hormones into the body that regulate body functions. **Developmental/teratogen:** Teratogen is a chemical that causes defects in development between conception and birth. **Carcinogen:** A chemical that causes cancer. **LD-50:** The lethal dose of a material, given all at once, which is expected to cause the death of 50 percent of an experimental population when exposure is by swallowing, through skin contact, or by injection. This one measure of the short-term acute toxicity of a chemical. **LC-50:** The concentration of a chemical in air or water to which exposure for a specific length of time is expected to cause death in 50 percent of an experimental population when exposure is through drinking or inhalation. This is one measure of the short-term acute toxicity of a chemical. **Phytotoxicity:** Describes the degree of toxic effect by a compound on plant growth. **Abbreviations:** L, liter; mg/kg, milligrams per kilogram; mg/L, milligram per liter]

Example chemical	Type of toxicity	Reproductive system					Immune system					Respiratory/ circulatory system					Nervous system					Endocrine system					Developmental/ teratogen					Mutagen					Carcinogen					Rat- oral LD-50 (mg/kg)	Bluegill 96-hour LC-50 (mg/L)	Phytotoxicity	Bioaccumulation
		H	R	F	B	I	H	R	F	B	I	H	R	F	B	I	H	R	F	B	I	H	R	F	B	I	H	R	F	B	I	H	R	F	B	I	H	R	F	B	I				
Permethrin	A																																									2,280	0.0008		
insecticide	C																																												
Metolachlor	A																																									2,780	15		(7)
herbicide	C																																												
Nitrate	A																																									[2]0.0039	[2]1.21		(7)
fertilizer	C																																												
DDT[1]	A																																									150	0.0086		
insecticide	C																																												
Mercury	A																																									[3]26	[3]0.2		(4)
insecticide	C																																												
Arsenic	A																																									[5]763	[5]0.02		(4)
insecticide	C																																												
Total ammonia	A																																										[6]0.26–2.97		
fertilizer	C																																												
Sodium chloride	A																																									3,000	9,627		
salinity	C																																												

[1]DDT is 1,1,1-trichloro-2,2-di(4-chlorophenyl)ethane.
[2]LD-50 value is average of 0.0012–0.0066 mg/kg in rats, LC-50 value is average of 0.42–2 mg/L in fish.
[3]Mercuric chloride (inorganic) for rats; methylmercury (organic) for fish.
[4]Some chemicals with mercury-carbon and arsenic-carbon bonds can bioaccumulate.
[5]Arsenate/arsenite (inorganic) for rats; arsenobetaine/arsenocholine/dimethyl arsenic acid (organic) for fish.
[6]pH 8.
[7]Bioaccumulation occurs in vegetation.

For some agricultural chemicals, the series of events that leads to these effects is straightforward. For example, ammonia is oftentimes applied to crops as a nitrogen source (fertilizer) and is detected at high concentrations (greater than background concentrations) in animal waste. Ammonia is acutely toxic to fish at low concentrations (at or near background concentrations) (see "Human and Ecosystem Health Effects of Agricultural Chemicals"), such that an ammonia or manure spill can cause local fish kills (Wilton, 2002; U.S. Environmental Protection Agency, 2012f). The observation of a fish kill causes concerns about the health and stability of the aquatic ecosystem. For other chemicals, complex cause and effect relations, combined with other chemicals and environment processes, result in multiple environmental concerns. Nitrogen provides an important example of this complexity (see "Nitrogen").

The magnitude of a water-quality effect is linked to the strength of the chemical source (concentration), the characteristics of the chemical (for example, toxicity and persistence), and the water flowpaths coming from that source. When these characteristics and factors are well understood, cause-effect relations for an adverse effect can be quantified for a specific location over a specific timeframe. Therefore, agricultural activities can be implemented to minimize or diminish the movement, and thus, the water-quality effect. An understanding of these cause-effect relations with the understanding of specific flowpaths can help set realistic expectations for the effectiveness of an agricultural activity to diminish adverse effects on water quality.

Everyone and everything has a connection to the environment. The environment is the source of air and water.

Application of nitrogen before planting (Iowa). Photograph by Paul Capel, U.S. Geological Survey, 2008.

It is where people live and recreate. A healthy, sustainable environment is critical to the well-being of society. Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (U.S. Environmental Protection Agency, 2012i; U.S. Department of Agriculture, National Agricultural Library, 2015). Environmental concerns about agriculture arise when agricultural activities cause adverse effects on the health and (or) ecological sustainability of people and ecosystems. These effects are the result of complex interactions not just between agriculture and the natural environment (noted earlier), but also among agriculture, the environment, and choices of human society.

Nitrogen

Nitrogen is one of the elemental building blocks of living organisms and a critical component of amino acids and deoxyribonucleic acids (DNA). Nitrogen can be present in many chemical forms in the environment. Nitrogen changes back and forth among these different forms through natural biological and chemical reactions. For crop production, the natural supply of nitrogen is often supplemented with synthetic fertilizer and manure in the forms of nitrate, ammonia, and (or) organic nitrogen (fig. 2.4).

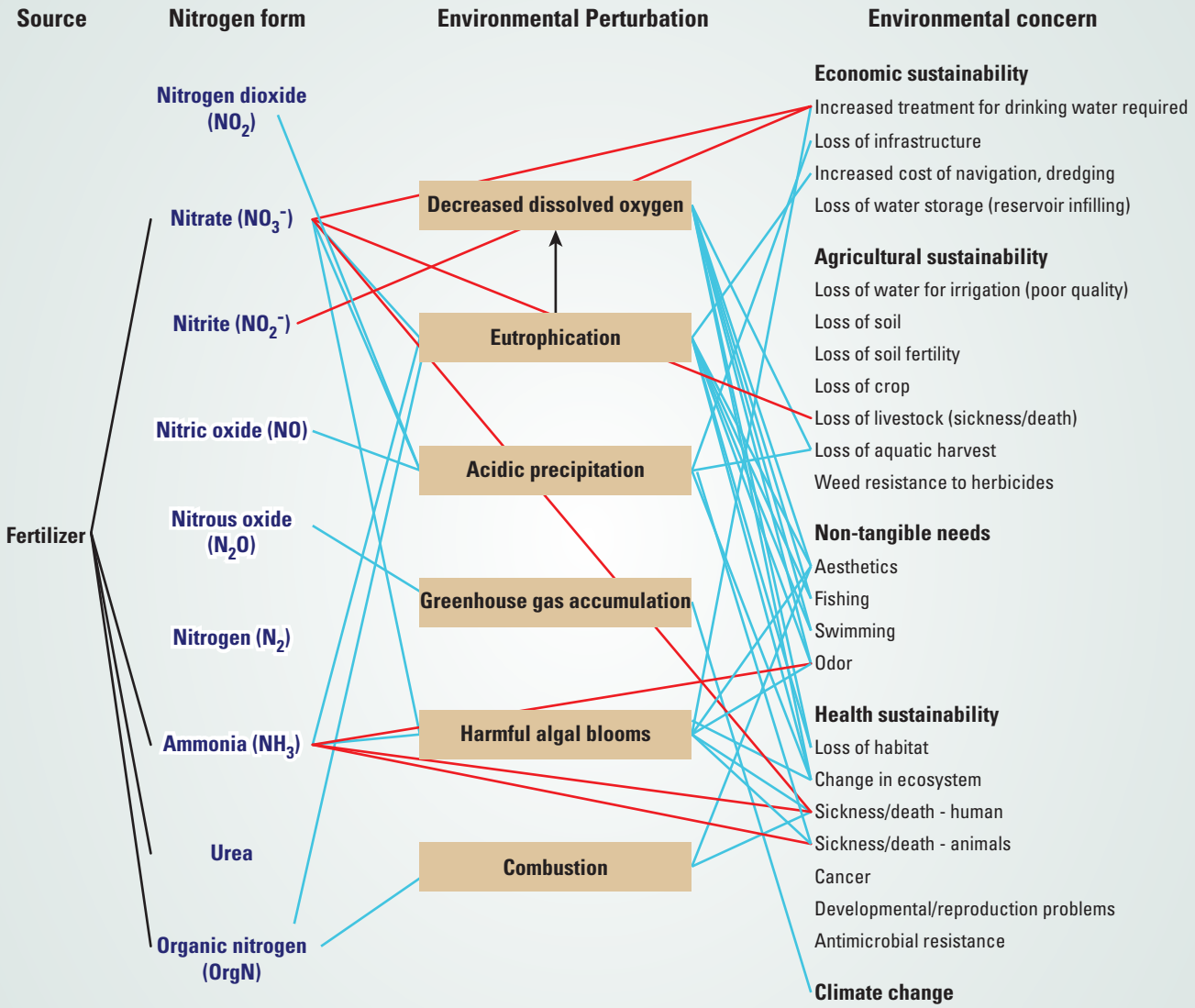
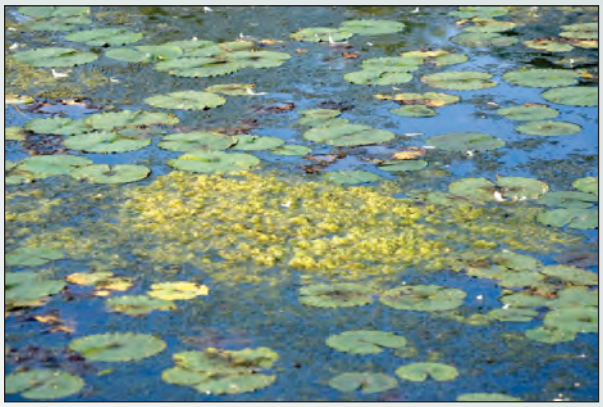


Figure 2.4. The complex connections among nitrogen from fertilizer and various water-quality and other environmental concerns. The lines show the many potential pathways that connect the sources of nitrogen used in agriculture with the many different concerns. A realized concern has an adverse effect on economic or agricultural sustainability, aesthetics and recreation, human and ecosystem health, or climate change. The nitrogen that is applied as fertilizer, both chemical and manure, undergoes transformation through chemical and biological reactions to different forms of nitrogen. Each of these forms of nitrogen interacts with the environment in a different way and through different processes. Some forms of nitrogen can cause direct adverse effects on the environment (shown by direct lines (red) from a nitrogen form to an environmental concern). Some of the nitrogen forms can cause environmental perturbations (changes in the condition of the environment, blue lines), which then can produce adverse effects on the environment (Capel and Hopple, 2018).

Some forms of nitrogen can cause health problems for humans or other organisms (fig. 2.4). Some of these problems directly affect the environment. Nitrate can be toxic to some livestock—because they are not able to metabolize it—as well as to infants younger than 6 months of age, in which it can cause methemoglobinemia, or "blue-baby" syndrome. Ammonia has a strong odor, can cause breathing problems in humans (Agency for Toxic Substances and Disease Registry, 2013), and is toxic to fish (Russo, 1985). Other concerns indirectly affect the environment. For example, nitric oxide can react with water in the atmosphere and contribute to acidic precipitation that can damage buildings and other infrastructure. Nitrous oxide is a potent greenhouse gas that traps heat 310 times more effectively than carbon dioxide and is one of the key compounds that leads to ozone depletion (Ravishankara and others, 2009). Nitrate, ammonia, and organic nitrogen, when present in surface water, act as fertilizers and increase the growth of aquatic plants. This process, known as eutrophication, creates a number of environmental concerns (fig. 2.4).

Eutrophication can occur naturally over centuries as environmental processes erode rock and organic matter and transport them to streams. However, over the past 5–10 decades, agriculture and other human activities have caused eutrophication rates to increase dramatically (Dubrovsky and others, 2010). Runoff from fertilized fields and livestock areas can contain high concentrations of nitrogen, accelerating the eutrophication process. Excess nitrogen entering a stream, at rates exceeding the capacity of the stream to assimilate it, can disrupt normal equilibrium of the stream chemistry, which can in turn have many cascading negative effects, sometimes permanently disrupting and changing the ecosystem. Many streams and rivers flow into lakes, estuaries, and oceans; therefore, the excess nitrogen delivered to these water bodies may cause eutrophication far from the original nitrogen source.

The eutrophication process can cause both short-term and long-term effects. The primary effects of excessive plant growth can include a reduction in the aesthetic value of the water body, unpleasant odors, decreased recreational activities, and disruption to navigation. The secondary effects of eutrophication can have cascading adverse effects on water quality, the food web, and the aquatic organisms that it supports, including decreases in water clarity, dissolved oxygen concentrations, usable habitat, and species diversity. The cascading effects begin with decreased water clarity, which decreases the depth of light penetration, and, consequently, decreases the ratio of oxygen to carbon dioxide in the water column. With less light penetration, **photosynthesis** is hindered or blocked, resulting in increases in carbon dioxide concentrations and decreases in available oxygenated habitat. Water bodies are particularly susceptible to this at night, when the algae and plants continue to respire, but are no longer producing oxygen through photosynthesis. As biomass decays in the water column, oxygen also is consumed and carbon dioxide is released. This process is especially acute for mussels, fish, insect larvae and other invertebrates, and other organisms that require well-oxygenated water in order to survive (Camargo and Alonso, 2006). Some aquatic organisms are able to tolerate low oxygen concentrations and reduced light conditions and can survive, or even thrive, in the eutrophic water. For example, blue-green algae, which typically are responsible for the formation of green "scum" on the surfaces of water bodies late in the summer, have specialized pigments that allow them to photosynthesize under low light conditions. Some blue-green algae can release toxins that are harmful to aquatic fauna, terrestrial animals, and even humans. Under the conditions caused by eutrophication, blue-green algae can perpetuate this negative cascade accumulation of events, helping change well-oxygenated, native aquatic ecosystems, which are more biodiverse but may be relatively unproductive, to a condition of higher productivity but relatively low species diversity.



A eutrophicated pond with extensive aquatic plant and algal growth, adjacent to agricultural fields (Minnesota). Photograph by Paul Capel, U.S. Geological Survey, 2009.

Summary

Agriculture in the United States supplies a large part of the Nation's food, feed, and fiber needs. Hundreds of different crops and agricultural products are grown each year in the United States to meet the needs and expectations of society. In response to both societal demands and market forces, agriculture has expanded, diversified, modified the landscape, and intensified. Crop and animal yields have increased through advances in mechanization, genetics, breeding, biotechnology, and chemicals.

For commercial success, each agricultural crop and animal requires its own set of agricultural activities—procedures that fulfill the requirements of the production of crops or animals—space, soil, water, nutrients (plants), food (animals), protection (from pests and weather), and disposal of wastes. Agricultural activities include growing and harvesting crops and animals, modifications of the landscape, application of chemicals, and disposal of wastes. Many of these activities include the application of chemicals to the land—fertilizers and soil amendments for crop growth and soil health, herbicides for weed control, fungicides for fungus control, and insecticides for insect control.

There is considerable public concern—as well as scientific evidence—that many agricultural activities adversely affect the quality of water, air, and soil, and the overall health of the environment. These effects are the result of complex interactions among agricultural activities, natural processes, societal needs, and market forces—interactions that must be understood on a fundamental scientific basis in order to design agricultural policies and management approaches that can successfully address the sustainability of agriculture and the environment. Many of the environmental concerns originate from the movement of water, agricultural chemicals, and sediment from agricultural areas through water and air. The identification and characterization of transport pathways into, through, and away from agricultural areas are essential for understanding connections and relations between agricultural activities and their environmental effects.

Agriculture in the Panhandle of Texas

The panhandle of Texas (fig. 1.3), in the southern High Plains, has a semi-arid climate, receives an average of only 44 cm of precipitation annually, and has a growing season averaging 185 days each year. The flat landscape of the southern High Plains is dotted by thousands of closed-basin depressions. This landscape overlies the vast High Plains (Ogallala) aquifer. Prior to settlement, short-grass prairie covered the entire region, which was home to bison and other prairie wildlife that thrived on abundant grass resources. The region was (and is) critical habitat for migrating birds that travel the Central Flyway. Hunter-gatherer Native Americans (Apache and Comanche) lived in the area. Early European explorers referred to the southern High Plains as the Llano Estacado, or staked plain, because of the vast featureless vistas.

With few exceptions, this region of Texas was largely isolated throughout early European settlement, and opened to westward expansion about 1875. In 1879, the State of Texas sold 12,000 km^2 of land to finance the building of a new State Capitol. The new landowners created the XIT Ranch to run cattle until the land could be parceled off. Circa 1885, with the introduction of barbed wire, fences were erected to contain longhorn cattle being brought into the area. Within the next year, 2,000 km^2 of range were fenced and some 100,000 cattle had been purchased. By the late 1890s, because of difficulties posed by droughts, prairie fires, and declining markets, the XIT Ranch began selling off land.

With the attraction of seemingly plentiful groundwater extracted by windmills in the High Plains (Ogallala) aquifer, homesteaders began pouring into the region during the early 1900s. Wheat and sorghum were common crops, but, with increasing irrigation and improved farming technology, cotton and corn also were planted. By 1930, cotton was an important crop. Cattle ranching, while declining in economic importance, remained important in the area. With the advent of new drilling and pump technology in the 1930s–1940s, widespread drilling of irrigation wells aided agricultural expansion. The development of a large beef cattle feedlot industry in the 1960s reinforced the importance of cattle, with dairy cattle also becoming increasingly abundant.

Currently, beef and dairy cattle, as well as wheat, corn, cotton, and sorghum, are important in the panhandle region. Water from the Ogallala aquifer is extremely important to agriculture. In many parts of this region, the **water table** is declining and economic concerns for this dwindling resource have led to more research into water conservation practices, irrigation efficiencies, development and use of more drought-**tolerant** crop commodities, mechanisms of recharge, as well as contamination from agricultural chemicals (fertilizers and pesticides) (Gurdak and others, 2009; McGuire, 2009). Other recent USGS studies on the evaluation of effects of agricultural activities and natural processes on groundwater quality in the southern High Plains include Gurdak and Qi (2006), McMahon and others (2006), Stanton and Fahlquist (2006), and McMahon and others (2007).

The landscape of the Western Panhandle of Texas. (*A*) The short-grass prairie with a shallow, intermittent salt lake typical of the time before agriculture, (*B*) sorghum field, and (*C*) the view from the air (23 square kilometers). Photograph A by Wyman Meinzer, U.S. Fish and Wildlife Service, Muleshoe National Wildlife Refuge, 2008; photograph B from U.S. Department of Agriculture, Natural Resources Conservation Service, Texas, 2010; photograph C from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010.

Chapter 3—Changes in the Nation's Agriculture Over Time

How are Past and Future Changes in Agriculture Connected to Water Quality and Water Quantity?

Native American Indians began farming the North American continent as early as 5,000 BCE. The native people planted seed from the most productive wild plants, and with many years of this selective practice created crop varieties that were adapted to diverse environments from the cool northern Great Plains to the hot, dry Southwest. Their farming system was based on corn, beans, and squash, although various other crops (tobacco, sunflower, and potatoes) also were grown (Hurt, 2002).

Agriculture for European settlers began in the 1600s (fig. 3.1). Although they adopted corn into their agriculture, the settlers largely retained their traditional European farming practices in raising grains, apples, tobacco, and livestock. Little attention was given to crop rotation, fertilization, or proper tillage practices. During the latter part of the 1700s, agriculture expanded across the Appalachians and along the Gulf Coast. Commercial production included cotton exports and an expanding food market, which thrived along rivers where farmers could easily ship produce to market. In the southwestern areas of the country, Spanish colonists established agriculture using irrigation for cultivation of grapes, fruits, vegetables, and grains, and also grazed cattle (Hurt, 2002).

The Louisiana Purchase and the "Indian Removal Act" (early 1800s) rapidly extended westward settlement, opening new opportunities for agricultural and economic development (fig. 3.2). Land with sufficient rainfall was used for crops; arid grasslands and scrublands were used for grazing. New technology, such as subsurface drains (tiles) and Government support for the conversion of wetlands to farmland, opened vast expanses of fertile land, particularly in the Midwest (fig. 3.3) (Dahl and Allord, 1996). The "Homestead Act" further encouraged westward development of agriculture by giving out free land on the (arid) Great Plains. By the mid-1800s, successful agriculture developed in the Northwest, such as potatoes in Idaho and fruit and vegetables in Oregon. By 1910, irrigation allowed large-scale fruit and vegetable agriculture in the Central and Imperial Valleys of California, which became some of the most productive agricultural land in the world.

In the early 1900s, the Nation realized that if agricultural production was to be successful on the Great Plains and throughout the West, then some of the land would have to be irrigated. The National Reclamation Act of 1902 (Public Law 57-161; 32 Stat. 388) provided funding for irrigation projects designed to "reclaim" arid lands in 17 Western States. Initially, five projects were constructed in 1903: Milk River in Montana, Truckee River in Nevada, North Platte River in Nebraska and Wyoming, Salt River in Arizona, and the Gunnison River in Colorado. Later projects included Hoover Dam in Nevada and Grand Coulee Dam in Washington. More than 180 irrigation projects resulted from the Reclamation Act, which brought water to 40,000 km^2 of farmland and made large-scale agriculture possible in much of the West. Many of these projects have had adverse environmental impacts since their construction (Bureau of Reclamation, 2011).

The early 1920s brought a rapid expansion of agriculture largely due to advances in mechanization with new tractors and combines. Availability of trucks allowed for the harvest to be moved more easily. Overproduction led to agricultural surpluses and a collapse of agricultural prices, and the beginning of an agricultural depression that lasted almost two decades. The removal of native plant cover and overproduction, combined with severe droughts and extraordinary heat in the 1930s, eventually led to the "Dust Bowl" in widespread areas of the Great Plains. The topsoil on the barren fields literally blew away with strong prairie winds. Without topsoil, the land was useless for growing crops or grazing. The Dust Bowl was one of the defining moments in the Nation's agriculture. In response, Congress passed laws to facilitate soil conservation and assist agricultural development. The Dust Bowl, together with the Great Depression, left the farm economy in turmoil and led to greater Government involvement. Since then, conservation has been intertwined with agricultural production.

During the last half of the 20th century, the extent of agricultural land did not substantially change (compare fig. 3.2 for 1949 and 2002), although agricultural activity became more intensive on much of the existing farmland. Mechanization of farming helped reduce the agricultural labor force by 50 percent between 1950 and 1970 (Conkin, 2008). (See "Agriculture in the "Delta" region of Mississippi," in Chapter 6, as an example of the changes in farm labor.) By the 1970s, the USDA pushed the idea of "get big or get out" and planting "fence row to fence row" to encourage full production of farms to feed the Nation and increase exports (Anderson and Jansen, 2010). Small farms were consolidated (fig. 3.4), and the major gains in productivity occurred on large farms.

EXPLANATION

- Crop (landscape) and animal changes
- Biological and chemical changes
- Regulatory and societal changes
- Mechanical changes

Note:
USDA: U. S. Department of Agriculture
EPA: U. S. Environmental Protection Agency
FDA: U. S. Food and Drug Administration

Year

- 1500 Corn, cotton, potatoes and tobacco domesticated by Indians in South and North America
- 1600 Early 1600s European colonists learn agricultural practices from Indians
- 1700 National landscape undergoes large scale deforestation and drainage of wetlands (1700s to early 1900s)
- 1830 First steam engine locomotive in the United States by Peter Cooper (New York)
- 1840 Growing use of factory-made agricultural machinery increased farmers' need for cash and encouraged commercial farming (1840s)
- 1850 Expansion of agriculture westward as Eastern farm soils become exhausted
- 1860 Growing market for factories producing bone and lime for agricultural supplements
- 1862 Formation of the U. S. Department of Agriculture and the passage of the Morrill Act, which established land for agricultural colleges
- 1869 Completion of Transcontinental Railroad
- 1900 Information on plant genetics, proposed by Gregor Mendel, is used to accelerate plant breeding
- 1903 United States Reclamation Service (precursor to the Bureau of Reclamation) was established and aided in the development of many large agricultural irrigation and drainage projects
- 1910 Passage of the First National Pesticide Act regulated the composition of pesticides sold to consumers
- 1921 Manufacturing of synthetic ammonia (Haber-Bosch Process) begins in the United States
- 1930 Beginning of the series of droughts coined the "Dust Bowl"
- 1932 Switch from open-pollinated towards hybrid corn
- 1933 Agricultural Adjustment Act of 1933 established the Commodity Credit Corporation to stabilize, support and protect farm prices and supplies
- 1935 Passage of the Soil Conservation and Domestic Allotment Act
- 1939 World War II helps shift farming from animal to mechanical power
- 1941 Passage of the Rural Electrification Administration Act funds to aid establishment of reliable, affordable electricity in rural areas
- 1947 Invention of center-pivot irrigation by Frank Zybach (Nebraska)
- 1950 Average farm size increases and there are fewer farms (1950s-1970s)
- 1954 Passage of Agricultural Act of 1954 authorized a Commodity Credit Corporation reserve for foreign and domestic relief
- 1956 Passage of Agricultural Act of 1956 established the Soil Bank Program to reduce crop surpluses by taking cropland most subject to erosion out of production for up to 10 years
- 1960 97 percent of farms have electricity
- 1960 Confined animal feeding operations (CAFOs) are used for livestock
- 1961 Green Revolution, promoting high yield agriculture from improved crop hybrids and fertilizer supplements is led by Norman Borlaug
- 1962 Publication of Rachel Carson's *Silent Spring* brings public attention to the environmental effects of pesticides
- 1968 Mechanization of farming helps reduce the agricultural labor force by one-half (1950-1970)
- 1970 Formation of the Environmental Protection Agency, a consolidation of several federal agencies previously dealing with environmental issues
- 1970 USDA pushes the idea of "plant hedgerow to hedgerow" and "get big or get out" encouraging full production of farm acreage
- 1971 Passage of the Clean Water Act (CWA) to restore and maintain the integrity of the Nation's waterways through prevention of point and non-point pollution sources
- 1972 Passage of Federal Environmental Pesticide Control Act classified pesticides as "general" or "restricted" use and required certification for restricted use
- 1975 Glyphosate (herbicide) is registered for commercial use
- 1979 U. S. Supreme Court rules that genetically-modified life forms can be patented
- 1979 Advances in genetics (recombinant gene technology) allows for mass production of synthetic hormones for additives in animal feed
- 1980 Improvements to no-till planting equipment increases the number of farmers converting to conservation tillage
- 1980 Specialization and intensification of farming leads to increased numbers of confined animal feeding operations (CAFOs)
- 1982 Rural Clean Water Program establishes federally sponsored program to address agricultural non-point source pollution
- 1985 Formation of the Conservation Reserve Program (CRP) volunteer program providing cost sharing for removing environmentally sensitive land from agricultural production (1985 Farm Bill)
- 1989 EPA finds 74 different pesticides in the groundwater of 38 states
- 1990 Increases in numbers of organic farms (1990s)
- 1990 Formation of the Wetland Reserve Program (WRP) establishes long-term (30-year to permanent) contracts with landowners conserving wetlands (1990 Farm Bill)
- 1992 Food and Drug Administration declares that genetically-modified foods are "not inherently dangerous" and do not require special regulation
- 1996 Passage of Food Quality Protection Act (FQPA) fundamentally changes the way EPA regulates pesticides, required a complete re-assessment of pesticide tolerances
- 1996 Formation of the Environmental Quality Incentives Program (EQIP) provides technical, financial, and educational assistance for a wide range of agri-environmental activities
- 1996 Widespread use of genetically engineered glyphosate-tolerant crops contribute to the rise in "no-till" tillage practices
- 1998 Passage of the Harmful Algal Bloom and Hypoxia Research and Control Act requires a plan for controlling hypoxia in the northern Gulf of Mexico
- 1999 Development of the Unified National Strategy for Animal Feeding Operations outlines plan using existing legal regulatory authority to reduce water quality and public health impacts from improperly managed animal wastes
- 2001 *Bacillus thuringiensis* (*Bt*) plant-incorporated biopesticides (insecticide) are registered for use by EPA
- 2002 Implementation of organic labeling system by the USDA
- 2002 Passage of the Farm Security and Rural Investment Act of 2002 creates a National Dairy Program, also significantly increases spending for conservation programs, creating the Conservation Security Program and the Grasslands Reserve Program
- 2005 Passage of the Energy Policy Act of 2005 supports increased use of biofuels
- 2008 Wind farms generate electricity in 31 states
- 2008 Crop agriculture is the largest producer of nitrous oxide (greenhouse gas), 70% of annual emissions (2008)
- 2010 Fifteen weeds have developed resistance to glyphosate (herbicide) in the United States (1996-2010)

Figure 3.1. Important events in the changing agriculture of the Nation that could be related to water quality and quantity (Grey and others, 2012). For further information on the history of agriculture in the United States, see U.S. Department of Agriculture, Agricultural Research Service (2008) and Spielmaker (2012).

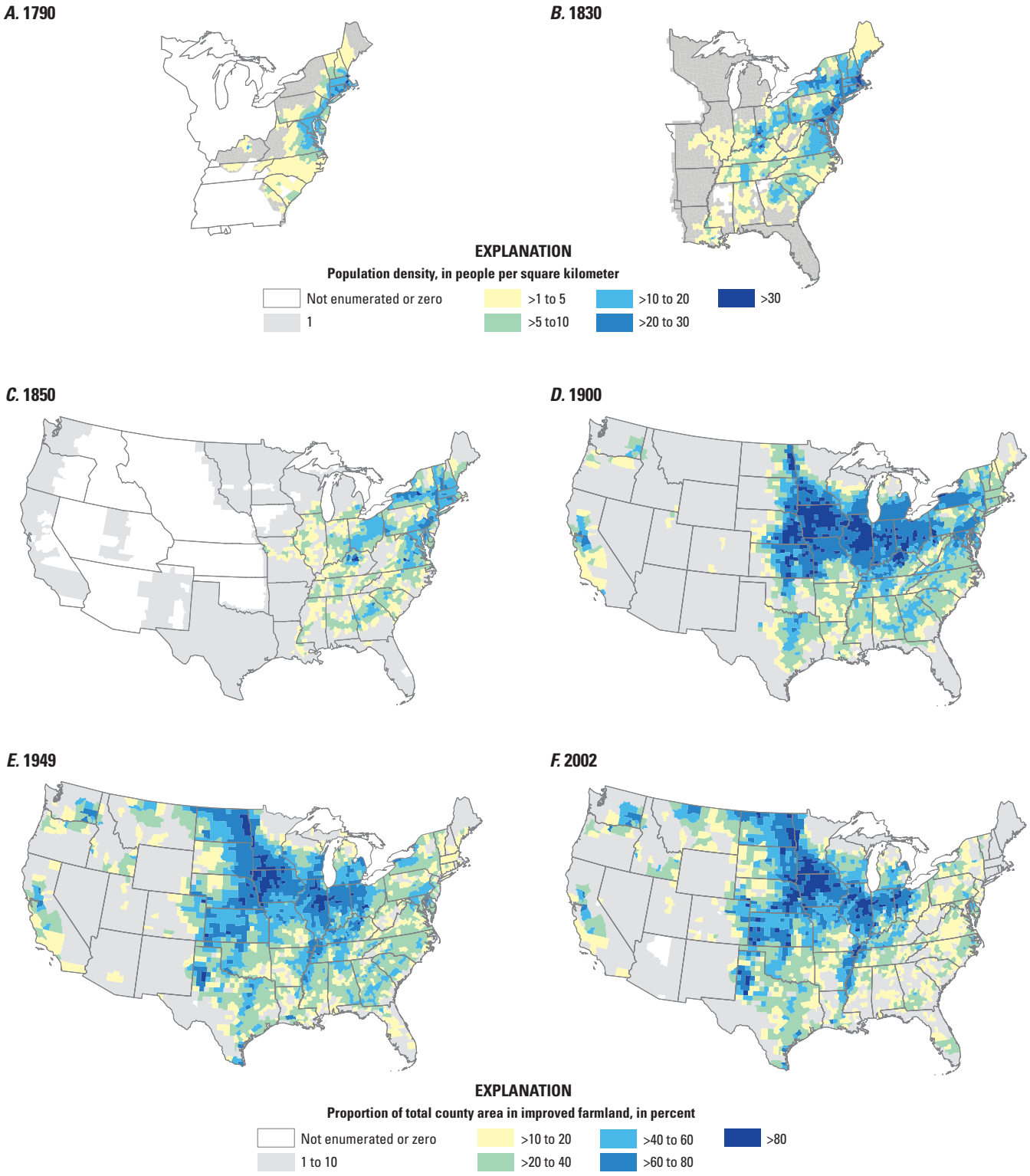


Figure 3.2. Expansion of agricultural lands in the United States over time. Population density is used as a surrogate for agricultural lands in (*A*) 1790 and (*B*) 1830. Data for actual agricultural lands are not available before 1850. Agricultural lands as a percentage of county area in (*C*) 1850, (*D*) 1900, (*E*) 1949, and (*F*) 2002 (Baker and Capel, 2011).

Figure 3.3. Agricultural land was expanded through drainage and irrigation. (*A*) Hand dug subsurface drains in Wisconsin, 1916; (*B*) steam engine digging surface drains in southern Minnesota, 1922 (see "Big Ditcher Quickly Turns Swamps Into Farms"); (*C*) construction of irrigation canals in Washington circa 1880; (*D*) construction of Grand Coulee Dam, Washington, 1941 (for hydroelectric power and irrigation). Photograph *A* courtesy of the University of Wisconsin Archives; photograph *B* by Paul E. Walline, courtesy of Michael A. Johnson; photograph *C* courtesy of the Yakima County Museum, Washington; and photograph *D* from Bureau of Land Management.

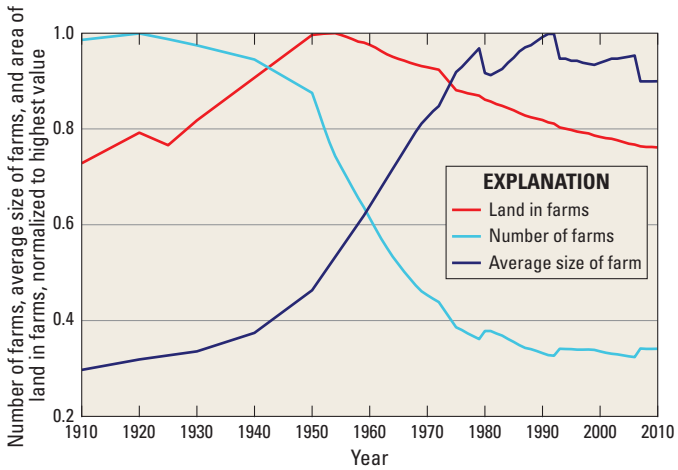


Figure 3.4. Changes in number of farms, average size of farms, and area of land in farms in the United States from 1910 to 2010. Data are presented as normalized values, where the maximum value is equal to 1. Maximum land area in farms equals 488 million hectares (1952–54). Maximum number of farms equals 6 million (1910–50). Maximum average size of farm equals 188 hectares (1991–92). Intensification of agriculture after the 1950s led to fewer and larger farms. Land area in farms has slightly decreased, partly due to improvements in agricultural technologies, which has led to higher yields (Grey and others, 2012).

"Big Ditcher Quickly Turns Swamps Into Farms"

From *Popular Mechanics*, March 1922 (Windsor, 1922):

> "The immense scale on which reclamation of swamp lands in Freeborn and Mower counties, in southern Minnesota, is carried on, means that, within a short time, great tracts will be added to the productive lands of the state. Work is being concentrated on a tract of 15,000 acres, which has been subdivided into eight units of from 1,000 to 3,000 acres each. Each unit is in turn subdivided into farms, most of which contain either 80 or 120 acres.
>
> "The chief agent in this reclamation work is a wheel excavator of unusual design and capacity. This 76-ton ditching machine crawls steadily ahead like some great land monster, and as it advances it digs a ditch that is 12 ft. wide on top and 7 ft. deep. A huge revolving wheel scoops out the dirt and a conveyor belt is kept busy carrying it out 20 ft. to the side where it builds up a spoil bank. Working steadily with a crew of five men, the machine, which is 65 ft. long overall and has a 110 hp engine can drive a ditch ahead at the rate of about a quarter mile in a working day.
>
> "After the tile drains are laid, the sides of the ditches are thrown in to cover the tile. This work is done with a grading machine drawn by a tractor. Submains and laterals are added after the main drains have been laid. Then follows the building of bridges, roads, and groups of farm buildings. Work is done on a big scale, dozens of teams, workmen, and tractors being employed. Artesian wells are driven, fences built, and in short time the marshlands have been changed into highly productive farms."

The increased efficiency of mechanized farms, combined with the use of fertilizers and advances in crop genetics, allowed farmers to produce large excesses of food, which required new markets (cattle feeding operations and international exports). Some agricultural land was removed from production for conservation purposes, to reduce excess production, and allow for expansion of urban areas, resulting in nearly 15 percent decrease in domestic cropland from 1949 to 2007 (1.93–1.65 million km^2) (Nickerson and others, 2011).

Crop and Animal Changes.—Crops primarily provide food for people, feed for animals, fibers for clothing, and biomass for fuel. Early subsistence farming gave way to commercial farms that produced for distant markets. Although agriculture in the United States had always been diverse, throughout much of American history the major crops have been corn (predominantly for animal feed), wheat (for human food), oats (for horse feed), cotton (for fiber), and more recently soybean (for feed and food) (fig. 3.5). The soybean was first adopted as a commercial crop in the early 1930s and have become the second largest crop in the Nation. Before World War II, a variety of crops, including legumes like clover, were planted in rotation to replenish the soil nitrogen and avoid nutrient deficiency of the soil.

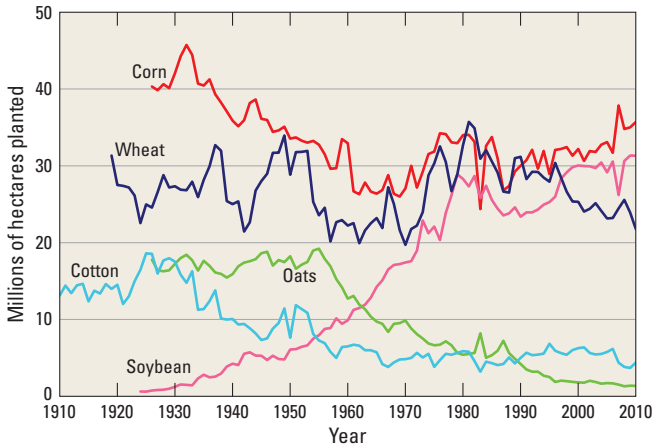


Figure 3.5. Changes in corn, soybean, wheat, oats, and cotton planted in the United States from 1910 to 2010 (Grey and others, 2012).

Technological advances in the 20th century changed the face of agriculture, leading to dramatic increases in crop yields starting in the 1930s (fig. 3.6, table 3.1). Hybrid varieties were first developed for corn and widely adopted after the Great Depression. Building upon the success of corn, hybrids for other crops were developed for the United States and the world during the 1950s and 1960s; these advances were often referred to as the "Green Revolution" (Borlaug, 1972). Compared to crops produced through open pollination, the hybrids gave increased yield and had attractive characteristics such as enhanced disease resistance or drought tolerance.

Beginning in the 1940s, the availability of synthetic nitrogen fertilizers and herbicides allowed for the intensification of crop agriculture. Table 3.1 shows corn as an example. Altogether, these advances dramatically increased crop yields (fig. 3.6) so that, starting in the mid-1950s, grain surpluses were common. Beginning in the mid-1990s, genetically modified crops that were embedded with herbicide resistance, insecticidal properties, or other desirable characteristics were introduced. The majority of the corn, soybean, cotton, and sugar beet crops that are planted today are genetically modified varieties (see "Genetically Modified Crops").

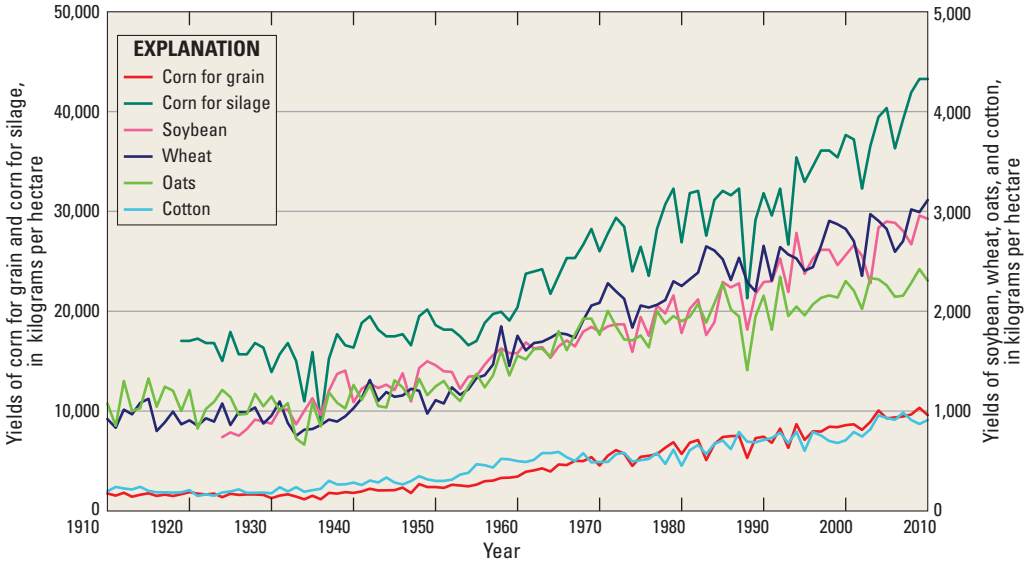


Figure 3.6. Average yields of corn for grain and corn for silage, soybean, wheat, oats, and cotton in the United States from 1910 to 2010 (Grey and others, 2012).

Table 3.1. Changes in corn production in the United States from 1800s to 2009.

[Data source: Grey and others (2012). **Abbreviations:** $, dollars; kg, kilogram; ft, foot; in., inch; %, percent; –, not applicable]

	Circa 1800	Circa 1850	Circa 1900	1950	2000	2009
Planted area: all corn (hectares)	–	–	40,300,000	33,600,000	32,200,000	35,900,000
Harvested area: corn for grain (hectares)	–	12,100,000	38,400,000	29,300,000	29,300,000	32,800,000
Harvested area: corn for silage (hectares)	–	–	1,440,000	1,990,000	2,460,000	2,270,000
Production: corn for grain (kg)	–	18,600,000,000	67,600,000,000	70,200,000,000	251,000,000,000	334,000,000,000
Production: corn for grain ($)	–	–	–	4,222,366,000	18,499,002,000	48,588,665,000
Production: corn for silage (metric tons)	–	–	24,400,000	37,200,000	92,700,000	98,200,000
Yield: corn for grain (kg/hectare)	–	1,525	1,764	2,398	8,592	10,199
Yield: silage (metric ton/hectare)	–	–	17	19	38	43
Seed	Open pollination	Open pollination	Open pollination (hybrids emerging)	Hybrid	Genetically modified (29%), herbicide (glyphosate) tolerant (5%), insect (*Bt*) resistant (18%)	Genetically modified (91%), herbicide (glyphosate) tolerant (82%), insect (*Bt*) resistant (69%)
Plant spacing	Mounds 3–6 ft (spacing in rows or scattered)	40–44 in. rows (horse width)	20–40 in. (experimental new widths)	36–42 in. (adjustable to tractor width)	30 in. or less	20 in.
Rotation	Corn, beans, squash	Corn, wheat/rye/oats/barley/turnips, clover, fallow (4–5 year rotation)	Corn, legume (pea, clover, alfalfa) (variable year rotation)	Corn, oats, soybean, alfalfa (4–5 year rotation)	Corn, soybean/wheat (2–3 year rotation)	Corn, soybean/wheat (2–3 year rotation)
Soil tillage	Moldboard plow (horse power)	Steel plow (horse power)	Steel plow (tractor power)	Conservation tillage with herbicides	Conservation tillage with herbicides	Conservation tillage with herbicides
Nitrogen fertilizer: source	Manure, fish remains	Guano, manure	Chemical (from atmospheric nitrogen through Haber-Bosch process, manure)	Chemical, manure	Chemical, manure	Chemical, manure
Nitrogen average U.S. application rate–selected states (kg/hectare)	–	–	–	65	152	140
Phosphorus fertilizer: source	Mineralized bone material, manure	Phosphate rock, coprolites (fossilized animal fecal matter), manure	Phosphate rock, manure	Phosphate rock, manure	Phosphate rock, manure	Phosphate rock, manure
Phosphorus average U.S. application rate–selected States (kg/hectare)	–	–	–	46	64	60

Genetically Modified Crops

Conventional breeding methods involve the hybridization of crops or animals to enhance or combine desirable traits. Such techniques have been used for thousands of years to improve crop yield and resilience. In recent decades, molecular genetics technology—involving such methods as gene cloning, protein engineering, and DNA-strand insertion—has been used to create genetically modified (GM) crops in which a broad range of desirable traits have been enhanced or introduced. By far, the most widely used applications of GM technology, however, have involved the engineering of crops to be resistant to specific herbicides, to impart insecticidal properties to the plant itself, or both, called "stacked traits" (National Research Council, 2010). Other aspects of genetic engineering research focus on methods to increase crop yields, biomass production, or growth rates; increase tolerance to stress (from drought, cold, or salinity); delay ripening; increase oil content; or produce chemical substances for use as pharmaceuticals.

Although GM crops have been grown in a wide variety of locations around the world since 1996, the United States has been the world leader in implementing these technologies (Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability, National Research Council, 2010). GM tomatoes were introduced in 1994 as the first commercial GM crop. At present, GM cotton, soybean, and corn—first introduced in 1995, 1996, and 1997, respectively—are the most widely planted GM crops in the United States. GM versions of these crops have largely replaced most of the conventional varieties throughout the country (fig. 3.7). GM canola, papaya, sugar beets, and alfalfa (commercialized in 1995, 1999, 2005, and 2011, respectively) also have been introduced to American agriculture.

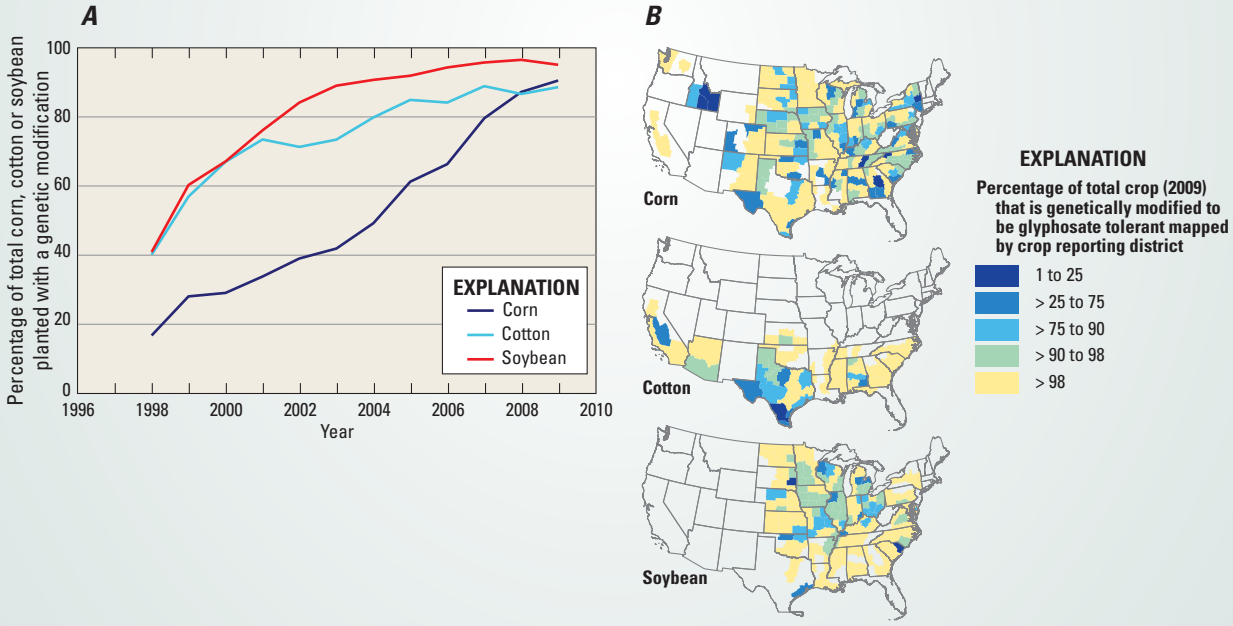


Figure 3.7. (*A*) Genetically modified corn, cotton, and soybean harvested in United States from 1996 to 2010. (*B*) Percentage of total corn, cotton, and soybean (2009) that is genetically modified to be glyphosate tolerant mapped by crop reporting district (Grey and others, 2012).

Herbicide-tolerant GM crops are designed to survive treatment with a single, broad-spectrum herbicide such as glyphosate, glufosinate, or imazethapyr. As of 2009, glyphosate-resistant GM crops comprised about 85, 82, and 89 percent of all GM cotton, corn, and soybean, respectively, in the United States (Grey and others, 2012). These and other herbicide-tolerant GM crops were produced to save the grower time and money, narrow the variety of conventional herbicides used, and reduce soil erosion by diminishing or eliminating the need to till the soil. Glyphosate was first registered for use in the United States in 1974, and the first glyphosate-resistant crop was introduced in 1996 (Monsanto Company, 2013). Glyphosate is less persistent in the environment than many conventional herbicides.

As a result of the widespread use of glyphosate on both GM and non-GM crops, several weed species have developed resistance to the herbicide in the United States and around the world. In 1998, the first glyphosate-resistant weed was reported in the United States. As of 2015, 35 weed species are known to be resistant to the herbicide (Heap, 2016). In response to this important challenge, GM crops resistant to herbicides other than glyphosate have been introduced. Concerns have arisen about the ability of glyphosate to chelate with some metals (manganese, zinc), which can result in micronutrient deficiencies in glyphosate-resistant crops. The cultivation of GM crops have been associated with reduced abundance and biodiversity of several invertebrate species (Bohan and others, 2005).

Insect-resistant GM crops have a gene from the naturally occurring soil bacterium *Bacillus thuringiensis* (B_t) inserted into their DNA. The B_t bacterium produces a protein that is activated in the gut of susceptible insects to produce a toxin specific to those insects. In B_t crops, the ability to make this toxic protein has been transferred to the entire plant. Because the protein must be ingested to be activated, and is specific to the target insect, the protein is relatively non-toxic to mammals and other non-target organisms. The cultivation of insect-resistant GM crops offers the potential to save the grower time and money, and has led to reductions in the amount and variety of conventional insecticides used (see section, "Changes in Conventional Pesticide Use Due to Development of Genetically Modified Crops," Chapter 8). However, because of the continuous exposure of insects to the B_t toxin, the U.S. Environmental Protection Agency (EPA) mandated that non-B_t crops be planted among or adjacent to areas planted with B_t crops, in order to avoid (or slow) the development of B_t resistance among these insect species (National Research Council, 2010). It has been observed that non-B_t crops planted near high-density B_t cropped areas receive the same benefits (higher yields) as do the B_t crops, owing to region-wide reductions in the populations of the target insects (Hutchison and others, 2010).

Resistance of the cotton bollworm to B_t cotton between 2003 and 2006 was documented in Mississippi and Arkansas (Tabashnik and others, 2008), but current numbers of B_t-resistant insects are not well documented. Some environmental concerns have become evident from the cultivation of B_t crops, including harm to beneficial insects, gene transfer to native plant species, and allergenic effects of the toxin. B_t crop residue has been reported in streams near agriculture fields, but the environmental effects of this phenomenon remain unclear (Rosi-Marshall and others, 2007).

Animals have always been an important part of the Nation's agriculture. Through much of American history, most farms raised animals for family food, for market, and to help with farm work. Horses were used to pull the machinery for tilling, planting, and harvesting. By the 1950s, horses had largely been replaced by self-propelled tractors (Gardner, 2002). This led to a decrease in the numbers of work horses, and thus a major decrease in the production of oats (fig. 3.5). Livestock breeding developed more productive animals. Average milk production, per cow, increased 4.4 times between 1944 and 2007 (Capper and others, 2009).

The surpluses of grain gave rise to the development of cattle feeding operations in the 1960s, enabling the increased production of relatively inexpensive meat (Ebeling, 1979). Electricity allowed for mechanization of beef and dairy operations as well as the heating and cooling of enclosed animal facilities, which changed the production of hogs, poultry, and dairy cattle (Conkin, 2008). The use of antimicrobials allowed the expansion of feeding operations to hogs, chickens, and turkeys by controlling the spread of disease under the concentrated conditions in which the animals were kept (Khachatourians, 1998; U.S. Environmental Protection Agency, 2012c). As a result, animal agriculture moved from being highly dispersed across the landscape to more concentrated areas (fig. 2.1*B*).

Mechanical Changes.—The Nation's agriculture started largely as subsistence farming with horse-drawn, single-row plows. The mechanical inventions of the past two centuries have transformed agriculture into large-scale, commercial ventures with self-propelled, air-conditioned, satellite-positioned tractors that can plant up to 24 rows of crops at one time. In the early to mid-1800s, inventions like the iron plow, interchangeable parts, mechanical harvesters, and the cotton gin transformed agriculture. Railroads brought agriculture products to market. Near the end of the 19th century, the invention of steam-powered machines opened the way for drainage and irrigation projects throughout the Midwest and West. The subsequent development of internal combustion engine technology led to the invention self-propelled tractors and harvesters (White, 2008).

The period between 1930 and 1970 saw dramatic growth in the Nation's agriculture through a combination of advances in mechanization, electrification, chemistry, and genetics (Conkin, 2008). Horses were largely replaced by tractors (White, 2008). Combines were introduced in 1953, and by 1970, almost all corn in the Midwest was harvested and processed in the field. Electrification of rural areas was largely completed (97 percent of all farms) by the mid-1950s. Electrical power, together with the invention of center-pivot irrigation, facilitated the rapid expansion of irrigation.

In the past few decades, changes in farm machinery have largely been directed toward making existing approaches more efficient and precise. New machines were developed to allow efficient no-till planting. Computer and satellite technology has been incorporated into farm tractors for precision agriculture so that crop yields can be measured continuously across the field.

Biological and Chemical Changes.—Nutrients are the elemental building blocks upon which crops depend for successful growth. Once the nutrients were depleted from the soil, crop yields decreased. For centuries, nutrient requirements were fulfilled through crop rotations that included fallow years and, to a lesser extent, through the application of manure. In the 19th century, the major crop nutrients were identified as phosphorus, potassium, and nitrogen. Phosphorus was available as a natural mineral, whereas potassium was available from processed wood ashes or from other natural minerals. By the 1880s, both were marketed to farmers to increase crop yields. Nitrogen was the nutrient that was not readily available until 1913, when ammonia was first synthesized from atmospheric nitrogen and methane using the Haber-Bosch process (Galloway and Cowling, 2002). It was not until the 1940s, however, that nitrogen fertilizer (in the form of ammonia nitrate) became widely available for agriculture. Use of the chemical nitrogen fertilizer was quickly accepted, and steadily increased for decades (fig. 3.8). This led to increased crop yields (fig. 3.6, table 3.1). The ability to add all three major nutrients to soil on an annual basis allowed for the intensification of crop agriculture during the following decades.

In addition to fertilization, crops are protected from weeds, insects, fungi, and other unwanted organisms. Traditionally, crop rotations and cultivation were used to control weeds in agricultural fields. This changed with the development of synthetic chemical herbicides. In the 1940s 2,4-D and 2,4,5-T were introduced as the first herbicides. Early success of these herbicides led to the development of other chemical classes of herbicides, and an increasing dependence on herbicides over the following decades (fig. 3.8). As a result, 242,000 metric tons of herbicides (and plant growth regulators) were used in crop agriculture in 2009; 61 different herbicides were used in quantities of greater than 100 megagrams per year (Mg/yr; Grey and others, 2012). The widespread use of herbicides eliminated the need for routine cultivation of many crops. However, unwanted plants can develop resistance to herbicides, a phenomenon that has required the ongoing development and use of new herbicides to control the growth of weeds that develop such tolerance.

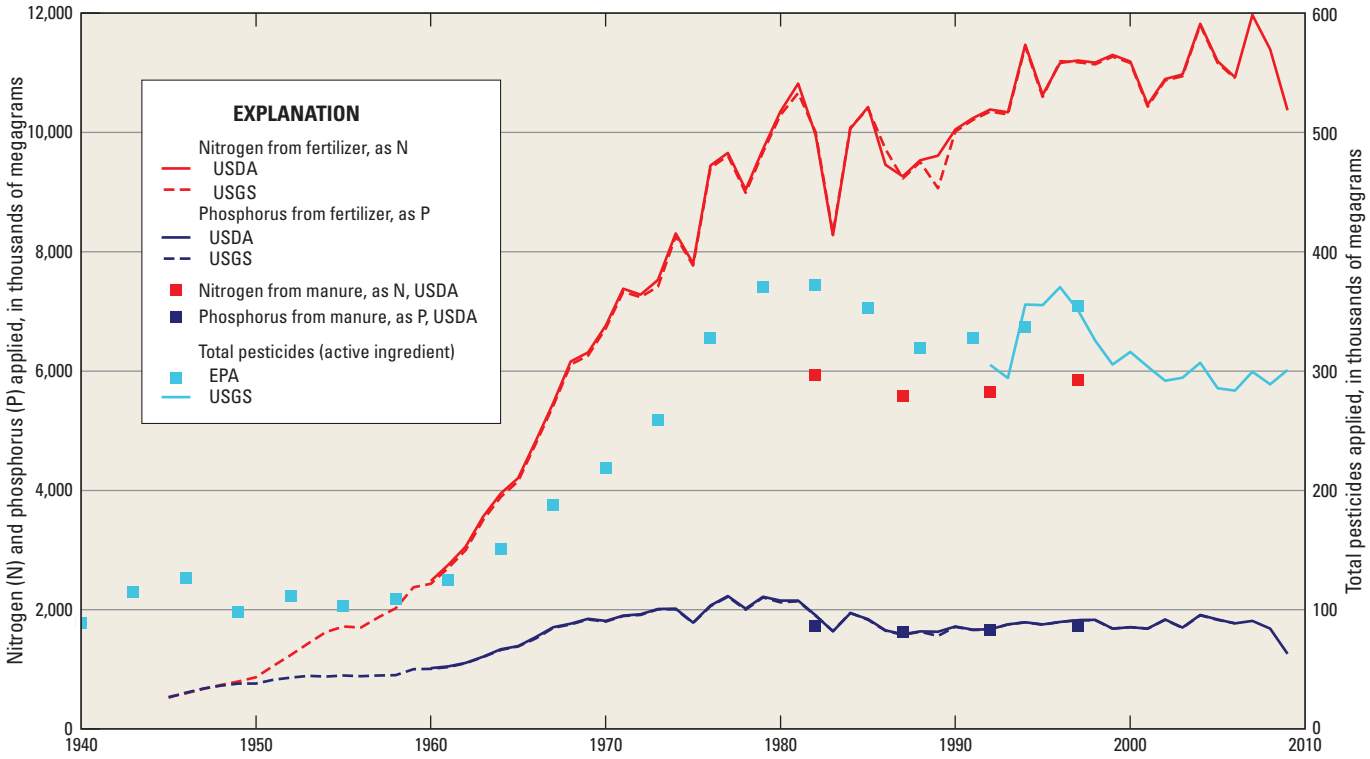


Figure 3.8. National applications of nitrogen, phosphorus, and total pesticides in crop agriculture in the United States from 1940 to 2010 (Grey and others, 2012). EPA, U.S. Environmental Protection Agency; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey.

In the 1970s, glyphosate was introduced as a broad-spectrum herbicide that could control almost all green plants. Through the use of genetic engineering, tolerance to glyphosate was incorporated into the biochemistry of crops (see "Genetically Modified Crops"). Glyphosate is the most extensively used pesticide in the United States (Grube and others, 2011). In recent years, many crop varieties have been genetically modified to incorporate multiple traits, including tolerance to more than one herbicide.

With the rise of intensified agriculture, much of farming relies on chemicals for controlling crop damage from unwanted insects. In the 19th and early 20th centuries, toxic metals (especially lead, arsenic, and mercury) were used to a limited extent for this purpose. After World War II, synthetic insecticides, such as the organochlorines (for example, DDT) and organophosphates (for example, parathion), were introduced and widely accepted. In the subsequent decades, a variety of other insecticides were developed and used in both crop and animal agriculture (fig. 3.8). By the early 1960s, it was discovered that DDT accumulated in animal tissues, causing a variety of health problems, including the thinning of eggshells in bald eagles and other predatory birds (Carson, 1962). This finding eventually led to a ban on DDT use in 1972, along with increased public awareness of the environmental impacts of synthetic insecticides and the need to develop safer, less persistent ones. In 2009, 17,400 metric tons of insecticides were being used in the Nation's crop agriculture; 26 of these compounds were used in quantities of greater 100 metric tons per year (Grey and others, 2012). Recombinant DNA technology allowed agricultural crops to be genetically engineered to produce a naturally occurring insecticidal toxin from the soil bacterium *Bacillus thuringiensis* (B_t), making the entire plant toxic to corn borers, budworms, bollworms, and other target insects (see "Genetically Modified Crops").

Many of the diseases that damage crops are caused by fungi and yeasts (for example, mold, rust, scale, blight, scab, and smut). These diseases have been controlled through the development and use of fungicides and, more recently, some genetically modified crops (for example, papaya). Sulfur has been used as a fungicide for many decades. In the past few decades, many new synthetic chemical fungicides have been developed and are now used widely. In general, these fungicides are disease-specific and expensive, so they generally are used in response to specific outbreaks of disease, rather than on the routine basis that is commonly used for herbicides and nutrients. In 2009, 47,500 metric tons of fungicides were used; 26 were used in quantities of greater than 100 metric tons per year (Grey and others, 2012).

Animal agriculture also has seen an increase in chemical use over the past several decades, although to a much lesser extent than for crops. Insecticides are used to control ticks and flies on cows and sheep. After World War II, penicillin and other antimicrobial drugs were used to reduce chronic illnesses in livestock—a concern that became increasingly problematic with the development of concentrated animal feeding operations (CAFO; U.S. Environmental Protection Agency, 2012c). Low ("sub-therapeutic") levels of antimicrobials and antiparasitics were used to improve growth and feed-use efficiency. As a result, since the 1980s, antimicrobials have commonly been added on a regular basis to feed for poultry and hogs and, to lesser extent, to feed for beef cattle (Khachatourians, 1998; Love and others, 2011). In 2009, there were 13,000 metric tons of antimicrobials used in animal agriculture, almost 4 times the amount used for people (U.S. Food and Drug Administration, 2010; Chai, 2010). As with weeds, the organisms that antimicrobials were designed to control can develop resistance to the compounds over time, reducing or eventually eliminating the effectiveness of the compounds in controlling the target species. As a result, the widespread use of antibiotics has caused concerns about the possibility that this practice may be reducing the overall effectiveness of antimicrobials in controlling disease in humans, as well as in livestock (Khachatourians, 1998; American Academy of Microbiology, 2009; Landers and others, 2012). In addition to antimicrobials, hormones also have been found to promote animal growth and increase meat and milk production. First introduced in 1951, bovine somatotropin (bST), also called bovine growth hormone (rBGH), is now widely administered to dairy cattle (Conkin, 2008; U.S. Food and Drug Administration, 2011). Hormones also were found to increase meat and milk production in cows. Other natural and synthetic growth hormones, such as testosterone, trenbolone acetate, and melengestrol acetate, are used to promote the rate of weight gain and (or) improve feed efficiency in beef cattle (U.S. Food and Drug Administration, 2002).

Changes Off the Farm.—Society and government have been strong influences on the direction and changes in agriculture throughout American history. The Federal Government has promoted agriculture. It provided public lands at little to no cost to settlers during various periods. By 1862, the USDA was created and land grant colleges were established for agricultural research. In 1902, the U.S. Reclamation Service (precursor to the Bureau of Reclamation) was established and aided in the development of many large agricultural irrigation and drainage projects. Establishment of transportation infrastructure (roads and railroads) as well as monetary assistance (credit and subsidies) also contributed to agricultural advancement.

Since the 1930s, the Government has used farm subsidies as incentives for soil and water conservation and environmental protection. The Great Depression and the Dust Bowl, which left the farm economy in turmoil, led to greater Government involvement. The Agricultural Adjustment Act of 1933 (Public Law 73-10; 48 Stat. 31) provided Federal Government subsidies to remove agricultural land from production to stabilize crop prices and reduce soil erosion (see "U.S. Department of Agriculture Conservation Programs"). This was followed by the Soil Conservation and Domestic Allotment Act (1935; Public Law 74-461; 49 Stat. 1148), which established the Soil Conservation Service to develop and teach erosion-control techniques. Setting aside land for erosion control spiked again after the mid-1950s with incentives to convert land back toward a more natural state as a result of enactment of the Agricultural Act of 1956 (Public Law 84-540; 70 Stat. 188) (establishing the Soil Bank Program) and the Food and Agricultural Act of 1962 (Public Law 87-703) (establishing the Resource Conservation and Development Program). The Farm Security and Rural Investment Act of 1985 sought to protect vulnerable lands such as highly erodible areas and wetlands through the Conservation Reserve Program. The 2002 Farm Bill substantially increased spending for conservation programs, creating the new Conservation Security Program and the Grasslands Reserve Program.

The Federal Government also has been active in protecting human health. The Pure Food and Drugs Act of 1906 (Public Law 59-384; 34 Stat. 768) required Federal inspection of meat products and led to the creation of the Food and Drug Administration (FDA). The first national pesticide act (Federal Insecticide Act of 1910; Public Law 61-152; 36 Stat. 331), originally promulgated to ensure the quality of commercial insecticides, was modified in the Federal Insecticide, Fungicide, and Rodenticide Act of 1947 (FIFRA) to protect human and environmental health. With the 1962 publication of Rachel Carson's "Silent Spring," environmental concerns on the use of agricultural chemicals were heightened when DDT was linked to the declining bald eagle populations

(Carson, 1962). As part of the Government response, the U.S. Environmental Protection Agency (EPA) was formed in 1970 and given the responsibility for FIFRA. With the increase in animal feeding operations, legislation including the Poultry Products Inspection Act (1957; Public Law 85-172), Food Additives Amendment (1958), and the Wholesome Meat Act (1967; Public Law 90-201) were enacted to protect public health in terms of meat and meat processing. More recently, the Food Quality Protection Act of 1996 (Public Law 104-170; 110 Stat. 1489) further mandated health-based standards for pesticides in food and provided incentives to create safer pesticides.

Changes in agriculture led to societal changes. During the 1950s to 1970s, the mechanization and consolidation of farms displaced many workers from farming to urban areas. By 2007, less than 2 percent of the American population worked on farms (Dimitri and others, 2005). Prior to this urban migration, much of the Nation's population were farmers or closely connected to agricultural communities, and held a diverse knowledge of agricultural life. By 2010, about 83 percent of the Nation's population lives in urban areas (Mackun and Wilson, 2011). Many urbanites have little to no contact with (or understand) agriculture. Often, Americans become aware of agricultural activities through the media, which in many cases focuses on the human and environmental health concerns. News about water-quality concerns from agricultural practices (such as those in Chesapeake Bay and the Gulf of Mexico), as well as the expansion of biofuels, continue to draw attention. Human-health concerns related to pesticides in foods, antimicrobials in meat and dairy products, and genetically modified crops in the food supply are perhaps even more widespread. These and other concerns have put public pressure on agriculture and have led to an increased demand for products from organic farms (see "Organic Agriculture").

Current and Future Challenges and Opportunities

Since World War II, there have been tremendous changes in almost every facet of agriculture, including the widespread use of self-propelled machinery, advances in plant and animal breeding, the development of new chemicals (fertilizers, pesticides, antimicrobials, and hormones) and genetically modified crops, and farm intensification. Advances in computer technology, such as the use of global positioning system (GPS)-guided precision agriculture, have improved planting accuracy and customized agrichemical applications. Public responses to potential adverse impacts on human and ecosystem health also have changed agriculture through regulations, conservation programs, and other government initiatives. Many of the current challenges and opportunities for agriculture are likely to continue into the foreseeable future—increased demand for its products; shortages of agricultural land and water, environmental impacts, and reliance on incremental solutions from new technologies, and sustainability.

Increased Demands for Agricultural Products.—A growing domestic and global population will drive increasing demands for agricultural products (food, feed, fiber, and fuel) and will present an enormous opportunity for agriculture. In 2012, the population of the United States was about 313 million and is projected to increase to 400 million by 2050 (Mackun and Wilson, 2011; U.S. Census Bureau, 2013). The world population is projected to increase from 6 billion to 9.1 billion people by 2050 (United Nations, 2009). This substantial increase in the American and global population will drive food demand and consumption. As a result, it has been estimated that global food production will need to increase by between 52 and 109 percent by 2050 (Tweeten and Thompson, 2008). Projected increases in population are anticipated to be most dramatic in developing nations, especially China and India, whose economies are experiencing some of the most rapid growth on the planet. The United States is the world's major provider of food aid to developing countries (60 percent) (Hanrahan and Canada, 2011). The increased demand for food, feed, fiber, and fuel will continue to challenge the Nation's agriculture, which operates on a continually diminishing area of cropland (fig. 3.4). The energy needs of human societies are vast and increasing. Because the use of traditional forms of energy (that is, oil, coal, natural gas, and hydroelectric power) involves a wide range of adverse environmental impacts from their development, distribution, and use—as well as the reliability of their supply—there has been considerable interest in the development of other, more environmentally benign and (or) reliable sources of energy since the early 1970s. Among these other sources of energy, several are intimately linked with agriculture. Biofuel, the product of the conversion of biomass to fuel sources, is one type of energy in which the United States has heavily invested (see "Biofuels"). In 2013, 1.4 percent of the Nation's energy consumption was met with biofuels (U.S. Energy Information Administration, 2014), but their importance may increase in future years. The trade-offs between producing biofuels, rather than food, on the finite amount of arable land and fresh water available are topics of societal and ethical concerns. In 2015, 44 percent of the Nation's corn harvest was used to produce biofuels (U.S. Department of Agriculture, Economic Research Service, 2016c).

The numbers and sizes of wind turbine "farms" are expanding in many agricultural areas, and competing for cropland. In the future, the same may be true for solar power facilities, should they be built on a large scale. Biogas facilities, which capture and burn reduced gases emanating from animal manures and other agricultural wastes, also may become more widespread in the future.

U.S. Department of Agriculture Conservation Programs

The Dust Bowl had a devastating effect on American agriculture in the 1930s, leading to the loss of topsoil from about 40 million hectares of land. This devastating event prompted the establishment of the first formal efforts by the Federal Government to promote soil conservation by the Nation's farmers—policies that continue to the present day. These voluntary programs have changed over the decades (fig. 3.9); they were designed to help farmers to conserve their land and to alleviate erosion, thus helping minimize or avoid the increased sediment loads and impaired water quality that erosion causes. The popularity of these programs increased and decreased over time, partially due to national and international demands on agriculture in the United States. Little or no land was included in conservation programs during and after World War II and during global wheat shortages in the 1980s. Brief descriptions of the principal programs in current use are presented below.

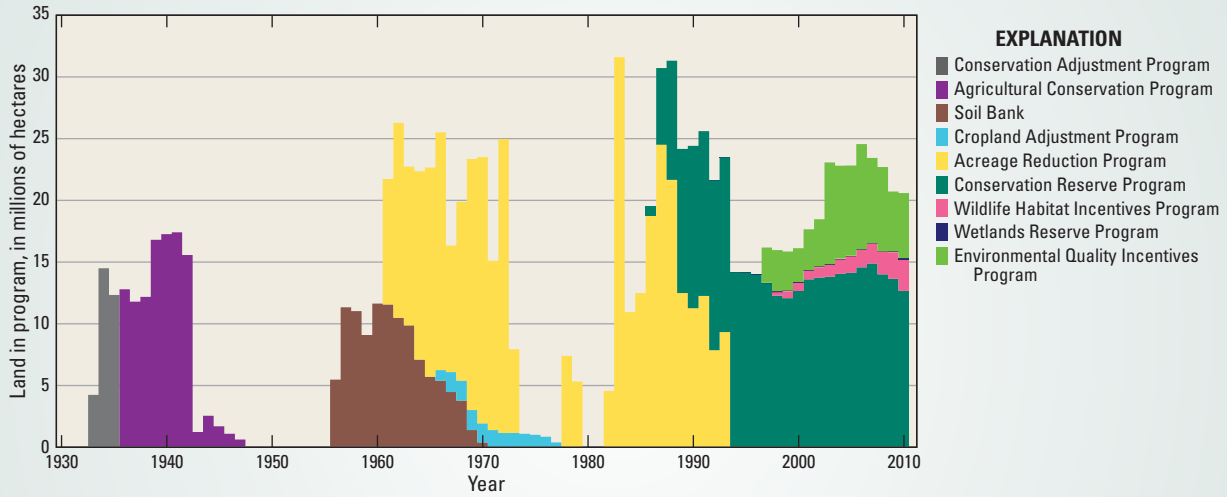


Figure 3.9. A number of U.S. Department of Agriculture programs have set aside land for conservation purposes over the past decades. Due to changes in the conservation programs, the total area has been highly variable (Grey and others, 2012; modified from Crosswhite and Sandretto, 1991).

The **Conservation Reserve Program** (CRP) was established in the 1985 Farm Bill as one of several approaches for reducing soil erosion (U.S. Department of Agriculture, Natural Resources Conservation Service, 2012b). The CRP provided incentives to remove highly erodible land from production. In this program, farmers signed a contract with the USDA agreeing to take the land out of production for 10 years. The original target was for about 18 million hectares. In 1993, 14.2 million hectares were enrolled, but decreased to 10.3 million hectares by 2014. Under the CRP, land is not simply taken out of production, but is stabilized and replenished by growing a vegetative cover such as grass, shrubs, or trees. The Federal Government provides incentives to farmers to enroll in this voluntary program by paying them for the loss of crop revenue while the land is out of production, and by sharing the costs associated with re-establishing native vegetation on the land. After the initial contracts expire, some are renewed and others are not. In order to continue to receive government support, farmers who return their land to agricultural production are required to meet rigorous standards.

The **Conservation Reserve Enhancement Program** (CREP) is a cooperative program in which the Federal Government partners with States, Indian Tribes, and local governments to provide long-term environmental protection for cropland, animal habitat, and pastureland (U.S. Department of Agriculture, Farm Service Agency, 2012). The area enrolled in this program is not included in figure 3.9. CREP, related to the CRP, is designed to protect and improve water quality by restoring and enhancing **riparian** habitat, estuaries, drainage ditches, and wetlands. The USDA and cooperating agencies provide technical assistance to help landowners plan and implement CREP practices, such as filter strips and forested buffers. The program provides incentives for farmers to enroll for periods of 10, 15, or 30 years. The landowners voluntarily plant or preserve their more environmentally sensitive lands—especially those close to water bodies—in perennial vegetation for the enrollment period and receive annual payments plus reimbursements for the cost of implementing these practices.

The **Wildlife Habitat Incentive Program** (WHIP) provides cost-share assistance to private landowners to help them implement improvements to wildlife habitat on agricultural lands. The Federal Government pays the farmer up to 75 percent of the implementation costs (U.S. Department of Agriculture, Natural Resources Conservation Service, 2009). WHIP was initially part of the 1996 Farm Bill, reauthorized in 2002, 2007, and 2008, but ended in 2014. WHIP agreements between the USDA and the landowner generally last for between 5 and 10 years. This program has proven to be a highly effective and widely accepted program across the country. By helping establish wildlife-habitat-improvement projects on any type of land, WHIP provides assistance to conservation-minded landowners whose land cannot meet the specific requirements of other USDA conservation programs.

The **Wetlands Reserve Program** (WRP) was established to protect, restore, and enhance the Nation's wetlands (U.S. Department of Agriculture, Natural Resources Conservation Service, 2012c). Conversion of wetlands to cropland was a common practice during the initial modification of the American landscape for agriculture. Since that time, however, wetlands have been found to represent some of the most biologically productive and useful ecosystems on Earth (U.S. Environmental Protection Agency, 2012b). Improved understanding of the critical importance of wetlands for protecting and enhancing water quality, for flood control, and as wildlife habitat, has motivated changes in wetland policy and management over the past several decades. As a reflection of this, the WRP was initiated by the 1985 Farm Bill and reauthorized or amended in every subsequent Farm Bill since then. In 1996, the maximum area of land that was authorized for enrollment in this program was 64,000 hectares. This was expanded in 2002. As of 2014, 1.1 million hectares of wetlands and related **uplands** were enrolled in the WRP across the Nation. The WRP was replaced by the Agricultural Conservation Easement Program in 2014.

The **Environmental Quality Incentives Program** (EQIP) is a voluntary program for farmers and ranchers who are willing to promote agricultural production and environmental quality (U.S. Department of Agriculture, 2012). It offers financial and technical assistance to participants who install structures or implement management practices on agricultural land (for either crops or livestock) that are environmentally sustainable. EQIP was approved in 1996 as an amendment to the 1985 Farm Bill and reauthorized in 2002 and 2008. As of 2014, about 7.9 million hectares of land receive conservation practices from the program.

Organic Agriculture

Organic foods are currently the fastest growing sector of the Nation's agricultural industry, with sales having increased from $1 billion in 1990 to $47 billion in 2016 (U.S. Department of Agriculture, National Institute of Food and Agriculture, 2018; U.S. Department of Agriculture, Economic Research Service, 2016a). Some of this growth in demand is likely derived from a growing public awareness of the human and environmental health concerns from agricultural chemicals. Growth in consumer demand for organic agricultural products (U.S. Department of Agriculture, Economic Research Service, 2010a) eventually led to (1) the enactment of the Organic Foods Production Act of 1990 (Public Law 101-624; 104 Stat. 3935) and its subsequent amendments, (2) the establishment of the National Organic Program by the USDA, and (3) the development of national standards for the production of foods certified as "organic" (U.S. Department of Agriculture, Economic Research Service, 2010a).

Organic agriculture is being practiced throughout the Nation on small areas of farmland (fig. 3.10). In 2011, 2.18 million hectares of agricultural land were certified as organic. This is 0.83 percent of total cropland and 0.49 percent of total pasture and grassland. Rates of adoption of organic methods vary considerably among different sectors of the agricultural industry, with relatively small areal percentages among the top field crops (0.26 percent for corn, 0.17 percent for soybean, and 0.63 percent for wheat), moderate rates among livestock (2.0 percent for layer hens and 2.8 percent for dairy cows), and the highest rates among fruits and vegetables (for example, 4.9 percent for apples, 12 percent for lettuce, and 14 percent for carrots) as of 2011 (U.S. Department of Agriculture, Economic Research Service, 2016b).

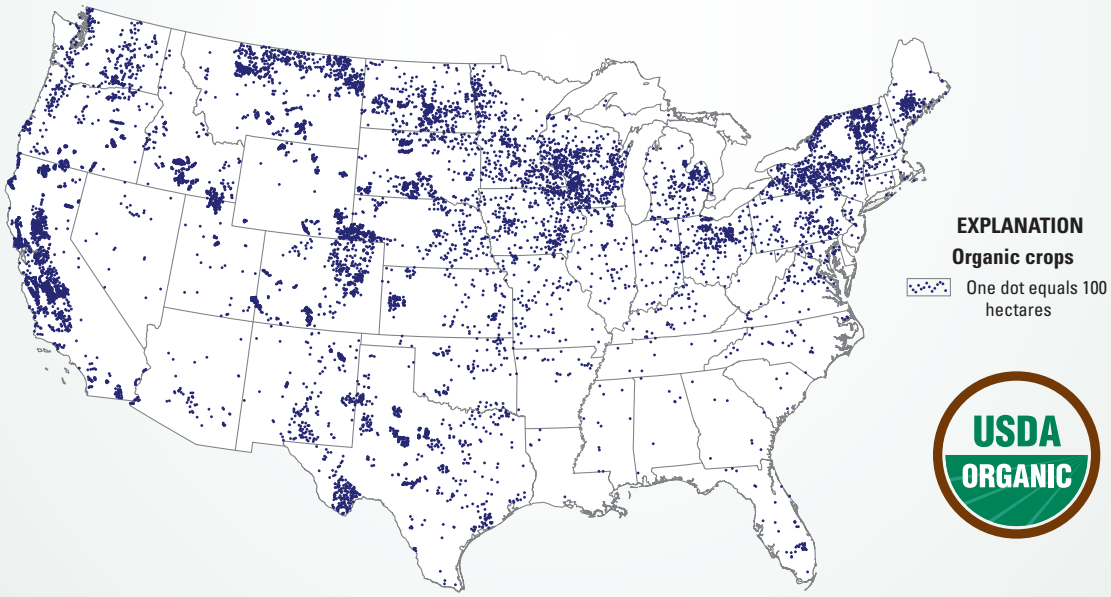


Figure 3.10. Organic agriculture in the United States, 2007. The cropland for organic agriculture is about 1 percent of all cropland (U.S. Department of Agriculture, 2016).

The USDA defines "organic production" as "a system that is managed … to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity" (U.S. Department of Agriculture, Agricultural Marketing Service, 2012a). Agricultural products that are certified as organic must be grown in soil to which no "prohibited substances" have been applied within the past 3 years and produced in a manner that does not include the use of genetic engineering, ionizing radiation, or sewage sludge. Crops are fertilized primarily through the application of animal manure and crop waste, the planting of leguminous cover crops, and the mechanical incorporation (tillage) of these materials into the soil on a regular basis. Many organic farms use an agricultural system, commonly referred to as "permaculture," that involves a much greater diversity of crops and livestock than most conventional farms. As suggested by the USDA definition given above, such systems place considerable emphasis on encompassing the full cycle of nutrient flow within the overall operation, using animal waste to fertilize crops that, in turn, are grown to produce feed for the livestock, in addition to other agricultural products.

Organic methods of pest control include a variety of physical, mechanical, and biological approaches—and, when necessary, the application of substances approved for use in organic agriculture. Although organic farming eschews the use of most synthetic chemicals used in conventional agriculture, the application of a considerable number of substances to the land—most of them naturally occurring—is permitted (U.S. Department of Agriculture, Economic Research Service, 2010a; U.S. Department of Agriculture, Agricultural Marketing Service, 2012b). Additional control of insects also is provided by the balance between insect predators and prey on organic farms (Crowder and others, 2010). Although conventional agriculture depends primarily on pesticide applications to control weed growth, organic agriculture typically relies on more complex crop rotations and tillage for this purpose (for example, Pimentel and others, 2005). The use of crop rotations also helps control insect damage and maintain soil fertility. In addition, the USDA has established standards to address the treatment of seeds, planting stock and livestock, as well as procedures for the handling of all foods certified as organic up to their time of sale. For example, the use of growth hormones or antimicrobials on livestock for any reason is prohibited (U.S. Department of Agriculture, Economic Research Service, 2010a; U.S. Department of Agriculture, National Institute of Food and Agriculture, 2011; U.S. Department of Agriculture, Agricultural Marketing Service, 2012a).

Soils that have been cultivated using organic methods are commonly found to have significantly higher amounts of organic carbon and nitrogen (Drinkwater and others, 1998; Tilman, 1998; Pimentel and Patzek, 2005), exhibit greater aggregate stability (Mäder and others, 2002), and show lower rates of nitrate leaching (Drinkwater and others, 1998; Pimentel and Patzek, 2005) than soils under conventional agriculture. This observation suggests that the more extensive use of cover crops and manure applications by organic agriculture—relative to conventional methods—can help compensate for any potentially adverse effects of tillage on soil quality (Drinkwater and others, 1998). More research is needed on the various ways that organic agriculture may affect the health of the ecosystems in which it is practiced, compared to conventional agriculture.

Biofuels

Biofuels are fuels produced directly or indirectly from organic matter (biomass), such as plants and animal waste. Corn-based ethanol is the most common type of biofuel produced in the United States, with approximately 34 billion liters produced in 2008 (Grey and others, 2012), whereas in Brazil, ethanol is produced from sugarcane. Biodiesel made from soybean also is important in the United States. In the future, other sources of biomass have the potential to be commercialized for biofuels. Switchgrass, a fast-growing variety of perennial prairie grass that can be grown in many areas of the country, has been explored as a future source of biofuels (Mitchell and others, 2014). Several other sources of biofuels have been suggested including algae, wood chips, animal manure, and crop residue.

The recent emphasis on the production of biofuels is at least in part due to national security issues related to creating a long-term and stable supply of fuel for the country. The Biofuels Initiative was implemented by the U.S. Department of Energy Biomass Program in late 2006 to help meet the goals of the Energy Independence and Security Act (Public Law 110-140; 121 Stat. 1492). The goal of this Act is to increase the production of renewable and alternative fuels in the United States and to reduce dependence on foreign oil. Two primary goals for the Biofuels Initiative and Biomass Program are to reduce the cost of ethanol so that it is competitive with gasoline and to produce 136 billion liters of renewable fuel (biofuels) by 2022 (as a partial replacement of gasoline). Because only 42 percent of total biofuels is allowed to be derived from corn grain, the Act also encourages the development of diverse crops as the basis of biofuel production. The production of ethanol from biofuels increased by about 30 percent between 2007 and 2008 and again by 13 percent between 2008 and 2009 (fig. 3.11). The Biofuels Initiative created an important market, increased demand, and encouraged more area to be planted in corn. In 2009, almost 35 percent of the corn production in the Nation was used in the production of ethanol. Some of the corn used for the production of ethanol has come from increases in corn production and some has come from an increase in yield (fig. 3.11), but the rest has come from a change in use of the existing production capabilities.

The use of corn for ethanol production poses several concerns. In the production of ethanol by current methods (2012), the ratio of the energy gained from ethanol to the energy needed to grow and process corn for ethanol is not large. This new area planted in corn comes at the expense of areas formerly used for other crops, the removal of land from conservation reserve programs, and (or) the addition of marginal lands that generally are not well suited for row-crop agriculture. The environmental impacts of the additional water, fertilizers, and herbicides that are needed to grow the increased corn are additional concerns. For example, in 2007 in northwestern Mississippi, about 184,000 hectares of cotton were replaced with corn (Welch and others, 2010). In Mississippi, corn requires more irrigation water and more fertilizer than cotton, so the switch has created two issues: it has exacerbated an already declining water level of the alluvial aquifer, and it has increased the export of nitrogen from the landscape to the Mississippi River, and, eventually, to the Gulf of Mexico (Coupe and others, 2012). The increase in corn production across the Mississippi River Basin may therefore be working at cross-purposes against the numerous management practices that are being implemented to decrease the load of nitrogen discharging to the Gulf of Mexico.

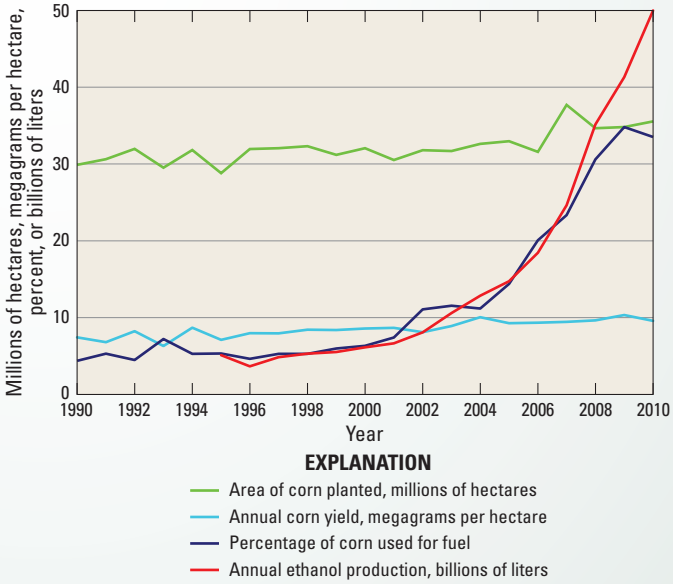


Figure 3.11. Annual area of corn planted in the United States, annual yield of corn for grain, percentage of corn for grain used for fuel, and annual ethanol production (Capel and Hopple, 2018).

Increased Shortages.—The area of land used for agriculture has decreased over the past few decades. In some areas, agricultural land has become more valuable for conservation, recreation, or urban development purposes. From 1949 to 2007, there was a 15-percent decrease in cropland area (from 1.94 to 1.65 million km^2) (Nickerson and others, 2011). It is estimated there will be an additional 13-percent decrease in cropland area by 2050 (down to 1.42 million km^2), whereas the area of urban lands is projected to increase from 3.1 percent in 2000 to 8.1 percent in 2050 (Nowak and Walton, 2005). Additional decreases in cropland may be due to climate changes, soil salinity, and lack of irrigation water. With this projected decrease in crop area over the next few decades, production from existing cropland must be increased to meet domestic and global needs.

Water is the primary limiting factor for agricultural production in many areas; this limitation is expected to increase as available freshwater resources are used at rates faster than they can be replenished (Schaible and Aillery, 2012). Rain-fed agriculture is dependent on the amount and timing of precipitation, whereas irrigated agriculture (supplied by either groundwater or surface-water withdrawals) has a more reliable source of water, resulting in increased agricultural yields. Water used for irrigation accounts for 61 percent of all non-consumptive withdrawals from surface and groundwater supplies in the United States (Barber, 2009). Although it is considered a renewable resource, groundwater is often available in relatively limited supply, and is truly renewable only when the rate of withdrawal is less than or equal to the rate of groundwater recharge. In some areas, recharge from rainfall is less than the rate of withdrawal, rendering the groundwater a non-renewable resource.

Phosphorus is an important nutrient for vigorous growth of plants. The United States is the world's largest producer of phosphorus fertilizer. The majority of the Nation's supply of phosphorus is mined from shallow geologic deposits. It has been estimated that the known global reserves of phosphate rock will last from 50 to 100 years and the domestic, easily mined reserves will last about 25 years given the current rate of consumption (Cordell and others, 2009; Vaccari, 2009). Because no other element can substitute for the biological role of phosphate, options for preserving and recycling phosphate sources would help to extend the lifetime of the current supply. These options might include reduction in use while sustaining crop yield, minimization of the phosphorus lost in field runoff, reclamation from livestock waste, reclamation of urban effluent, and improved technologies for mining currently inaccessible deposits (Herring and Fantel, 1993).

Changing Environmental Stresses.—It is expected that global climate change will increase average temperatures and change rainfall patterns for many arable areas in the United States, which could force a spectrum of change from locally grown hybrids to large changes in cropping patterns.

Urbanized areas continue to expand and compete for farmland (South Dakota). Photograph by Paul Capel, U.S. Geological Survey, 2010.

Perhaps even more important is the potential for more variable weather and more extreme events—such as droughts, floods, hurricanes, tornadoes, and wildfires—in the coming decades. More frequent extreme events could be disruptive locally and (or) regionally and will be difficult to plan for and mitigate. Crop agriculture may be looked to for methods to help sequester excess carbon in the crops and in the soil. The beginnings of market-driven incentives to store soil carbon have been initiated (Kollmuss and others, 2008). The storage of carbon from crop residue is supported by the goals and methods used for soil conservation, such as the use of continuous no-till tillage, but may oppose the goal of producing biofuel from crop residue (Cruse and Herndl, 2009). Row-crop agriculture also is likely to come under greater scrutiny for its part in the production of nitrous oxide, a greenhouse gas that traps heat approximately 310 times as effectively as carbon dioxide. In 2010, row-crop agriculture was the Nation's largest producer of nitrous oxide, having released almost 70 percent of total estimated emissions (U.S. Environmental Protection Agency, 2012a).

Reactive nitrogen chemical forms (forms other than atmospheric nitrogen gas, N_2) are being produced through human activities at more than twice their natural rate. This is occurring in part because of fossil fuel combustion and the cultivation of legumes, but primarily from the synthesis of fertilizer from atmospheric nitrogen gas, discussed earlier (Galloway and Cowling, 2002). This extra reactive nitrogen, in addition to increasing crop yields, contributes to the formation of atmospheric smog and haze; adversely impacts forests; causes acidification of soils, lakes, and streams; contributes to global warming and to the destruction of the ozone layer; and contributes to the eutrophication of our streams, lakes, reservoirs, and oceans, odors from livestock operations, and toxicity to fish (see "Nitrogen" in Chapter 2).

Many of the lands that were enrolled in some Federal land conservation programs in the 1990s are nearing the end of their contract (typically 10–15 years) (see "U.S. Department of Agriculture Conservation Programs"). The area of cropland in Federal conservation programs decreased by 3 percent from 1997 to 2002. The return of retired, environmentally vulnerable cropland to production is a cause of environmental concern, including loss of wildlife habitat and loss of sediment, nutrients, and pesticides to streams (Zelt and Munn, 2009). Choices are continually made to put these vulnerable lands back into some form of production or keep them out of active crop production to protect the environment.

The use of corn and soybean for biofuel production has increased over the past decade. The expansion of the area needed to grow crops for biofuels has reduced the amount of land available to grow crops for food, feed, and (or) fiber or returned previously retired, environmentally vulnerable lands to production and, in some areas, increased the use of water and chemicals on crops for biofuels (Welch and others, 2010).

Incremental Solutions from New Technologies.—The current genetically modified crops (corn, cotton, and soybean) have been a commercial success that has led to continued expansion to new crops (U.S. Department of Agriculture, Economic Research Service, 2017) and new varieties with more than one genetically modified trait. It is probable that the area of land on which genetically modified crops are grown in the Nation will continue to expand. The widespread adoption and expansion of genetically modified crops carries with it potential unknowns. There are scientific and societal issues associated with the production and expansion of genetically modified crops including increases in resistance by the pests, food labeling (for consumers who are concerned about potential adverse effects on humans or other non-target organisms), long-term impacts on wild organisms through inadvertent hybridization, potential losses of genetic diversity, and over reliance on a limited number of chemicals (Snow and others, 2005). Genetic modifications also are being explored in animals. Future efforts within this realm may include the introduction of livestock with such traits as increased efficiencies of nutrient uptake from food, decreases in the amounts of waste excreted, improved adaptability to heat stress, improved parasite and disease resistance, and increased growth rates (U.S. Food and Drug Administration, 2012). Other advances in biotechnology will continue to affect change in both crop and animal agriculture (Senthil-Kumar and Mysore, 2010; Rodrigues and others, 2012; Eldakak and others, 2013; Sherman and others, 2015).

The use of computer technology in agriculture continues to advance. The Nation had a goal of connecting all of rural America with broadband Internet (U.S. Department of Agriculture, 2011), analogous to the goal of bringing electricity to all of rural America during the Rural Electrification programs of the 1950s. The easy availability of satellite mapping equipment (global positioning systems, or GPS), together with user-friendly computer interfaces, have led to substantial improvements in the accuracy of land leveling, planting, and applications of chemicals—a suite of advances that is often referred to as "precision agriculture." The use of GPS-guided planters helps avoid losses of crop acreage owing to uneven rows, and utilizes information on soil, tillage, and previous yields to allow for customized, spatially varying agrichemical applications to help maximize crop yields. Precision agriculture holds the future promises of decreasing the amounts of chemicals that are applied to the landscape, and modifying tillage and planting to minimize harm to environmentally sensitive areas within a field. A vast array of computer-controlled sensors is used to monitor physical parameters, such as temperature, soil moisture, and humidity, in real time in orchards, making it possible to apply irrigation water and agricultural chemicals at specific times and rates to individual trees, according to their particular physiological needs at the time.

Nanotechnology has found widespread application in consumer products, but its incorporation into agriculture is not widespread (Parisi and others, 2015). The application of chemicals as nanoparticles could increase the efficiency of their use, and provide better control over their rates of release to the crop(s) of interest. The development of GPS-linked nano-environmental sensors could allow monitoring of soil moisture and crop yield throughout agricultural landscape (Scott and Chen, 2012). In many ways, nanoparticles are currently at the same stage of development as insecticides were in the 1960s and genetically modified crops were in the 1990s. Nano-materials offer many potential benefits for agriculture, but also present many unknowns regarding human and environmental safety. Although nanoparticles are widely used in food packaging, the presence of nanoparticles in the food itself is likely to cause concerns among some consumers.

Sustainability.—Incremental solutions aim to meet the future challenges of agriculture by staying within the present system. In addition to these solutions, the science is beginning to point to solutions that will have a "transformative" shift from the present agricultural system to a new and more comprehensive approach that will take into account the complex interactions between humans and the environment (Foley and others, 2011). These solutions are based on changes made not only on the farm, but also at the consumer level—changes that could ultimately alter the way food is produced and what is eaten. On-the-farm solutions include organic farming and increased diversity of crops and livestock. Consumer solutions include changing dietary habits and educating consumers about their role in sustaining agricultural production for future generations. One example of an area in which both consumers and farmers can play a part is the reduction of food waste. Globally, food waste, generated both during harvest and after consumer

purchase, accounts for nearly 40 percent of all food produced (Foley and others, 2011). Any reduction in such waste made at either the consumer or farm level will in effect increase overall yields without having to increase production.

Most would agree that there exists a primary mandate for this Nation's agriculture to feed the population in an environmentally and economically sustainable manner. Agriculture needs to be able to produce its bounty and help provide a healthy environment for this generation and the scores of generations to come. Environmental impacts of agriculture have been a continuing concern since its beginnings, but were first brought to the Nation's attention following the period of the Great Dust Bowl. Tillage practices, modifications of the natural hydrology, manure disposal, chemical applications, groundwater withdrawals, and other agricultural activities have affected the quality of the Nation's air, streams, lakes, groundwater, estuaries, and coastal areas. Nutrient enrichment issues are of particular concern in the Gulf of Mexico, Chesapeake Bay, and other coastal areas. Loss, degradation, and salinization of soil will continue to be concerns, as well as diminishing water resources for irrigation. Until now, the Federal Government has dealt with these concerns through subsidies and incentive programs to change agricultural activities, regulation, and building of infrastructure (drainage, irrigation, and channel modifications). Some have suggested that society, through the Federal Government, has developed an unwritten "contract" with agriculture within which society itself pays the cost of environmental impacts (non-point pollution and other impacts) rather than agriculture paying these costs. It has been suggested that agriculture should be held responsible for the complete costs of production including the costs of environmental impacts and stresses (Kling, 2010). All these demands on agriculture probably call for different paradigms of production in the future—paradigms that place primary value on both yield and sustainability. This future can be led by the collective vision of individual producers, by agribusiness, by consumer choice (market forces), by advocacy groups, and (or) by government, taking ownership of the future demand for environmentally and economically sustainable agriculture to work toward the common goal.

Summary

Agriculture has changed dramatically since the days of the early settlers and subsistence farming. It has responded to the needs of society for food, fiber, feed, and fuel through expansion, intensification, and adoption of new crops and new technologies. Agricultural expansion in the United States fundamentally changed the American landscape. The lands most suitable for agriculture, forests and grasslands, were cleared first. Arid lands and wetlands were made arable by the introduction of irrigation and drainage technologies, respectively. Landscapes that were not conducive for crop agriculture were used for grazing.

Advances in mechanization, electrification, chemistry, and genetics combined to create the unprecedented growth in yields of both crop and animal agriculture from the 1950s through the 1970s. More recently, advances in biotechnology have further increased yields. This growth and intensification of agriculture has had adverse effects on agricultural lands and the broader environment. Many early farmers used their land in ways that degraded its ability to continue supporting agriculture in the future. As a result, soil was depleted of its nutrients and (or) lost altogether through wind and water erosion. Increasing demand for agricultural products has led to increases in the use of agricultural chemicals, the widespread introduction of genetically modified crops, and extensive modifications of natural water movement, resulting in a variety of important, if inadvertent, environmental concerns.

Because demand for food, feed, and fiber will continue to grow, agriculture will continue to face these and other challenges into the future. Extensive improvements in our understanding of the connections between agricultural activities and water quality will be needed to meet these challenge.

Agriculture In Eastern Nebraska

Prior to the arrival of European settlers, the area that today is Colfax County in eastern Nebraska was primarily a vast expanse of rolling hills covered with tallgrass prairie (fig. 1.3). A network of streambeds cut through the prairie landscape, some fed by seasonal rainfall and others by springs. The prairie soil was deep and rich, supporting grazing buffalo herds, providing dens for coyotes and wolves, and supplying abundant food for prairie chickens, quail, grouse, and wild duck and geese. Along the rivers and protected from prairie fires, hardwood forests provided habitat for deer, elk, antelope, raccoon, otter, beaver, muskrat, and mink.

In the mid-1800s, American settlers came to the area seeking land for pasture to graze cattle and sheep, and to grow corn. In 1856, the first town was settled, in the bottomlands where water and fuel were easily obtained. Prior to the building of the Union Pacific Railroad, only about a dozen families could have been considered actual settlers in the area. Having already built the eastern part of the transcontinental railroad, the Union Pacific extended the line west from Omaha and completed its line across southern Colfax County by 1866. As settlement pressure increased, cattlemen were pushed westward and pasture land was converted mostly to the production of cultivated crops, such as corn, alfalfa, wheat, and oats. By the 1900s, corn and wheat were the main cash crops being grown. By the 1930s, however, cattle and hog production had increased substantially, and the crops shifted toward livestock feed, such as corn and oats. As cultivation of the lands progressed, increasing water demands led to the use of water from streams and the installation of wells to provide more irrigation water for use on the fields. In the late 1940s, a center-pivot irrigation system that could accommodate hilly terrain was invented. During the droughts of the 1950s, many farmers were forced to invest in irrigation systems to remain in business, leading to the widespread use of center-pivot irrigation systems. Ponds also were constructed for watering livestock. Most lakes and ponds in that area were not naturally occurring but were constructed as impoundments for this purpose. A major trend from 1940 to 1990—in this and many other agricultural areas across the Nation—saw the consolidation of farmland into fewer, larger farms.

Corn and soybean are the most important crops. Over the past decade there has been an appreciable increase in the area of corn planted. Concentrated animal feeding operations for cattle also have become common. Since 2007, there has been an appreciable loss of farmland enrolled in the Conservation Reserve Program (CRP; U.S. Department of Agriculture, Farm Service Agency, 2013; see "U.S. Department of Agriculture Conservation Programs"). Recent studies by the USGS on the effects of agriculture on water quality and quantity in eastern Nebraska have focused on groundwater age and quality (McGuire and others, 2012), groundwater levels and storage (McGuire, 2011), effects of irrigation on baseflow of streams (Stanton and others, 2010), and influence of nutrients and habitat on stream ecosystems (Frankforter and others, 2009).

The landscape of eastern Nebraska. (*A*) The tallgrass prairie typical of the time before agriculture, (*B*) typical cropped fields, and (*C*) the current view from the air (23 square kilometers). Photograph *A* from U.S. Fish and Wildlife Service (Boyer Chute National Wildlife Refuge), 2011; photograph *B* by Jason Vogel, Oklahoma State University, 2011; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2011.

Chapter 4—Terrain, Climate, Soil, and Water

Why is Agriculture Located Where It Is?

The location of agriculture is determined by natural, economic, and societal factors. The natural environment offers a wide range in conditions of crop requirements: space, sunlight, warmth, water, gentle slopes, proper soil, and drainage. On some lands, these conditions are ideal, and crops and commercial agriculture thrive. On other lands, however, rugged slopes, poor (infertile) soil, lack of or excess water, and (or) inhospitable climate make commercial agriculture unprofitable or even impossible. Most agricultural lands are somewhere between the ends of the spectrum. In general, the natural factors that govern the extent of crop agriculture are terrain, climate, soil, and soil water. It is the combination of these four natural factors that allow specific crops to be grown in certain areas.

Agriculture has evolved over time and changed the natural vegetation on the landscape to agricultural vegetation (see "Initial Modification of the Landscape for Agriculture"). Early European settlers in America practiced agriculture primarily for subsistence, and farmers grew a wide range of crops and livestock in order to survive. Their choice of crops and animals was likely similar to those in the areas from which they had emigrated, and may not have been particularly suited to the natural conditions of their new homes. Today in commercial agriculture, in which crops and livestock are produced for widespread distribution and consumption by others, farmers tend to grow crops that are well suited to the particular conditions of the area in order to maximize production with minimal inputs.

Cropland (row crops, grains, fruits, nuts, and vegetables, but not including hay) occupies about 13 percent of the total land area of the United States (fig. 2.1*A*; Baker and Capel, 2011). Agricultural land also is used for pastures (lands that have been seeded and primarily are used for the production of domesticated forage plants), hay (grasses and legumes, such as timothy and alfalfa, respectively, that are typically cut, dried, and stored for livestock fodder), and rangelands (lands on which the native vegetation, such as grass, grass-like plants, and shrubs, is grown for animal grazing). Grasslands (pasture and hay) and rangelands occupy another 41 percent of land area in the United States.

Terrain

Agricultural land used for commercial production is constrained by both elevation and slope. Only 1 percent of land used for commercial agriculture within the conterminous United States is above 2,000 meters (m) elevation (Baker and Capel, 2011). These high elevation areas generally have low temperatures, high wind velocities, high precipitation, appreciable snow accumulation, and, largely as a result of these factors, poor soil quality.

The slope of the landscape also is an important determinant of its suitability for agriculture, because slope affects soil formation, climate, water drainage, soil water availability, and the operation of machinery. Areas that are nearly level (3-percent slope or less) generally are suitable for row-crop agriculture. Flat areas, however—such as the **floodplains** of rivers and streams, coastal areas, and glaciated landscapes—commonly contain wetlands where soils are wet through much or all of the year. American agriculture has traditionally excavated ditches and (or) installed subsurface drains in these flat areas to lower water levels in the soil either permanently or seasonally to enable crop production. Such drainage modifications have reduced the area of wetlands by more than one-half (about 56 percent, Dahl and Allord, 1996; Dahl, 2006). These flat or nearly level slopes pose no constraint for farm machinery. Gently rolling areas (from 3 to 6 percent slopes) also are not serious obstacles to cultivation, but intense or sustained rainfall can cause soil erosion, so terracing is sometimes implemented to reduce soil erosion. Steep slopes are not readily accessible by farm machinery and also are subject to erosion and soil loss. Slopes that are too steep for row crops may still be suitable tree fruit orchards, grapes, vineyards, vegetables, other grains, or animal grazing.

The distribution of major crops among areas of different slopes across the conterminous United States is shown in figure 4.1. Nearly 82 percent of the cropland in the conterminous United States occupies land with slopes of 3 percent or less, including nearly all land planted in cotton, rice, and citrus. Only about 8 percent of crops are grown on land with 4-percent slopes. About 20 percent of grassland is on slopes steeper than 5 percent.

Initial Modification of the Landscape for Agriculture

The expansion of agriculture in the United States resulted in widespread change to the natural landscape as farmers converted forest, wetlands, prairie grasslands, and scrublands to agricultural lands (table 4.1). The resulting modifications of the landscape changed the water budgets and water flowpaths of many areas, and substantially altered each type of ecosystem present.

Table 4.1. Natural vegetation in the United States that was converted to agricultural land.

[From Baker and Capel, 2011. **Total cropland area in class:** Does not include grasslands and hay. km^2, square kilometer]

Natural vegetation class	Total land area in class (1,000s km^2)	Total cropland area in class (1,000s km^2)	Total grassland and hay area in class (1,000s km^2)	Land in class converted to cropland (percent)	Land in class converted to grassland and hay (percent)	Total agricultural land (percent)
Broad-leaf forest	2,092	190	429	9.1	20.5	21.0
Needle-leaf forest	1,163	10	117	0.9	10.1	4.3
Grassland	2,208	520	1,074	23.6	48.6	54.0
Wetland	1,014	250	177	24.7	17.5	14.5
Shrubland	1,271	30	156	2.4	12.3	6.3
All land	7,748	1,000	1,953			

From Forest to Agriculture.—Deciduous and coniferous forest covered about 40 percent of the conterminous United States prior to the arrival of European settlers. The forests were cut for timber and space, and the cut areas were burned to remove stumps and the understory plants. These practices interrupted the natural nutrient cycles that had previously depended on the decay of leaves, fallen trees, and other organic materials to replenish the soil. The removal of the native land cover affected the amount of water and soil retained in the landscape. Prior to their removal, the tree roots and other vegetation had helped to stabilize the soil, whereas the forest canopy captured rainfall and returned it slowly to the atmosphere through evapotranspiration. Rainfall that reached the forest floor was retained in the leaf litter, sometimes collecting in depressions to form temporary pools. Much of the water that infiltrated the land surface was retained for long periods (weeks to months) within the organic-rich soils, and released slowly throughout the year to feed perennial streams. With the loss of the forest canopy, the rain fell directly upon the soil and caused increased surface runoff and increased erosion.

From Grassland to Agriculture.—Grasslands covered about 30 percent of the United States prior to the introduction of agriculture (fig. 5.1*A*). These grassland areas generally received less precipitation than do the forested areas, but the deep-rooted grasses helped to capture and store rainfall in the soil for slow release to the atmosphere and nearby surface waters. Seasonal fires halted the encroachment of tree seedlings and other invasive vegetation onto the grassland areas, and helped maintain the fertility of the soil. With the invention of the **moldboard plow**, the thick sod could be easily turned, exposing organic-rich soil that was ideal for cultivating crops. At the same time, however, the conversion to agricultural land destroyed the native habitat, reduced the frequency of seasonal fires, decreased the amount of evapotranspiration, and increased surface runoff and erosion. Because agricultural crops covered the landscape only seasonally rather than throughout the year (as the original grasses had done), the soil became much more vulnerable to erosion by water and wind.

From Scrubland to Agriculture.—Arid scrublands covered about 17 percent of the United States prior to agriculture (fig. 5.1*A*). These areas do not receive enough natural rainfall to produce the dense natural vegetation found in forests, wetlands, and grasslands. In their natural state, scrublands return most of the rain that they receive back to the atmosphere through evapotranspiration, and many streams and rivers are dry except during flooding events. The advent of irrigation allowed these dry lands to become extremely productive for agriculture. The irrigation water was obtained from aquifers and mountain snowmelt. In some areas, large irrigation projects included the construction of dams and reservoirs to capture the snowmelt, canals to distribute the water, and ditches to capture the excess water. The addition of the irrigation water transformed the water budgets and water flowpaths in these areas. In many of the areas where available surface-water irrigation was scarce, the local water table declined as water from the underlying aquifers was withdrawn faster than it was being replenished by recharge. In these areas, the salinity in surface waters and soils increased because irrigation water was applied too sparingly to enable flushing of accumulated salts from the soil.

From Wetland to Agriculture.—Wetlands, areas where **saturated soils** support a rich array of water-tolerant vegetation, covered about 13 percent of the United States prior to agriculture (fig.5.1*A*). Most of these wetlands were small and widely dispersed. Some wetlands were seasonal, whereas others were permanent. Wetlands retain excess rainfall because of their low-lying topography and sponge-like soils. As agriculture expanded into these areas, surface ditches were dug to divert water into adjacent streams. In some areas, subsurface drains were installed to bring the water level farther below the land surface. Because of their rich vegetation and the slow rates at which water flows through them, wetlands are characterized by highly active ecosystems that efficiently capture and store large quantities of nutrients. The highly fertile soils created by these ecosystems were excellent for cultivating crops, resulting in some of the most productive lands in the country. Drainage of these areas, however, also destroyed the wetland ecosystems, and increased the volume and velocity of water that flowed off the land surface into nearby streams and rivers.

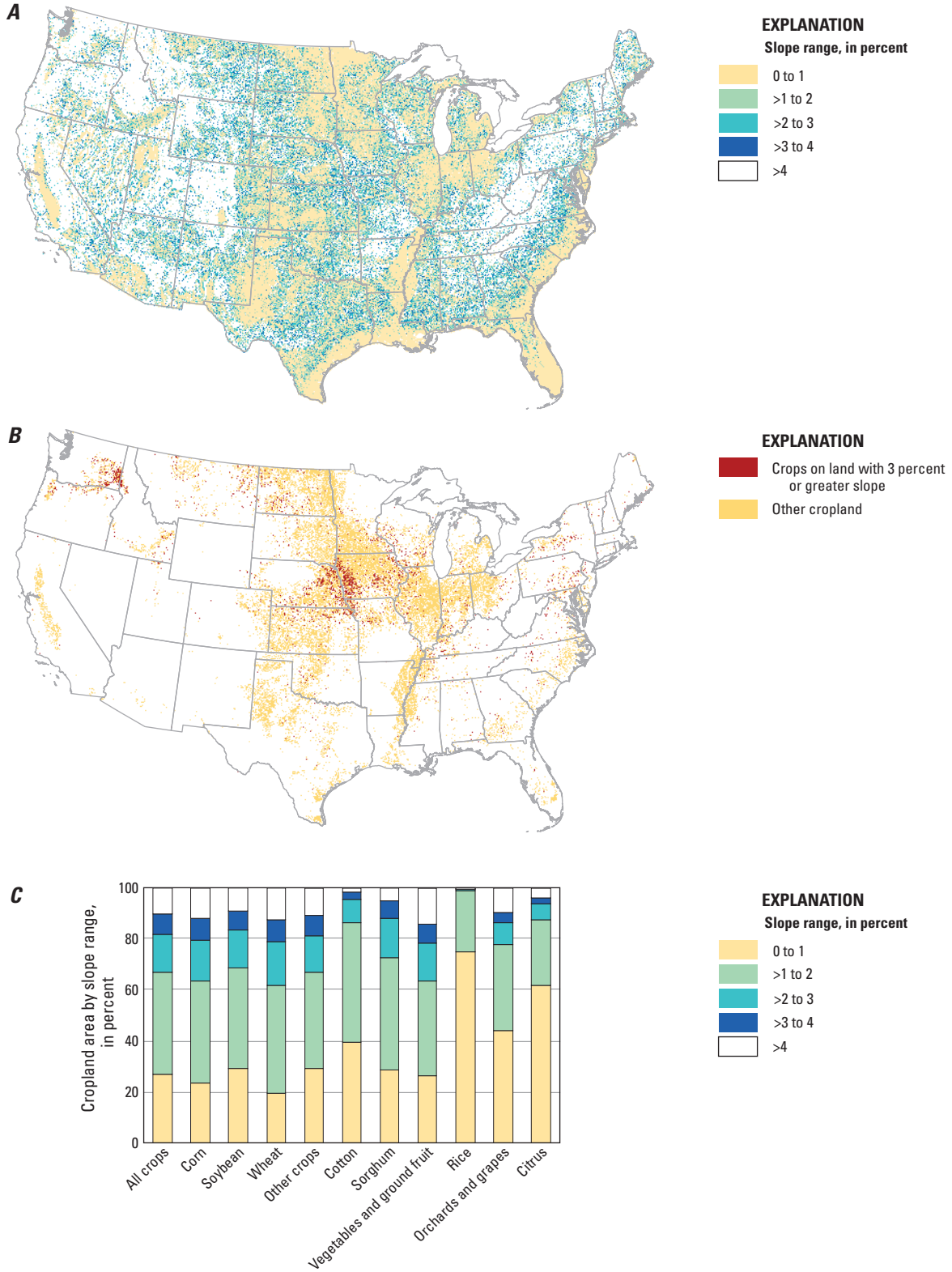


Figure 4.1. (*A*) Slope (or gradient) of land in the United States; (*B*) areas of steep slope (greater than 3 percent) used for cropland; and (*C*) percentage of cropland area used for selected crops for each slope class in the United States (Baker and Capel, 2011).

Local Climate

Climate is a primary determinant in the location of crops and accounts for much of the regional difference in the types of crops grown across the Nation. The climate of a location (average or prevailing weather conditions) is defined by the precipitation and sunlight (solar radiation that determines light intensity and temperature) it receives. Climate is largely determined by latitude, terrain, elevation, and proximity to ice, snow cover, and water bodies.

The light and heat provided by the sun are essential for the formation of chlorophyll and the operation of photosynthesis in plants. Different plants have different requirements for the amounts of light and heat that they need to reach maturity. For many plants, the growth rate from emergence to maturity is directly related to the total amount of thermal energy absorbed by the organism over its lifetime. Each plant has its own minimum temperature threshold for development. Cumulative growing degree-days is a metric used to quantify the solar radiation requirements for crops and to represent the accumulated product of time and temperature above the minimum temperature threshold for a given crop for each day (fig. 4.2; Ahren, 2011). One degree-day for a specific crop represents one 24-hour period with an air temperature 1 degree Fahrenheit (°F) above the minimum temperature threshold for that crop. For example, the minimum temperature threshold for corn is 50 °F. Thus, if the air temperature remains at 53 °F (3 °F above the threshold) for 24 hours, three degree-days are accumulated for corn. The distribution of growing degree-days across the United States for some major crops is shown in figure 4.2. The number of accumulated growing degree-days, however, does not capture

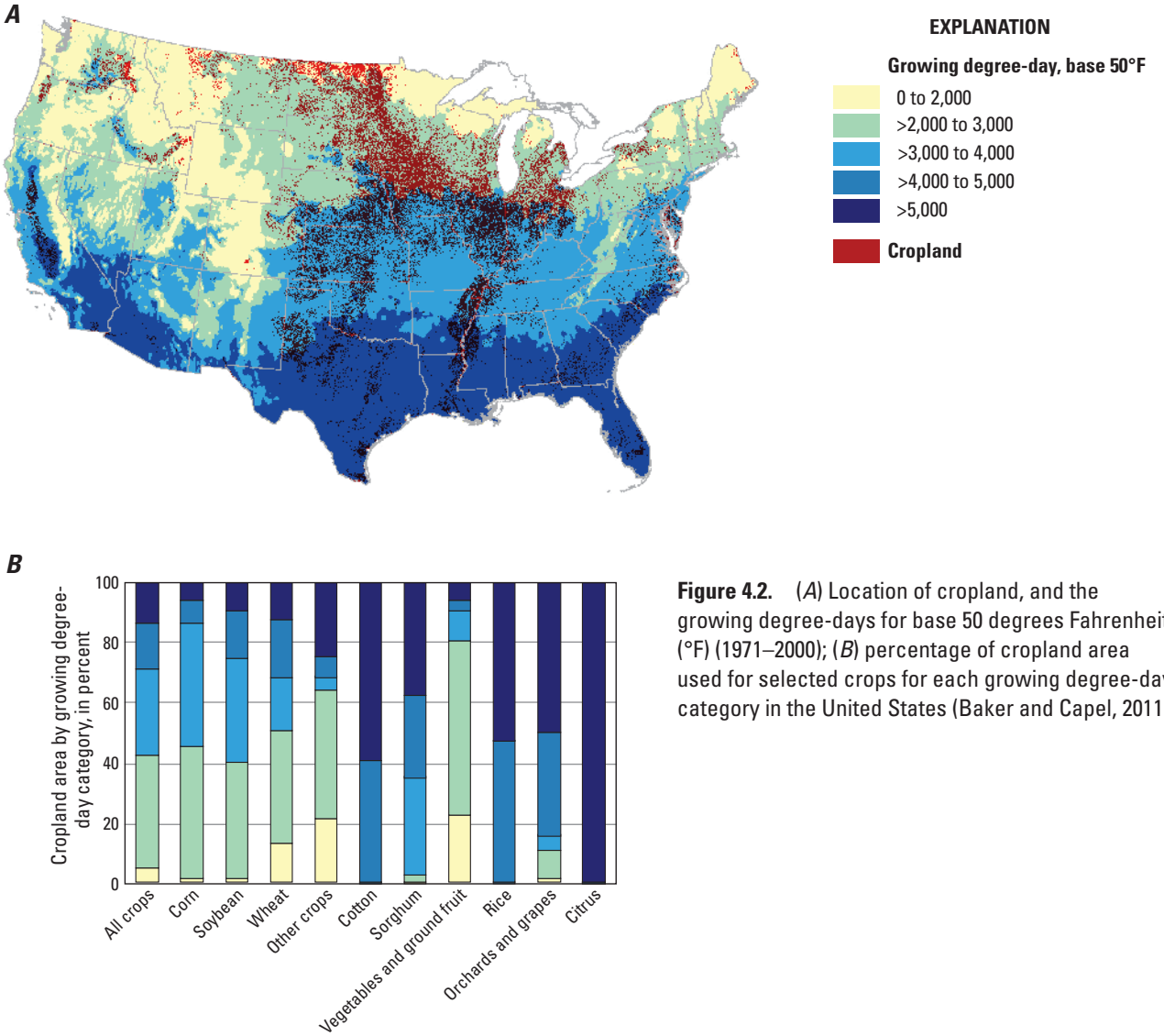


Figure 4.2. (*A*) Location of cropland, and the growing degree-days for base 50 degrees Fahrenheit (°F) (1971–2000); (*B*) percentage of cropland area used for selected crops for each growing degree-day category in the United States (Baker and Capel, 2011).

all of the effects of temperature on crop growth. Many crops stop growing when the air temperature exceeds a certain maximum value. In addition, some crops, such as apples, grapes, and winter wheat, require a period of cold dormancy in order for seeds or fruit to develop. Spring-seeded annual crops, such as corn, soybean, rice, and cotton do not require this period of cold dormancy in order to mature.

Plants take up water from the soil through their roots. In natural landscapes, soil water consists largely, if not entirely, of precipitation that has infiltrated into the soil. The quantity of precipitation that falls at any given location has a strong effect on the plants that thrive there. The distribution of precipitation across the United States and the percentage of cropland within each precipitation category for some major crops are shown in figure 4.3. Different plants have different requirements for the amount of water that they need in order to develop to maturity. Plants give off water as they grow (a process called **transpiration**). A plant's transpiration varies as a function of air temperature, humidity, and soil water availability. It changes during the course of the day and the course of the growing season. If water is not available to the plant (because soil moisture has dropped below its wilting point, or for some other reason), transpiration cannot occur.

In many parts of the Nation, the amounts and timing of precipitation are sufficient to meet crop water needs. In some areas, however, although the overall annual precipitation is sufficient to meet crop growth requirements, rain does not fall during the season when the water is required. In such cases, crop water needs can be met by using groundwater or water drawn from storage in reservoirs (fig. 4.4). In other areas where annual precipitation does not meet crop water requirements, precipitation is supplemented by irrigation water drawn from another part of the same watershed (perhaps the water retained as snow at high elevations), from a different watershed, or from "mined" groundwater. Mined groundwater is water that is extracted at a rate exceeding recharge, resulting in declines in the water table (Galloway and others, 2000; Bartolino and Cunningham, 2003). In some cases, the mined groundwater has been in the ground for centuries or millennia, and may have entered the subsurface at a location far from its point of extraction.

Examples of the three precipitation/irrigation scenarios described above can be found in Mississippi, California, Texas, and Washington. The Delta region of Mississippi (Chapter 6) receives ample precipitation for the common crops, but at the wrong times of the year for efficient crop growth. Some of the precipitation that falls on the Delta, however, recharges the groundwater system. As a result, irrigation, derived from the local groundwater, is used extensively to supplement rainfall. In recent years, intensive agriculture within the area has required more water than is recharged every year, resulting in a substantial lowering of the water table. California's Central Valley (Chapter 8) has temperatures and soil conditions that are ideal for a wide variety of crops, but receives an insufficient amount of precipitation over the course of the year to support those crops. To the east, however, the Sierra Nevada Mountains receive abundant precipitation in the form of snow. As the snow melts in the spring, it provides water that flows down through the riverine system, and is used extensively for irrigation within the Central Valley. In the Western Panhandle of Texas (Chapter 3) and other areas in the Great Plains, extensive irrigation is required in order to grow the types and quantities of crops that are planted. Much of the water used for irrigation within this area is obtained by mining groundwater from the High Plains (Ogallala) aquifer system, water that was recharged thousands of years ago. Groundwater mining has been common in many areas of the Great Plains, causing water-table elevations to decline sharply beneath much of this region. In central Washington (Chapter 7), abundant water from snowmelt in the Cascades is used extensively for irrigation. Canals and irrigation systems have been built to change the direction of water flow along the land surface, moving the water across natural watershed divides—a procedure known as interbasin water transfer (see "Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Too Dry for Agriculture," in Chapter 7).

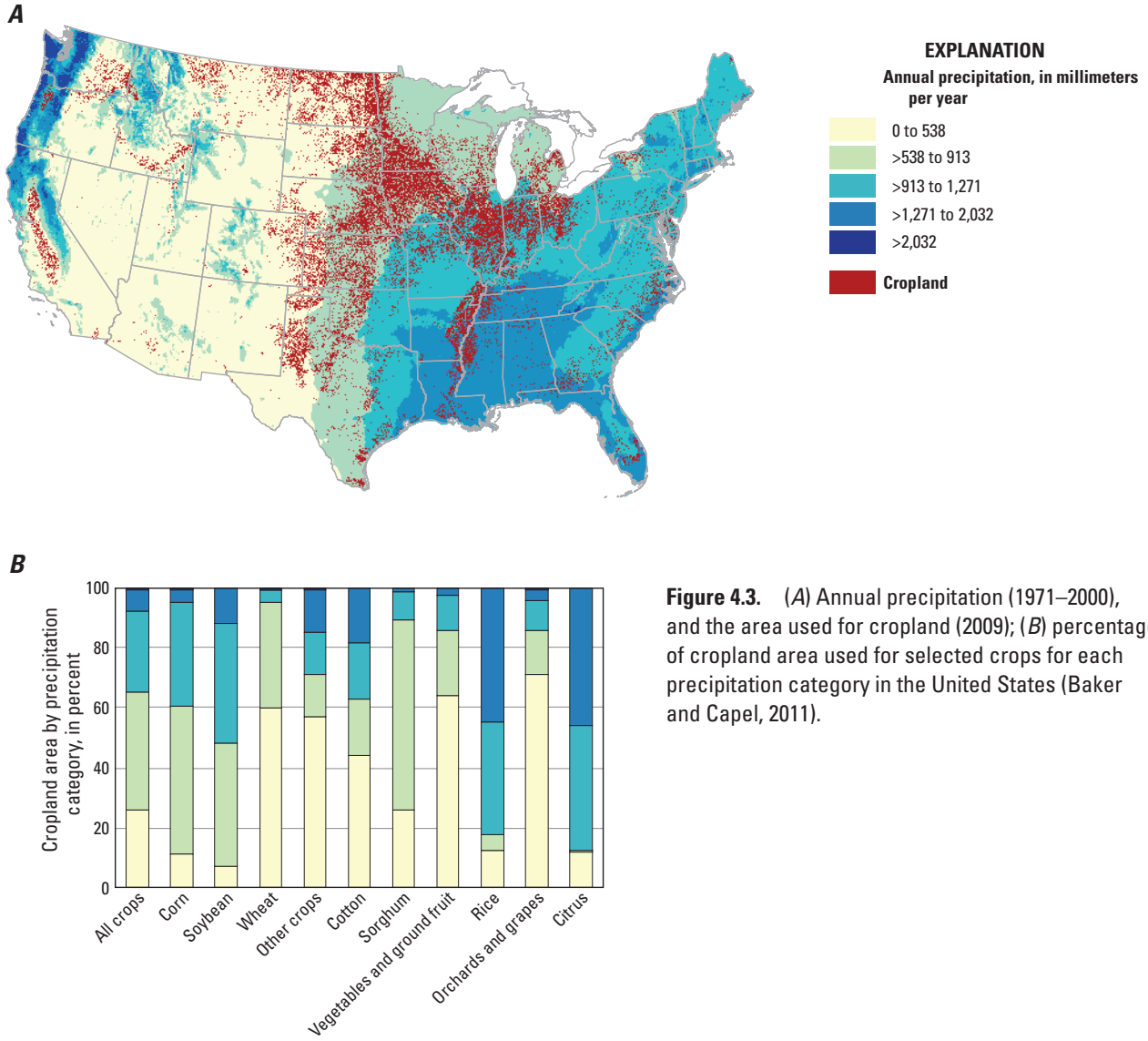


Figure 4.3. (*A*) Annual precipitation (1971–2000), and the area used for cropland (2009); (*B*) percentage of cropland area used for selected crops for each precipitation category in the United States (Baker and Capel, 2011).

The combined effects of precipitation and temperature in determining the most appropriate places to grow various major crops across the conterminous United States are illustrated in figure 4.5. Wheat can be grown in a variety of climates, largely because its heat and moisture requirement thresholds are lower than those for other major crops. Sorghum can tolerate drier climates, but is not as tolerant of cold temperatures as are many varieties of wheat. Corn and soybean are well adapted to the wet springs, humid summers, and dry autumns of the Midwest. In contrast, rice and cotton can be grown only in limited areas of the country. They can be grown in areas with similar temperature ranges, but rice is constrained by high water requirements. Crops that are most likely to be irrigated are rice, nuts, citrus and other tree fruits, and grapes (fig. 4.5*C*). A wide range of **cultivars** has been developed for each crop, and many of them have been bred specifically to produce acceptable yields under less favorable conditions, such as a short growing season or low precipitation.

Livestock are usually not as constrained by climate as crops can be, because most such constraints can be overcome with additional inputs of fuel and other resources, such as shelter, water, and feed. As a result, animals are often grazed on rangelands with a growing season that is too short or too dry to support cultivated crops on an economically viable basis. These marginal lands may also be used to grow grasses used for hay, in order to provide food for livestock during the winter.

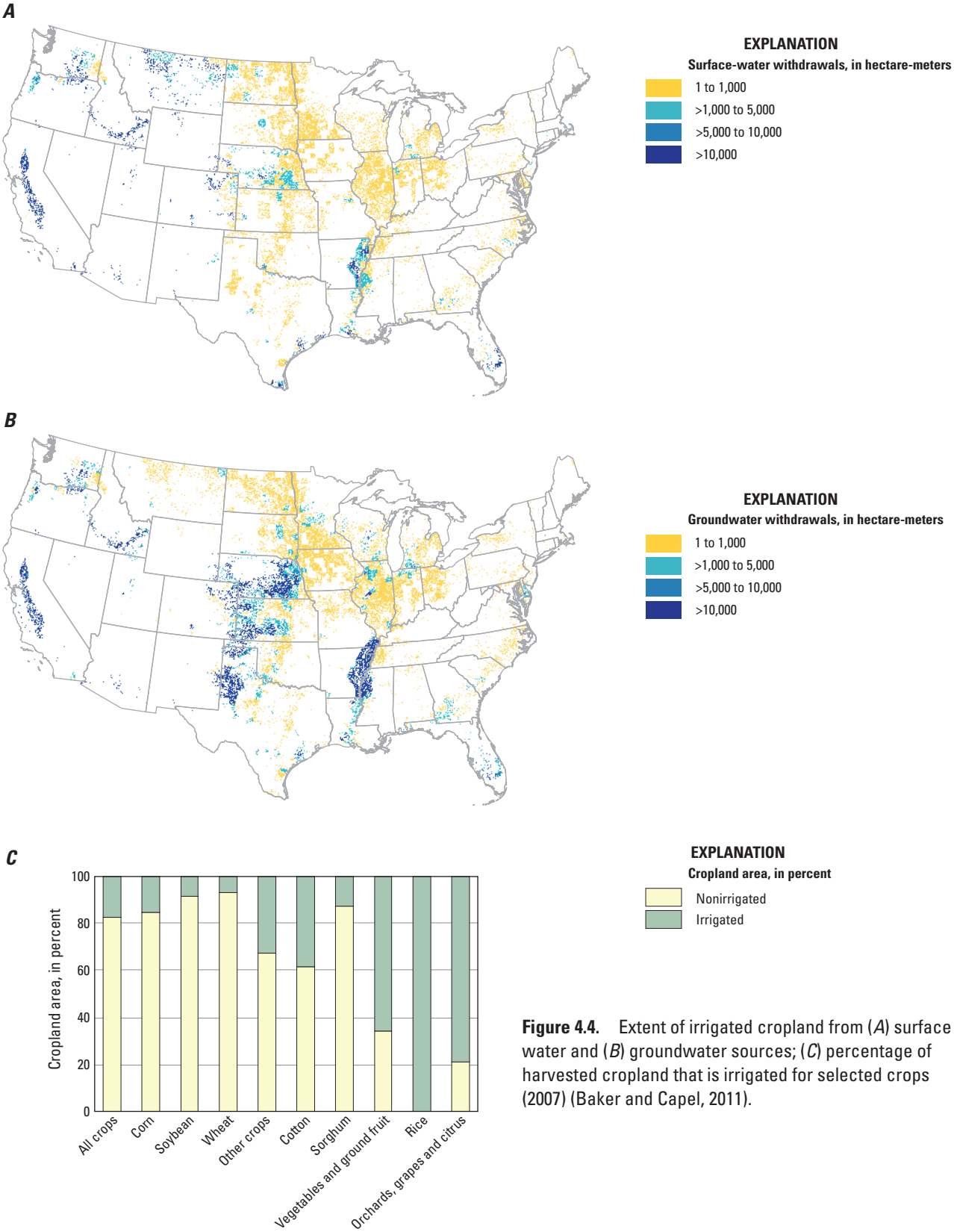


Figure 4.4. Extent of irrigated cropland from (*A*) surface water and (*B*) groundwater sources; (*C*) percentage of harvested cropland that is irrigated for selected crops (2007) (Baker and Capel, 2011).

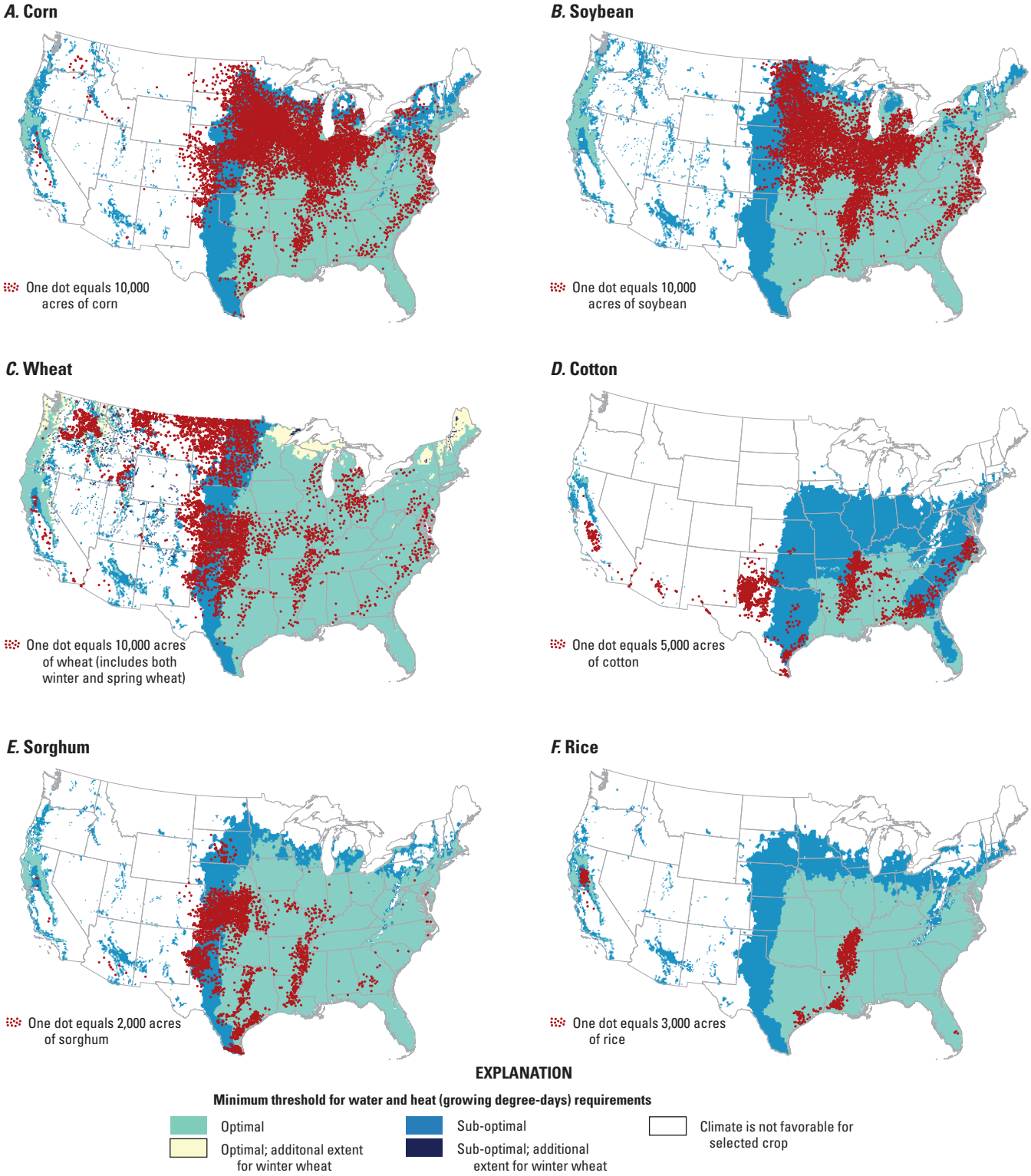


Figure 4.5. Location of favorable climate for growing selected crops (2007) based on average annual growing-degree-days (GDD) and evapotranspiration (ET) (Baker and Capel, 2011).

Soil

Soils provide physical support for plant roots, as well as most of the water, nutrients, and symbiotic organisms that plants require to survive. Soils are formed by the simultaneous actions of rock weathering and the decomposition of vegetation and other organic materials (principal source of organic matter). The degree to which vegetation can thrive in a given soil is determined by a number of soil properties. These include soil depth, texture (grain-size distribution), organic-matter content, nutrient concentrations, mineralogy, and the degree of weathering. Some areas—such as those containing dunes, shifting sands, salt flats, rock debris, desert detritus, glaciers, and snow fields—are not amenable to growing crops, but most areas in the Nation have soils that are or can be made suitable for commercial agriculture. Many soils, however, require amendments to provide optimal growing conditions for plants.

Soil depth is not a limitation for crops in most locations. Most crops need at least 100 cm of soil to grow, although some crops can be grown in shallower soils (Fischer and others, 2002). Shallow soils, which are common on steep slopes underlain by bedrock or hardpan, are highly erodible.

The texture of a soil is defined by the relative proportions of sand, silt, and clay that it contains (Folk, 1980). Texture, together with organic matter content, influences a wide variety of soil properties, including water-holding capacity, erodibility, and permeability to both water and air. Sandy soils allow water to move more freely and provide greater root aeration than do clay soils. However, clay soils have a greater water holding capacity than sandy soils. Soils with a high percentage of silt and clay are more easily eroded than sandy soils under the same conditions. Differences in texture also affect the soil's content of organic matter, which decomposes more rapidly in sandy soils than in fine-textured soils. Although it is not practical to change soil texture, agricultural modifications can be implemented to make soils more suitable for growing crops. Organic matter content can be increased by adding manure or by leaving more crop residue on the surface. Soils with high water-holding capacities (rich in clay and (or) organic matter) can be artificially drained to allow for proper root development.

The fertility of a soil refers to its nutrient content, and, is one measure of its capacity to support plant growth. Some essential nutrients—especially nitrogen, phosphorus, and potassium—are needed in large quantities by plants. Other elements, such as selenium and boron, are needed in small quantities, and, thus, are often referred to as micronutrients. More than 65 percent of all cropland in the United States (including that used to grow hay) is supplemented with commercial fertilizer, lime (powdered limestone), and (or) other soil conditioners to improve soil fertility, water retention, **pH**, and ultimately, crop yield (U.S. Department of Agriculture, Economic Research Service, 2010b).

The mineralogy of the soil particles, together with organic matter content, determines the chemical characteristics of a soil, such as pH, salinity, and cation exchange capacity. Soil pH strongly affects the degree to which phosphorus is available for plant uptake and, thus, affects soil fertility. The pH of acidic soils is commonly adjusted by applying lime (powdered limestone). Some minerals produce soils that are highly saline and have high concentrations of sodium, which can either slow or prohibit plant growth. Clay minerals in soils strongly adsorb cations, such as calcium, magnesium, and sodium, exerting substantial effects over soil cohesion, crust formation at the soil surface, and water infiltration rates.

In addition to its texture-related classification system, the USDA also classifies soils according to eight capability classes indicating their capacity to support crop growth without any deterioration in this capacity over time. The eight classes are determined by position in the landscape, slope, soil depth, soil texture, soil moisture (wetness), soil chemical properties, erosion potential, and climate (Helms, 1992). The spatial distributions of these capability classes (fig. 4.6) indicate that most soils in the East and Great Plains are suitable for cropland (classes I–IV), whereas most of the soils in the interior West are more suited to grazing (classes V–VIII). Only about 6 percent of all crops are grown on soils with slight limitations on their use for agriculture (class I). Forty-four percent of crops are grown on soils that have moderate limitations (class II) and may require soil conservation measures to facilitate agriculture. Twenty-eight percent of crops are grown on soils that have severe limitations (class III) and require special conservation practices. Eleven percent of crops are grown on soils with very severe limitations (class IV) that restrict the choice of plants and require careful management. An additional 11 percent of crops are grown on soils considered unsuitable for cultivation (classes V–VIII). More than 50 percent of all tree nuts and fruits, and all grapes, are grown on soils categorized as class IV or higher. Because these crops do not require continued cultivation, they are more likely to thrive in these soils than row crops. Irrigation reduces many of the limitations of the class V–VIII soils. Wheat, cotton, and rice are more likely to be grown on poorer soils than are corn and soybean (fig. 4.6*C*). Still, many soils in the arid West are largely unsuitable for crop growth because of characteristics that are difficult to correct, such as shallowness, abundance of stones, low moisture-holding capacity, low fertility, and salinity.

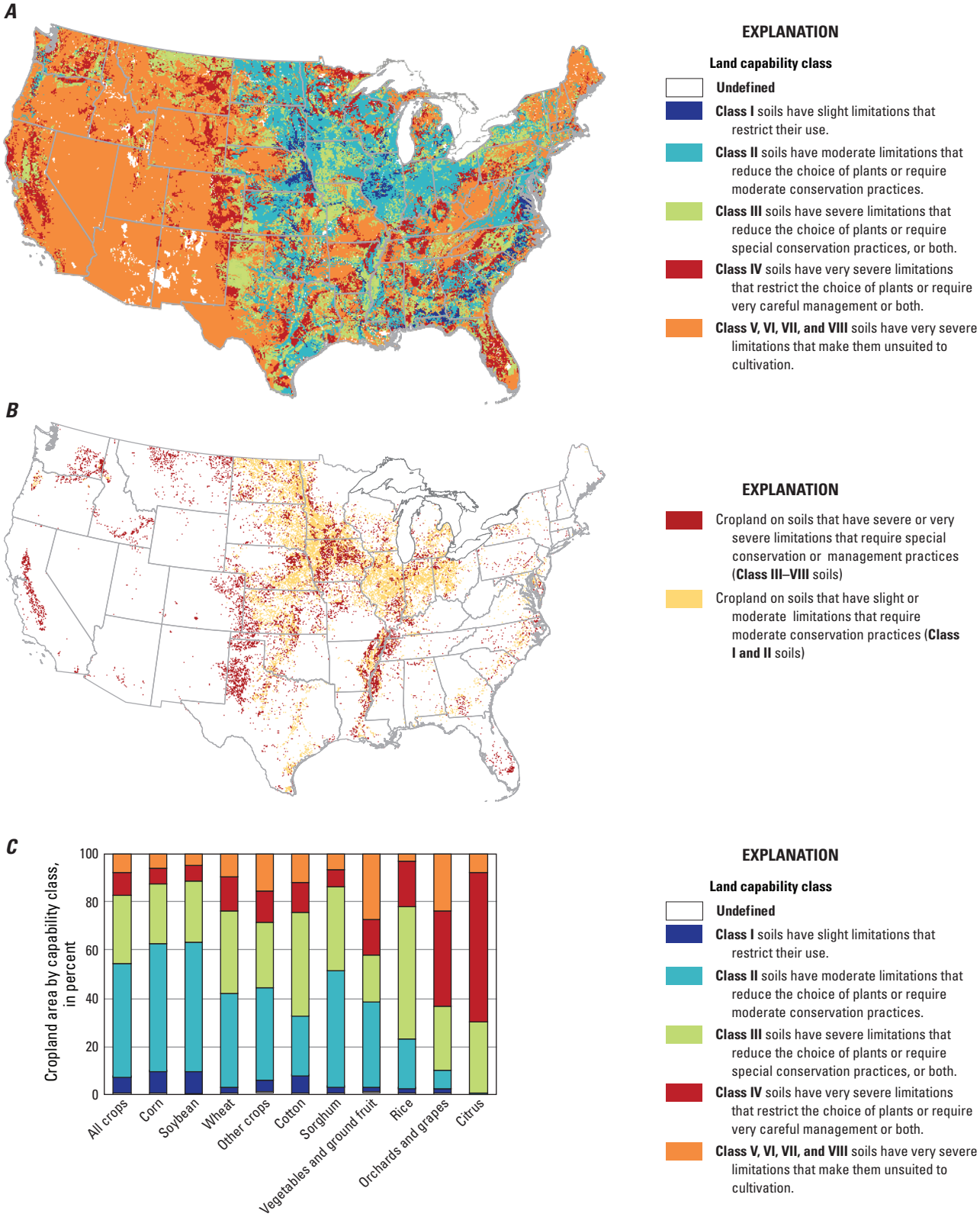


Figure 4.6. (*A*) Land capability class, (*B*) location of cropland, and (*C*) percentage of cropland area used for selected crops for each land capability class in the United States (Baker and Capel, 2011).

Water Needs

The amount of water in soil that is available to plants is controlled by terrain, climate, and soil characteristics. This amount is usually the limiting factor for the location of crop agriculture in many areas. The water in soil comes largely from precipitation, although in some locations soil water also can reach plants by way of groundwater or surface-water **flowpaths**. In most places, however, agriculture is highly dependent on the amount and seasonal patterns of available soil water from precipitation and irrigation where utilized. (Animal agriculture is not directly dependent on soil water, but it is affected by the quantity and quality of the groundwater and (or) surface water that is available for watering livestock and for growing their food.)

In addition to the soil texture and capability classes mentioned earlier, the USDA uses another classification system to reflect the dominant hazards that affect the use of different soils for agriculture (Helms, 1992). These hazards are associated with the limitations on plant growth posed by climate, soil, erosion, or excess water (fig. 4.7). Susceptibility to soil erosion from overland water flow or wind represents the predominant hazard affecting the use of most soils in the Nation. Fifty-four percent of crops are grown in "erosion class" areas, where erosion susceptibility and past erosion damage are the major factors affecting these soils. Twenty-three percent of crops are grown in "water class" areas, where poor drainage, excessive wetness, high water table, and (or) overland flow represent the predominant hazards. Most of the rice and citrus produced in the United States are grown on "water class soils." Similarly, many areas along the Gulf and East Coasts, and along river valleys across the Nation, have soils whose use for agriculture is limited by their excess water content. These soils can be (and often have been) artificially drained to overcome such limitations (fig. 4.8).

Excessive soil water is especially detrimental to crops during their growth and harvest. Moisture stress during flowering, pollination, and grain-filling is harmful to most crops—especially corn, soybean, and wheat. Excessive soil water interferes with root development and plant nutrient uptake, and can increase the risk of plant disease, and delay planting or harvesting (Rosenzweig and others, 2002). However, some of the most fertile cropland in the Nation is in areas with an overabundance of water in the soil. Most of the Midwest and Eastern Piedmont were originally wetlands and, as a result, are still underlain by poorly drained soils. The landscape has low slopes and annual precipitation rates that typically exceed evapotranspiration. Most of the present-day cropland in this area was made suitable for agriculture by artificial drainage, which made the fields accessible for planting and harvesting, and helped to minimize root damage caused by excess water. Crops that are most likely to be grown in areas that have been artificially drained are corn, soybean, and citrus (see "Availability of Data on Locations of Subsurface Drains").

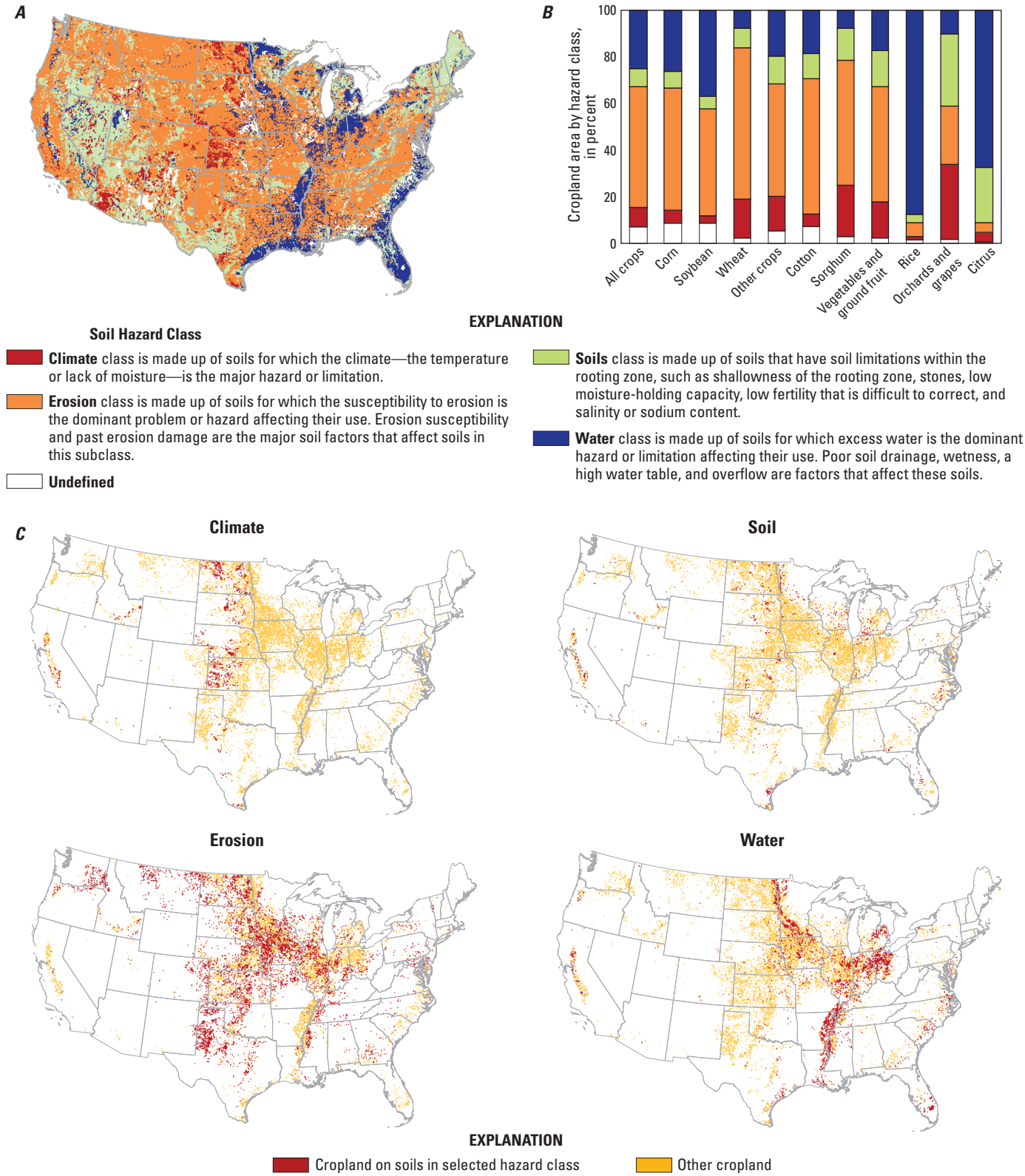


Figure 4.7. (*A*) Soil hazard class, (*B*) percentage of cropland area used for selected crops for each soil hazard class, and (*C*) location of cropland on each soil hazard class (climate, erosion, soil, and water) in the United States (Baker and Capel, 2011).

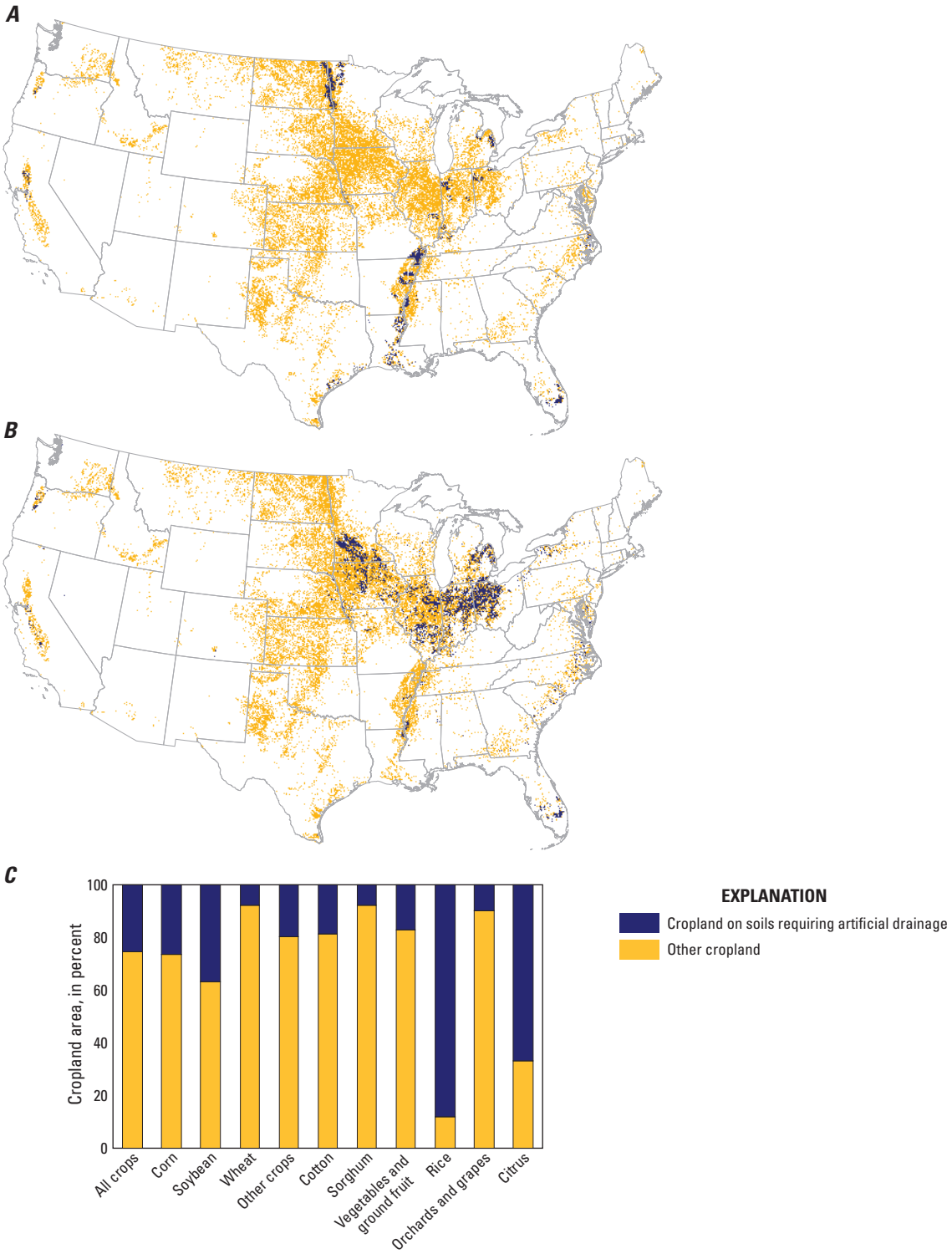


Figure 4.8. Extent of land in the United States underlain by soils for which artificial drainage (*A*) at the surface and (*B*) at the subsurface is likely required to remove excess water in order to cultivate cropland; (*C*) percentage of cropland cultivated for selected crops on the areas requiring artificial drainage (Baker and Capel, 2011).

Availability of Data on Locations of Subsurface Drains

Modern agriculture in much of the United States would not be possible without extensive drainage (see "Initial Modification of the Landscape for Agriculture"). Large areas of Ohio, Indiana, Illinois, and Iowa, along with many of the fertile lowlands along the Mississippi River Valley, Piedmont Plains, and southern Florida, would be too wet to farm. In addition, the development of irrigation in the West would have failed because of waterlogged soils and accumulated salt content.

Prior to European settlement, wetlands covered about 13 percent (more than 1 million km^2) of the land area of the conterminous United States (Dahl, 1990). About one-half of these wetlands have now been drained. Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin account for about one-third of the wetland area that was drained and converted to cropland (Pavelis, 1987). By 1987, more than 14 percent of the cropland in the conterminous United States had been made suitable for agriculture through artificial drainage (table 4.1).

The removal of excess water has resulted in reliable crop production in wetland areas. However, contaminants transported in runoff and subsurface drainage from cropland are often the major contributors to water-quality problems in our Nation's streams. For example, much of the nitrate that enters the Mississippi River and, subsequently, contributes to hypoxia in the northern Gulf of Mexico comes from water that has been artificially drained from agricultural fields in the Midwest (Petrolia and Gowda, 2006). The use of artificial drainage in irrigated areas with highly saline soils has led to elevated salinity (above background levels) in some western streams. In some cases, highly saline or nutrient-rich drainage waters have damaged aquatic ecosystems (Madramootoo and others, 1997).

Information on the location and areal extent of artificial drainage networks is crucial to understanding and quantifying their potential effects on water quality. The locations of surface drainage ditches are well known, because they are easily observable on the landscape. The extent of subsurface drainage systems, however, is poorly known in most areas because of their distributed nature, the extended period of installation, incomplete location maps, and a general lack of recent, systematic surveys of their spatial distributions. Surveys of on-farm drainage systems were included in the Censuses of Agriculture for 1920, 1930, 1969, and 1974. Censuses of drainage projects also were taken every 10 years from 1920 to 1960. In 1978, a Census of Drainage was conducted by county by the Soil Conservation Service (now known as the Natural Resources Conservation Service, NRCS) (U.S. Department of Commerce, 1981). In 1982 and 1992, statistically based surveys of both subsurface and surface drainage systems were carried out by the NRCS for the National Resources Inventory. Land capability classes (fig. 4.6) and crop information were used in these surveys to estimate the extent of artificially drained cropland between 1900 and 1985 (Pavelis, 1987). In addition to the lack of drainage information in recent decades, the lack of a consistent data-collection method has resulted in great uncertainty as to the locations of subsurface drains throughout the country.

Networks of subsurface drainage systems have been installed beneath agricultural fields in the last few decades. In many cases, these systems have been installed as patterned drainage (fig. 4.9) to improve control over soil water and thus increase crop yield. Landowners, however, are not required to report the installation of subsurface drainage systems or keep track of their locations. As a result, the locations of these networks are largely unknown.

Various approaches have been used to quantify the areal extent of subsurface drainage systems beneath agricultural lands. Statistically based farm survey methods generally provide county-level estimates of the area of drained land but do not provide the spatial resolution critical to many watershed studies. Statistically based surveys plus mapping of poorly drained soils overlain by cropland provides a spatial reference for areas that are likely drained. However, artificial drainage is not always installed in areas that could potentially benefit from it, and conversely, it is not always limited to poorly drained soils. Mapping of individual subsurface drains gives the most spatially detailed results for limited areas, but this mapping is labor intensive, expensive or, in many locations, not possible. Sometimes this mapping can be done by combining infrared aerial photography with soils information, but results are not always reliable.

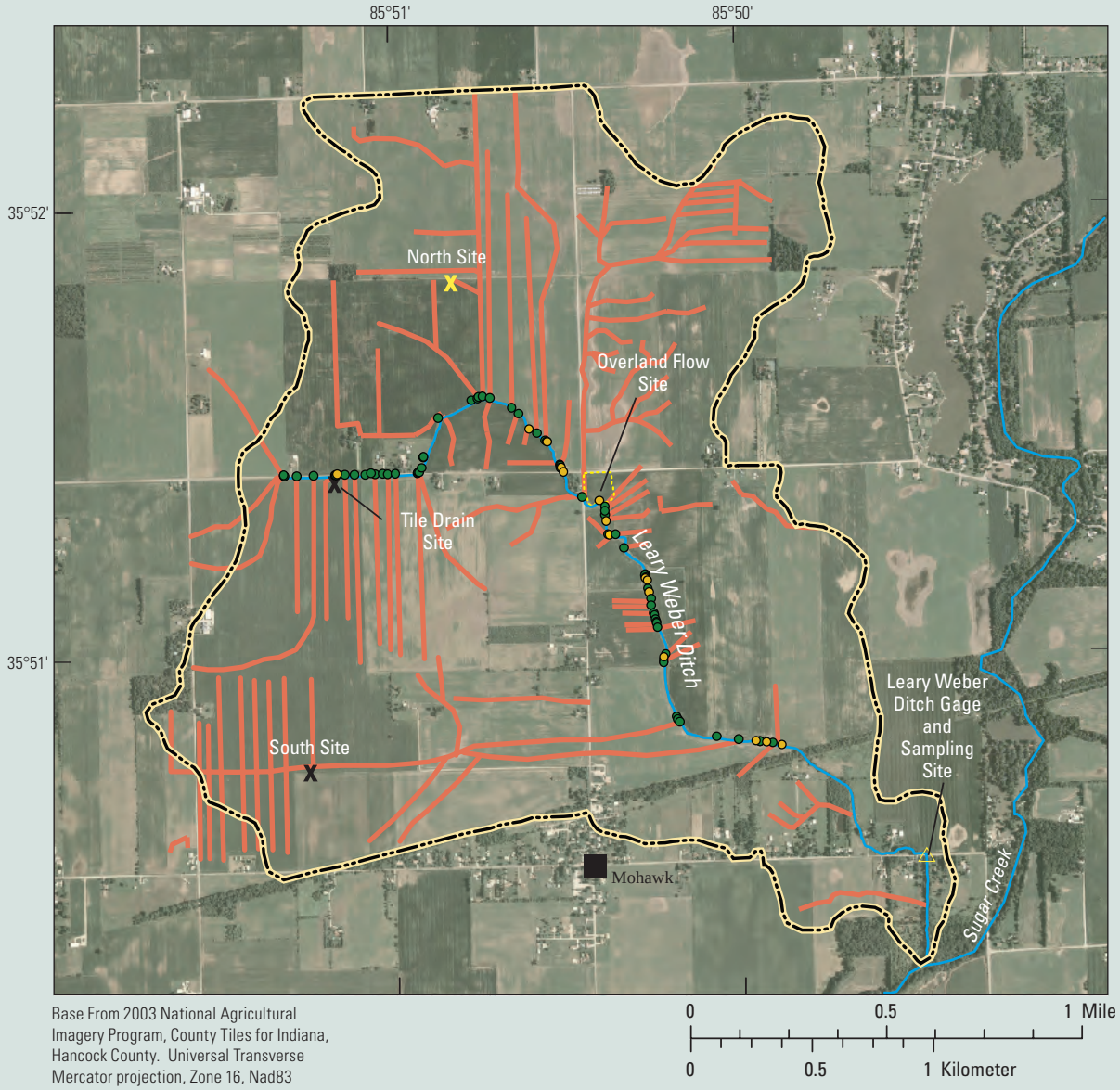


Figure 4.9. Approximate locations of the subsurface drains in Leary-Weber Ditch watershed, Indiana (Baker, Stone, and others, 2006).

The 2012 Census of Agriculture included two questions asking landowners about the number of acres of their land that are either (1) underlain by functioning tile drains, or (2) artificially drained by ditches (U.S. Department of Agriculture, 2013). The answers to these questions will likely be aggregated by county for public release. Once this information is made available, such information may be used to make State- and National-scale assessments of the extent and locations of artificially drained agricultural lands by combining it with the most up-to-date maps of cropland and poorly drained soils across the Nation. This level of information will still be insufficient, however, to fully address water-quality concerns in many locations. Because water flowpaths are local, each field has unique flowpaths to the stream. In order to make the best decisions for each field, the locations and extent of its subsurface drainage must be known. Knowledge of the specific location of subsurface drainage under individual fields conflicts with the tradition of privacy for landowners, but this knowledge would aid the science-based implementation of practices to improve water quality.

Summary

The location of agriculture in the United States is determined by natural, economic, and societal factors. The natural factors for the locations and extent of crop agriculture are terrain, climate, soil, and soil water. It is the manner in which these four natural factors are combined that allow specific crops to be grown in certain areas. Some lands have conditions that are nearly ideal for commercial agriculture. Other areas have rugged slopes, poor soil, either lack or have an excess of soil water and (or) have an inhospitable climate that make commercial agriculture either unprofitable or infeasible. Most agricultural lands, however, are between the two ends of this range. Today, most of the cultivated cropland, and grassland used for livestock is devoted to commercial agriculture, growing crops and livestock that are adapted to the particular conditions of the area to maximize production. In the United States, cropland (row crops, grains, fruits, nuts, and vegetables, excluding hay) occupies about 13 percent of the total land area. Grassland and rangeland occupy another 41 percent of the land area of the Nation.

Most crops are grown on gentle slopes (less than 3 percent) in areas where the temperature, precipitation, and soils are favorable for their growth. In many areas that are naturally too steep, too wet, or too dry for crops, the landscape has been modified to allow them to be grown and (or) thrive. Some of the natural limitations on crop growth can be overcome through agricultural modifications, but other limitations (such as climate) cannot be overcome. Agricultural modifications commonly affect water availability through irrigation and (or) drainage, and soil fertility (including soil organic matter) through the addition of manure, nutrients, and lime. In general, however, it is not feasible to modify the other natural factors—soil texture, soil depth, soil mineralogy, temperature, and terrain—at large spatial scales.

Agriculture in Maryland's Eastern Shore

In the 1640s, when the European settlers first arrived in what is now the Delmarva Peninsula, Maryland (fig. 1.3), they encountered a relatively flat coastal upland that was heavily forested with a mixture of evergreen and hardwood trees. Beneath the lush forests was a diverse understory of plants and wildlife cleft by steep ravines that carried streamflow to the Chesapeake Bay. Wetlands and riparian forests covered the lower elevations and were likely frequented by large flocks of migrating waterfowl.

With settlement came the clearing of the forests for timber, fuel, and agriculture. From 1658 to 1663, land patents were sold to wealthy immigrants who began raising livestock, cultivating corn, and supplementing their income by growing tobacco. Landowners acquired indentured servants to clear additional acreage in order to increase tobacco production. After 1720, the need for cropland expanded rapidly, driven largely by the increasing demand for wheat. Through the 1800s, the row-crop and animal agriculture underwent multiple cycles of growth and decline as farmers faced a variety of challenges, including reductions in soil quality. By 1900, the westward movement of farming had reduced the importance of Maryland's agriculture to the Nation, leading to a substantial decrease in farmland in the State. Given the high productivity of the farmland and the proximity to eastern cities, fruit and vegetable production became more prevalent during the early part of the 20th century. As the cost of fuel and transportation decreased, however, fruit and vegetable farmers on Maryland's Eastern Shore were unable to compete with producers in California, resulting in a shift to other products. In the 1950s, crop production on Maryland's Eastern Shore began to shift toward production of corn, soybean, and small grains to support the burgeoning poultry industry. Much of this change was driven by the availability of low-cost inorganic fertilizer that became available after World War II, when plants producing ammonium for munitions were converted to production of fertilizer.

Today, the region remains mostly rural, with continued cultivation of row crops, mostly corn, soybean, and small grains, although there is some pressure to convert farmland to housing and other urban uses. Some agricultural land is used for pasture and hay to support dairy production and, in recent years, specialty vegetable producers, greenhouse nurseries, and organic industries have increased and are filling a growing niche. Over the past few decades, impairments of water quality in Chesapeake Bay have been partly attributed to nonpoint-source pollution from agriculture, especially on Maryland's Eastern Shore, where agriculture remains the predominant land use. This has been an important factor for changing agricultural practices to better protect water quality in the area (Chesapeake Bay Program, 2013). Recent studies by the USGS in the Delmarva Peninsula and wider Northern Atlantic Coastal Plain have focused on nutrients and pesticides, including the hydrologic and geochemical controls on their distribution in groundwater (Ator and others, 2005; Ator, 2008); temporal trends (Debrewer and others, 2007; Denver and others, 2010); and their contribution from groundwater to surface water (Ator and Denver, 2012).

The landscape of Maryland's Eastern Shore. (*A*) The forests typical of the time before agriculture, (*B*) typical cropped fields, and (*C*) the view from the air (23 square kilometers). Photograph *A* by Judith Denver, U.S. Geological Survey, 2015; photograph *B* by Paul Capel, U.S. Geological Survey, 2010; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010.

Chapter 5—Water on the Pre-Agricultural Landscape

How Does Water Move Through Natural Watersheds?

Prior to human settlement, the North American landscape consisted of forest, grasslands, scrublands, wetlands, and barren areas (fig. 5.1). Adequate precipitation to support tree growth generally defined the forest-grassland boundary. Areas with insufficient precipitation to support grass gave way to scrubland. Deciduous broadleaf forests once covered most of the East, the Ohio and lower Mississippi River Valleys, and the middle Great Lakes region. Needle leaf forests covered much of the central and northern Pacific Coast, the higher elevations of the West, portions of the interior North, and a narrow belt in the Deep South. Grasslands covered much of the sub-humid interior lowlands of the Great Plains from Texas and New Mexico to the Canadian border. Scrublands were concentrated in the arid lowlands of the interior West, where vegetation varied from the dense, brushy chaparral of southern California to the cacti of the Southwest and the mesquite of Texas. The presence of wetlands was partly defined by topography, and wetlands were widely scattered across the humid portions of the landscape in low-lying areas. High densities of wetlands were found in the recently glaciated areas of the Midwest and in low-lying areas near coasts and large rivers, such as the Gulf Coast and the lower Mississippi River Valley.

Many of the characteristics shown on the maps in figure 5.1 are driven by geography. The broad humid area of the Eastern United States results from movement of moist air northward from the Gulf of Mexico. In contrast, the land mass of Mexico contributes appreciably to the aridity of the western landscape. Superimposed on this eastern-to-western moisture gradient is a general increase in evapotranspiration rates from north to south. At the local scale, the larger effects of regional climate on the water cycle are modified by topography, vegetation, and soil type (see "Soil Properties, Soil Water, and Soil Erosion"). These combined factors determine the amount of precipitation that falls on the landscape, how the water moves through the landscape, and how much of that water is retained and used by the vegetation within the landscape.

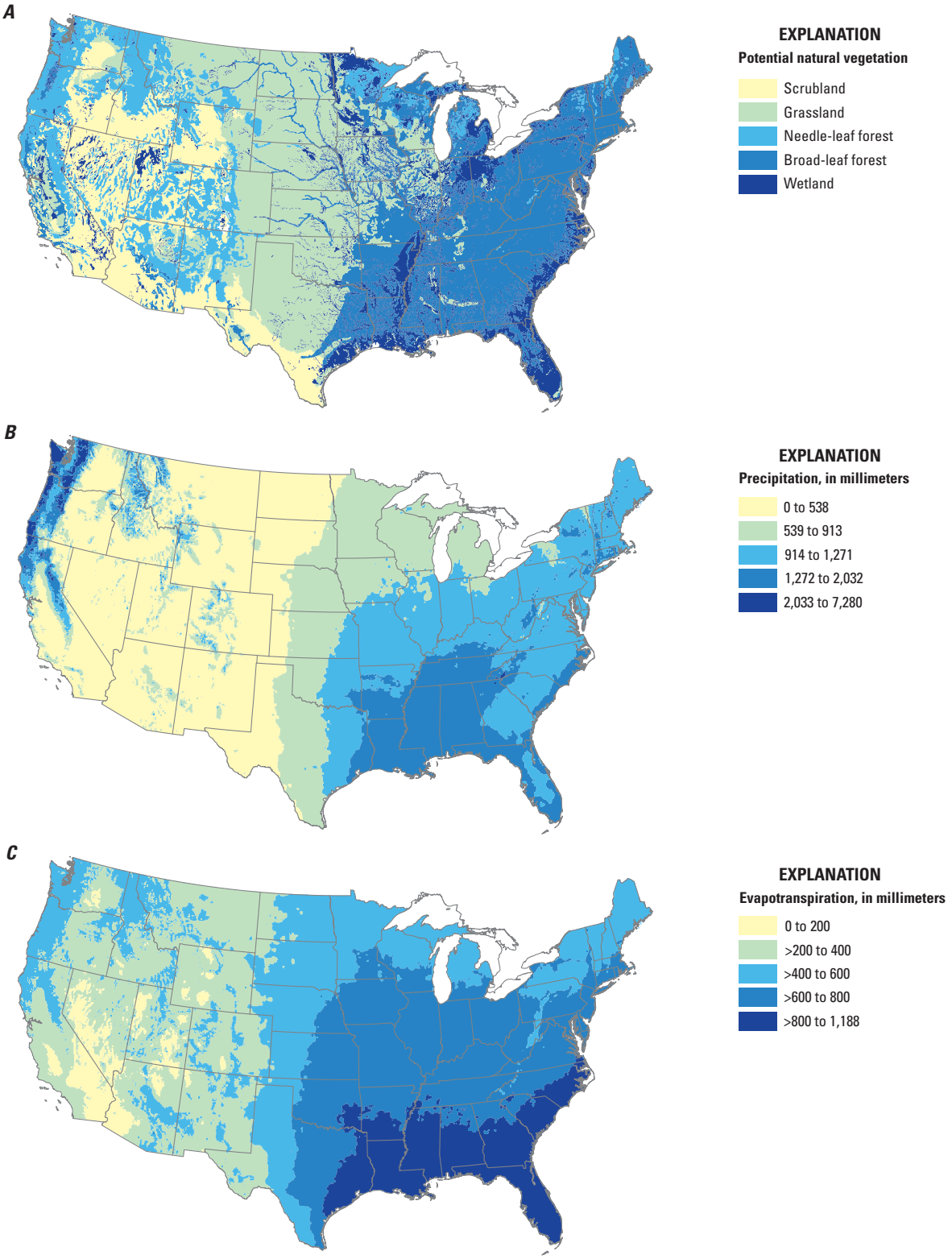


Figure 5.1. Spatial distributions of natural vegetation, average annual precipitation, and average annual evapotranspiration throughout the pre-agricultural conterminous United States (Baker and Capel, 2011).

Soil Properties, Soil Water, and Soil Erosion

Soil is the foundation of all terrestrial life. Soil is composed of solid earth materials, air, and water, with the solid phase containing both mineral and organic matter (fig. 5.2). The mineral component of soil forms when the parent rock material is broken down (weathered) by physical, chemical, and biological processes. Soil organic matter is formed from the decay of plant and other biological residues. Because of the varying effects of parent material, climate, topography, hydrology, and biological activity. Soil properties may vary dramatically from one location or depth to another.

Soils in many locations, however, tend to contain a characteristic series of layers with roughly similar features, reflecting the results of similar combinations of processes that lead to soil formation. As illustrated by the examples shown in figure 5.2, these layers, known as horizons, have different colors, texture (size distributions of their mineral particles), and (or) structure (degree of aggregation of individual particles).

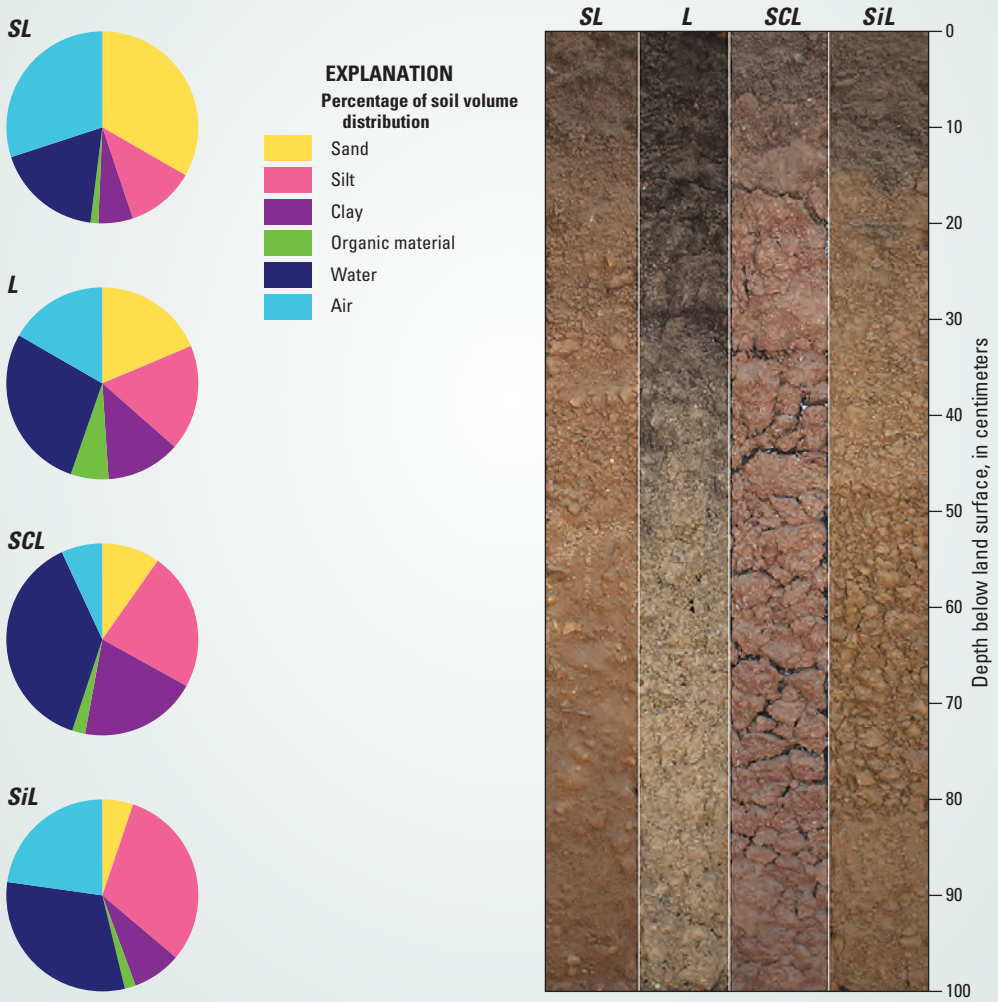


Figure 5.2. Compositions of four different soils are compared—sandy loam (SL), loam (L), silty clay loam (SCL), and silty loam (SiL). The pie diagrams show the volume distribution of the mineral solids (sand, silt, and clay), organic-matter solids, water, and air at field capacity. The soil columns show the variation in the color and degree of cracking over the top 1 meter. The darker colors indicate layers that are richer in organic matter (Capel and Hopple, 2018). Photograph by Scott Kronholm, University of Minnesota, 2010.

The uppermost (shallowest) soil layer consists largely of plant matter at various stages of decomposition. Below this uppermost layer lies the topsoil, which tends to contain a large amount of stable, decayed organic matter (humus), and mineral components derived from the weathering of the parent rock material in place. This layer also is the source of most of the water and nutrients for the plants, and home to most soil organisms (bacteria, fungi, arthropods, mites, earthworms, nematodes, insects, and others). The intense biological activity in this horizon is supported largely by energy obtained from the decomposition of plant residues during humus formation. Below this area lies the subsoil, which contains large amounts of iron and aluminum minerals leached from the overlying layers by infiltrating water and accumulated at this depth through chemical precipitation. The subsoil also contains weathered parent material. These uppermost layers contain most of the plant root systems, although some plants have deep roots that reach downward to greater depths. Deeper in the soil are zones that contain fragments of relatively unweathered parent rock material.

Weathering processes create mineral particles of different sizes (clay: less than 0.002 millimeter (mm), silt: 0.05–0.002 mm, sand: 2.0–0.05 mm; Soil Science Society of America, 2012). The distribution of the particle sizes determines the texture category of the soil. A soil with equal amounts of sand, silt, and clay (by weight) is referred to as a loam. In many soils, mineral particles become bound together by organic matter to form soil aggregates (fig. 5.3). The stability of aggregates is dependent upon the characteristics of the natural minerals they contain and the organic matter that holds these minerals together.

Soil aggregates, in turn, bind together to form clods. Between clods are pores, channels, and other conduits of different sizes and shapes. The small spaces within an aggregate are referred to as **micropores**, with diameters of 0.005–0.03 mm. The larger spaces between soil aggregates can act like small, interconnected pipes. The largest of these spaces, often referred to as macropores, are greater than 0.075 mm, and are formed by insects, earthworms, plant roots (after they have decomposed in place), and desiccation. The latter process creates channels in the soil from repeated cycles of expansion and contraction of clay particles in the soil as it absorbs water and subsequently dries out (fig. 5.4).

Figure 5.3. Soil aggregate with a plant root. Some individual mineral particles, such as the sand-sized particle of quartz, can be seen. The organic matter gives the aggregate the brownish color. Macropores can be seen throughout the surface of the aggregate. Photograph by Gustavo Merten, University of Minnesota-Duluth, 2011.

Figure 5.4. Macropores at the surface of a bare soil caused by desiccation. Photograph by Paul Capel, U.S. Geological Survey, 2009.

Water largely flows through macropores by gravity, which can be a fairly rapid process after precipitation events. In micropores, water flows at a slower rate through the soil matrix by way of capillary action, which is governed by the interfacial tension between water, air, and soil particles (capillary forces). Because of these capillary forces, soil water in small pores tends to be tightly held, but water in macropores tends to move freely. The extent to which water is stored in the soil matrix (table 5.1)—as well as the rate at which it moves through soil—is largely dependent on soil texture. In general, fine-grained (clayey) soils can hold more water than coarse-grained (sandy) soils. Three reference points are commonly used to characterize the water-holding capacity of soils. Saturation is the water content at which all pore spaces are filled with water (all air in the pores thus having been displaced by water). Field capacity is the maximum amount of water that a soil can hold for extended periods of time (days). Permanent wilting point is the lowest soil-water content at which plant roots are able to withdraw water from the soil.

Soil erosion is the process by which the forces generated by the movement of water and wind across the land surface cause the detachment of individual soil particles and their transport to other locations. During a rainstorm, this process can be initiated by the splash of a rain drop, which, if falling on a bare soil, can disrupt the soil structure (fig. 5.5), resulting in the transport of the dislodged soil particles downhill with the runoff. The runoff, in turn, accumulates in tiny flowpaths that can dislodge more soil particles. These tiny flowpaths can merge to form small channels (rills) in which the water may flow with greater energy and, thus, has a greater capacity to dislodge soil particles. These small flowpaths can, in turn, merge to form larger flowpaths (gullies) through which the water flows with even greater energy and greater capacity to erode soil (fig. 5.6). Rills and gullies are observed in both natural and human-altered landscapes, particularly in areas with substantial topographic relief.

Table 5.1. Water contents of three soil textures.

[From Neitsch and others, 2002]

Soil texture	Percent clay	Water content (fraction of total soil volume)		
		At saturation	At field capacity	At permanent wilting point
Sand	3	0.4	0.06	0.02
Loam	22	0.5	0.29	0.05
Clay	47	0.6	0.41	0.2

Figure 5.5. A rain drop splashing on a soil surface and dislodging soil particles. Photograph from U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSIA99138, 1999.

Figure 5.6. A gully formed from erosion (Kansas). Photograph by Jeff Vanuga, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSKS02008, 2002.

The loss of the soil has always been a major concern for crop agriculture. The areal extent of highly erodible cropland in the United States is shown in figure 5.7. In the 1930s, following the Dust Bowl, there was a substantial focus on soil conservation (Chapter 3), which was the impetus for many agricultural landscape modifications and many Federal subsidy programs (see "U.S. Department of Agriculture Conservation Programs" in Chapter 3). Soil erosion can be reduced with soil conservation practices, such as minimum tillage and no-tillage (see "Effects of Tillage on Runoff and Recharge" in Chapter 6).

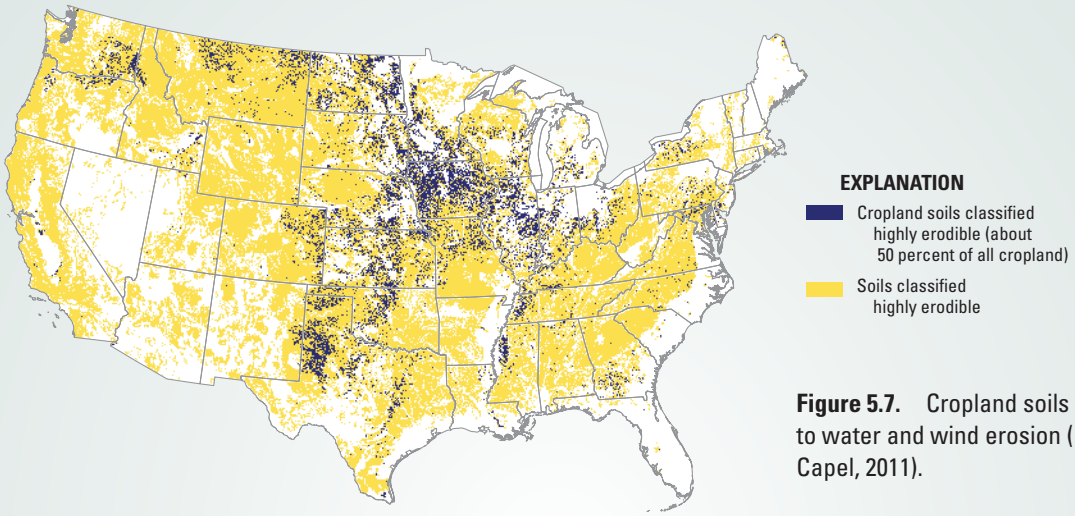


Figure 5.7. Cropland soils vulnerable to water and wind erosion (Baker and Capel, 2011).

Through years of research, the major factors in the soil erosion process have been identified and quantified in the Universal Soil Loss Equation and subsequent equations (U.S. Department of Agriculture, Agricultural Research Service, 2010). The erosion of soil from an agricultural field is understood as the product of the following factors in the equation:

$$A = R \times K \times S \times L \times C \times P \qquad (5.1)$$

where

A is the average annual mass of soil lost;
R is characteristic of the rainfall and climate;
K is characteristic of the soil;
S is characteristic of the topography;
L is the length of the field (uninterrupted field surface);
C is the choice of crop and land-cover management; and
P is the field-based agricultural modifications, such as installation of terraces, grassy waterways, and **buffer strips**.

Sedimentation, the settling of particles from water because of gravity and other forces, results when the energy of the water can no longer hold the soil (sediment) in suspension. In the landscape, sedimentation frequently takes place in topographical depressions, in the bottom of valleys, in buffer strips, and in grassy waterways where the rate of water movement (and its energy) decreases. Good land-management practices, such as the construction and (or) maintenance of buffer strips, are extremely important in reducing the transfer of eroded soil from the upland to the channel. Sediment in stream channels and floodplains is largely from eroded soils and eroded streambanks. It is one of the most frequent causes of impaired streams in the United States (U.S. Environmental Protection Agency, 2012h; Merten and others, 2016). Too much sediment in stream water decreases light penetration, which affects the productivity of the stream and disturbs the food chain; this in turn may lead to a change in the aquatic community of the stream by eliminating the base of the food chain. This elimination usually means that the more sensitive species that cannot adapt to a changing diet can no longer be present in that environment, and only the more hardy species can survive. Too much sediment also destroys habitat and buries bottom-dwelling aquatic organisms, such as mussels.

Watersheds and Water Budgets

Watersheds are defined as areas in which water collects and discharges through the mouth of a stream or river—often flowing into a larger body of water. Watershed boundaries are determined by the topography of the landscape, and the term watershed can be used to describe a vast range of sizes from the regional scale (for example, the Chesapeake Bay watershed) to areas less than 0.1 km^2 in size (fig. 5.8).

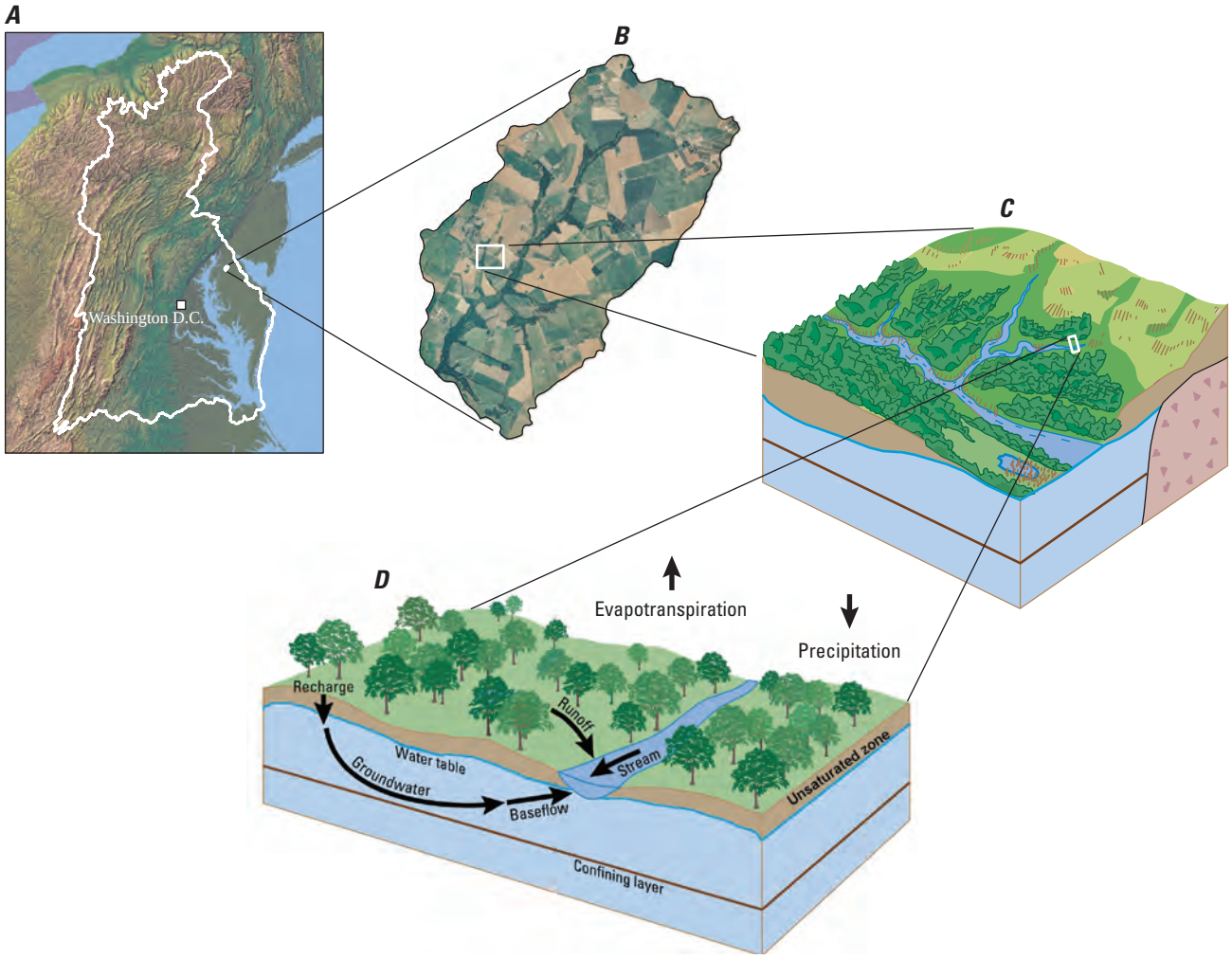


Figure 5.8. Relevant scales for water flowpaths and movement. (*A*) Regional scale, represented by the Chesapeake Bay watershed. (*B*) Watershed scale, represented by the Morgan Creek, Maryland watershed. (*C*) Catchment scale, shown in three dimensions to illustrate the connection between the surface and subsurface. (*D*) Field scale, showing the soil (brown) and groundwater (blue) zones. The arrows represent the water flowpaths for the components in the soil-water budget: precipitation, evapotranspiration, runoff, and recharge to groundwater to baseflow. Recharge from the topographically higher part of the watershed may flow into deep groundwater and leave the catchment as regional groundwater flow.

The small drainage networks where streams first appear in the uppermost portions of the landscape (catchments) can aggregate to form watersheds, which in turn can aggregate into regional-scale watersheds often referred to as basins. The amount of time required for water movement through watersheds, and the processes that control that movement, are different over this range of scales (table 5.2). At all scales, however, it generally is possible to estimate the timescales and flowpaths by which water moves into and out of these watersheds on the basis of climate, terrain, geology, land cover, and soil characteristics.

A common approach to understanding the important inputs and outputs of water through watersheds is to develop an annual water budget (Healy and others, 2007).

Precipitation (P) is the primary source of water entering the landscape for most watersheds. Precipitation can result as rain, snow, or other forms of frozen water. Average annual precipitation across the United States is shown in figure 5.1*B*. Water from precipitation exits the watershed by three primary flowpaths: water can return to the atmosphere by way of evapotranspiration, recharge to groundwater and eventually discharge to streams, lakes and wetlands, or flow directly over the land surface to water bodies.

Evapotranspiration (ET) is the sum of two processes—evaporation and transpiration. Evaporation (a physical/chemical process) is largely controlled by energy imparted by the sun and the capacity of the atmosphere to contain additional water vapor. Transpiration (a biological process) is the loss of water to the atmosphere from plants, which actively move water upward from the soil through the roots, to the stems, and eventually to the leaves, where it evaporates to the atmosphere. Estimates of average annual ET for the United States are shown in figure 5.1*C*. The measurement of ET is inherently difficult, so it typically is estimated by using mathematical relations that consider vegetation, precipitation, air temperature, wind speed, and solar radiation.

Water not evaporated or taken up by plant roots can move downward into the soil and eventually be incorporated into the groundwater system. For most natural watersheds, including those considered here, groundwater ultimately discharges into the streams that drain the watershed. This groundwater flow to streams (often called baseflow) is critical to the health of streams because it sustains streamflow during low-precipitation periods (Winter and others, 1998). As this description suggests, it is useful and important to recognize that the same water that moves down through the soil as recharge ultimately becomes baseflow, and, as a result, the movement of **recharge to groundwater to baseflow (RGB)** should be considered a single pathway that operates on timescales from days to centuries (table 5.2).

Runoff (RO) is water that flows over the landscape and directly into the surface waters that drain the watershed (for example, streams). The importance of runoff as a water flowpath is affected by precipitation, vegetation, topography, and soil characteristics. Precipitation in excess of what the landscape can assimilate at a given time produces runoff.

Table 5.2. Potential flowpaths and their associated transit times in a natural landscape.

[Blue cells indicate the typical time ranges for each flowpath under natural landscapes. Blank cells indicate that these flowpaths or time scales are not important for this type of catchment]

Flowpath	Transit time						
	Minutes	Hours	Days	Months	Years	Decades	Centuries
Flowpaths to the atmosphere							
Evaporation							
Plant transpiration							
Flowpaths to shallow groundwater							
Macropore flow through soil							
Matrix flow through soil							
Seepage from wetlands							
Flowpaths to streams							
Local groundwater flow							
Runoff							
Macropore flow through soil to stream							
Flowpaths to rivers and oceans							
Regional groundwater flow							

Thus, the propensity for runoff tends to increase with the volume and intensity of precipitation. In cold climates where snow accumulates on the landscape during winter, runoff events also result during spring snow melt and commonly cause flooding in some areas. As the timeframes in table 5.2 indicate, runoff typically occurs over minutes to hours following a precipitation event, but does not sustain surface waters during dry periods. Although streamflow increases caused by large precipitation events (for example, many centimeters of rainfall within a 24-hour period) are sporadic and short-lived, these large events primarily are responsible for shaping the stream channel and transporting sediment from erosion (see "Soil Properties, Soil Water, and Soil Erosion").

Runoff flowpaths are generally fast (fastflow) and, sometimes, high energy (fig. 5.9). In contrast, flowpaths that result in infiltration that recharges groundwater are generally much slower (slowflow) (table 5.2). Fastflow comes in contact only with the surface and (or) upper layers of the soil for short periods (hours to days). Slowflow (RGB), which eventually discharges to a stream, will come in direct contact with the soil and (or) aquifer materials for long periods (months to decades). There are other slow flowpaths, such as wetlands, which have varying degrees of contact with the soil.

Water in a stream is a mixture of the various sources of water that has moved off the landscape. The same flowpaths that move water out of the landscape deliver it to the stream. The mixture of slowflow and fastflow contributions to the stream forms a continuum that has been quantified by baseflow separation methods based on analysis of the stream hydrograph (Wahl and Wahl, 1995; Sloto and Crouse, 1996). Using these separation methods, the sources of water to a stream can be described as ranging from an end-member of 100 percent slowflow to an end-member of 100 percent fastflow. All natural streams can be located on this continuum (fig. 5.9). Streams in small watersheds can be categorized by their characteristic flowpath(s).

In practice, distinguishing between waters arriving at a stream by way of slowflow and fastflow is usually difficult. For example, water entering the shallow subsurface may find preferential pathways that bring it to discharge points near the stream in a matter of hours. Alternatively, in some cases recharge to groundwater by infiltration of precipitation causes the water table to rise above land surface, resulting in seeps or other flow pathways that rapidly deliver groundwater to the stream. These pathways are difficult to categorize because they have characteristics of both runoff and groundwater flow.

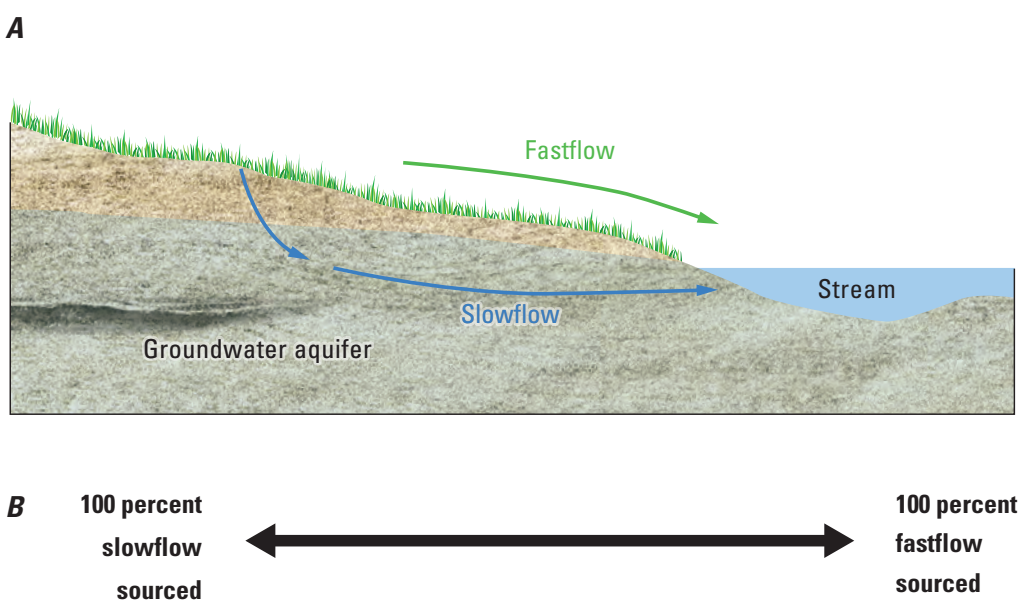


Figure 5.9. (*A*) Simplified diagram of the water flowpaths from the landscape to the stream. (*B*) Continuum of the water flowpaths from the landscape to the stream with water sourced from 100 percent slowflow to 100 percent fastflow.

From the perspective of streamflow, these pathways deliver water rapidly and contribute to the increased flows commonly associated with runoff. As a result, these pathways have traditionally been included in the RO component of the water budget. However, much of the water entering the stream by these pathways is not from the current precipitation event, and can be from months- or decades-old groundwater. As a result, the chemical characteristics of this water can be much closer to that of groundwater than to runoff from recent precipitation (Shanley and others, 2002).

Storage (S) of water in watersheds can occur in surface-water bodies (for example, lakes and wetlands), in subsurface environments (groundwater and soil moisture), and in snowpack. The storage of water in surface-water bodies can dampen high streamflow after precipitation events, and can help sustain streamflow during dry periods. For natural landscapes, the amount of water stored within the watershed can change on a year-to-year basis (ΔS); however, over multi-year periods, ΔS generally is a small component of the water budget for natural watersheds.

Wetlands are a broad term for any body of water formed when the groundwater elevation rises to land surface Wetlands can be connected to isolated from other water bodies and can range in size from the small trickle of a surface spring to vast expanses of flooded river plains to regional areas like the Everglades in south Florida. Wetlands fluctuate in size with precipitation events as well as with overall seasonal changes in water availability, and can be permanent or ephemeral (see "Agriculture in the "Delta" region of Mississippi" in Chapter 6). Wetlands can receive their water inputs from the atmosphere, surface runoff, flooding, and (or) groundwater. Seasonally, the flow of water can become almost stagnant, which allows sediment to settle to the bottom.

A simple annual water budget, on the basis of the five components discussed above, quantifies the amount of water (in units of water volume per land surface area) that moves through a watershed:

$$P = ET + RGB + RO + \Delta S \qquad (5.2)$$

where

P	is precipitation,
ET	is evapotranspiration (sum of evaporation and plant transpiration),
RGB	is recharge to groundwater to baseflow,
RO	is surface runoff, and
ΔS	is change in water storage within the watershed.

At the watershed scale, streams/rivers are integrators of all water flowpaths across and through the landscape (runoff, recharge to groundwater, surface-water flow). For many watersheds, annual streamflow (SF) is the sum of annual groundwater discharge to the stream plus annual runoff to the stream. At the watershed scale, streamflow is the component that can be quantified with the greatest certainty. Consequently, it is sometimes useful to replace the sum of RO + RGB in the water budget with SF and given as:

$$P = ET + SF + \Delta S. \qquad (5.3)$$

Morgan Creek, Maryland (fig. 5.8*B*) is used here as an example of an annual watershed-scale water budget. In the Morgan Creek watershed, the average annual precipitation is 110 cm, which is distributed throughout the year (upper part of fig. 5.10). In the pre-agricultural Morgan Creek watershed, which was mostly covered with trees and wetlands, it is estimated that 78 percent of the total outflow was due to ET. Large precipitation events resulted in short periods of high streamflow, which occurred in Morgan Creek frequently throughout the year (lower part of fig. 5.10). These events caused a rapid increase in streamflow by more than an order of magnitude, and then returned to the pre-event levels within a few days. These rapid increases in streamflow were the result of both direct runoff and rapid subsurface flowpaths.

Recharge to groundwater to baseflow (RGB) at the watershed scale generally occurs over much longer time scales than evapotranspiration and runoff (table 5.2). This is important because the longer transit times of RGB help to sustain streamflow during periods when there is no precipitation. For example, figure 5.10 shows a lack of large precipitation events during January and early February, yet streamflow is maintained at a relatively constant level over the entire period by the discharge of groundwater to the creek. In this case, simple analysis of the streamflow data based on baseflow separation (Sloto and Crouse, 1996) indicates that of the estimated 22 percent of precipitation not lost to ET, approximately one-half of this precipitation entered the stream by way of rapid pathways and one-half by way of long-term RGB. In arid regions—where the RGB pathway is minimal and depths to groundwater are greater—streams often go dry during periods without precipitation. Therefore, these streams are ephemeral.

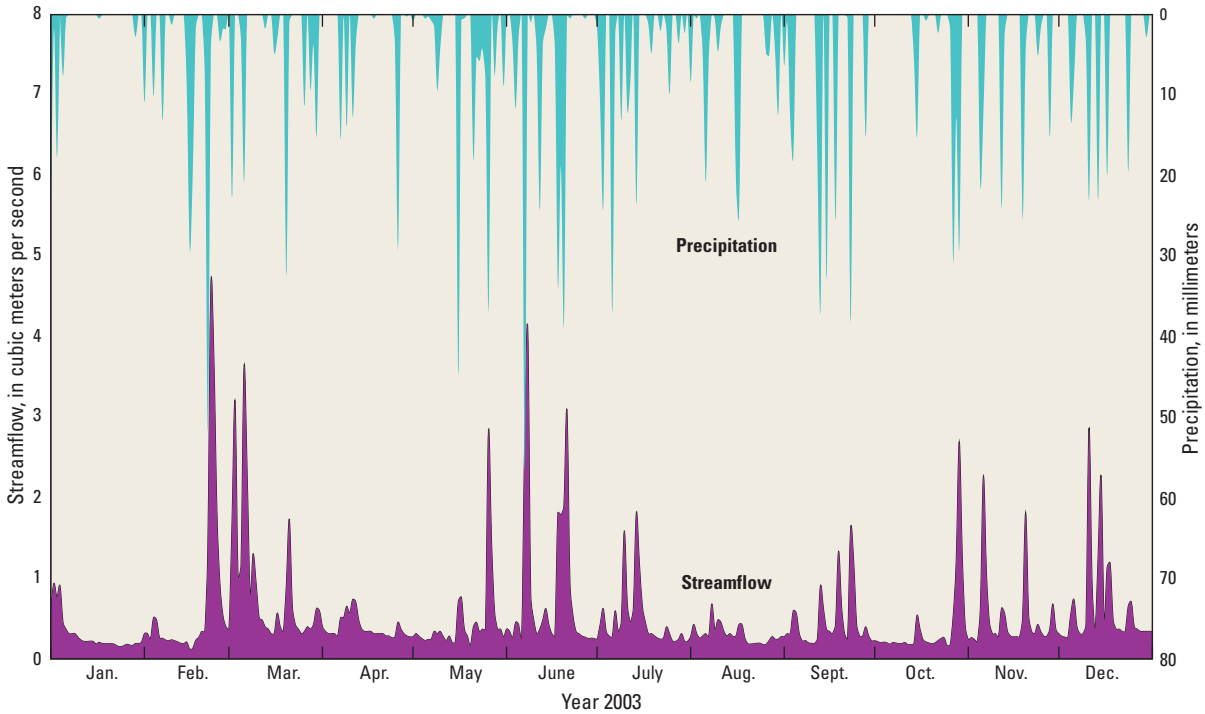


Figure 5.10. Precipitation and streamflow for Morgan Creek, Maryland, 2003. Morgan Creek is a 31-km^2 watershed in Kent County, Maryland (fig. 5.8*B*). This relatively flat, coastal landscape was naturally covered with a mixture of evergreen and hardwood trees in the upland areas and wetlands in the low-lying areas. Even during dry periods of the year, the stream never goes dry. The water at the lowest flows reflects discharge of groundwater to the stream, commonly called baseflow (RGB) (Capel and Hopple, 2018).

Field-Scale Water Budgets

In the context of agricultural chemical transport through watersheds, it is important to understand how water movement results at scales that are comparable to those of typical agricultural fields (less than 1 km^2). Field-scale water budgets can be constructed in a manner similar to that for watersheds. At the field scale, it is often convenient to define the physical boundaries of the water budget in the context of the field itself. Thus, field-scale water budgets are considered to stop at the edge of the field and at the bottom of the root zone (approximately 2 m below the land surface, fig. 5.8*D*) and do not include streamflow in the overall budget. Nevertheless, water can still be considered to leave the landscape by way of three primary pathways—ET, RGB, and RO—so that the equation used for watersheds can be applied at the field scale:

$$P = ET + RGB + RO + \Delta S. \qquad (5.4)$$

At the field scale, the timing, intensity, and duration of precipitation strongly affect the overall water budget. Consequently, it is useful to examine water budgets on daily as well as annual time scales. In most cases, precipitation is the only parameter in equation 5.4 that is easily measured, and, consequently, the other parameters generally are estimated. At the field scale, these estimates typically are made by using mathematical models where other measured parameters are used to determine the water budget (for example, temperature, wind speed, relative humidity, soil characteristics, land-surface slope; see "Quantifying Water and Sediment Budgets"). As examples, daily field-scale water budgets are examined here for three natural landscape types: humid grass, humid forest, and arid scrubland (figs. 5.11 and 5.12).

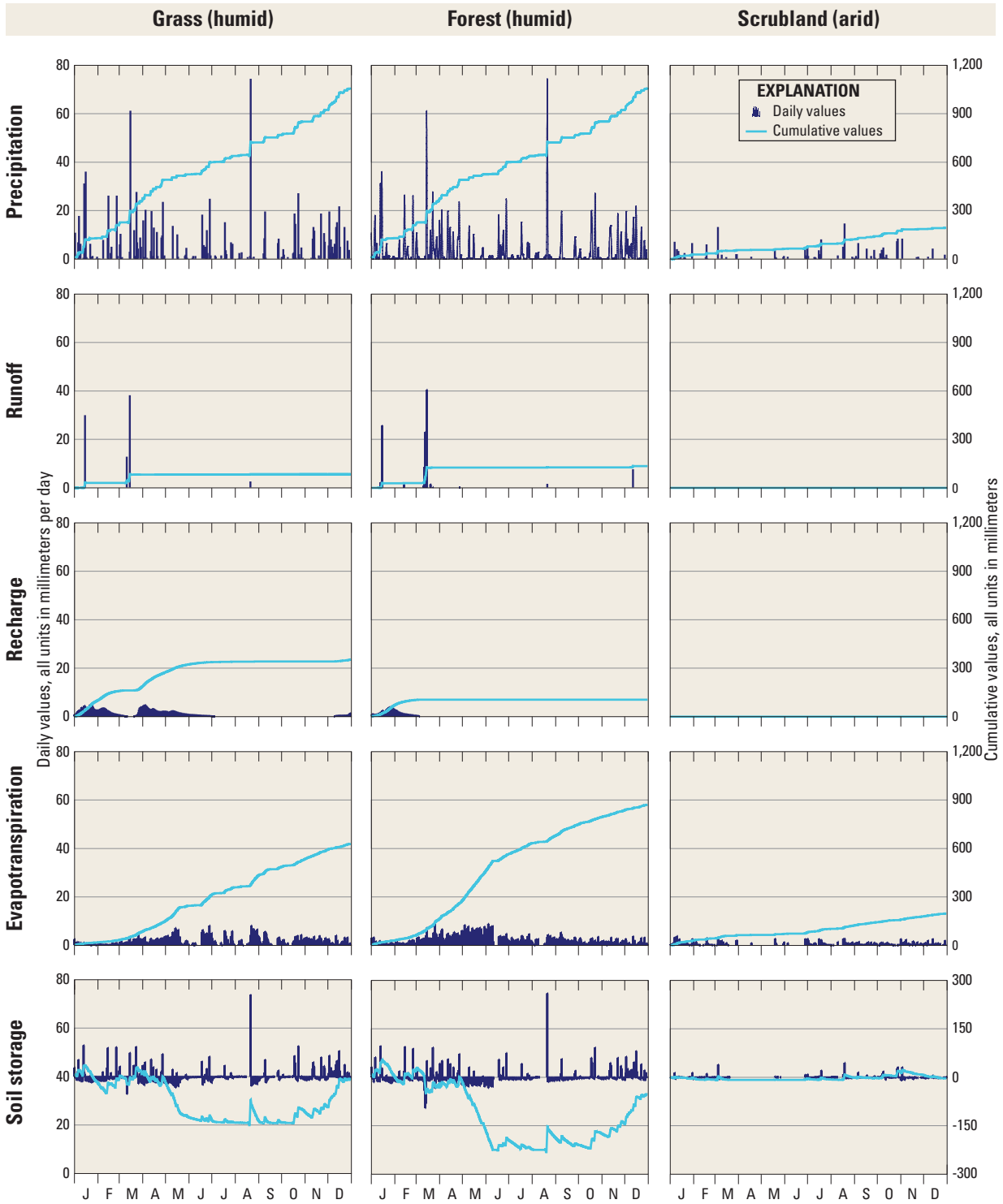


Figure 5.11. Estimates of daily precipitation, evapotranspiration, runoff, recharge, and change in soil water for three natural landscape types—grass (humid), forest (humid), and scrubland (arid). The scale of the y-axis changes among the water-budget components, but is the same across the types for a given water-budget component. The estimates are model results for a single year (2003) for the typical climate regimes of central Indiana (humid grass and forest) and central Washington (arid scrubland). For all three cases, the modeled landscape was a square with an area of 16.2 hectares, loam soil, and a 3 percent slope. (See "Quantifying Water and Sediment Budgets," Roth and Capel, 2012a).

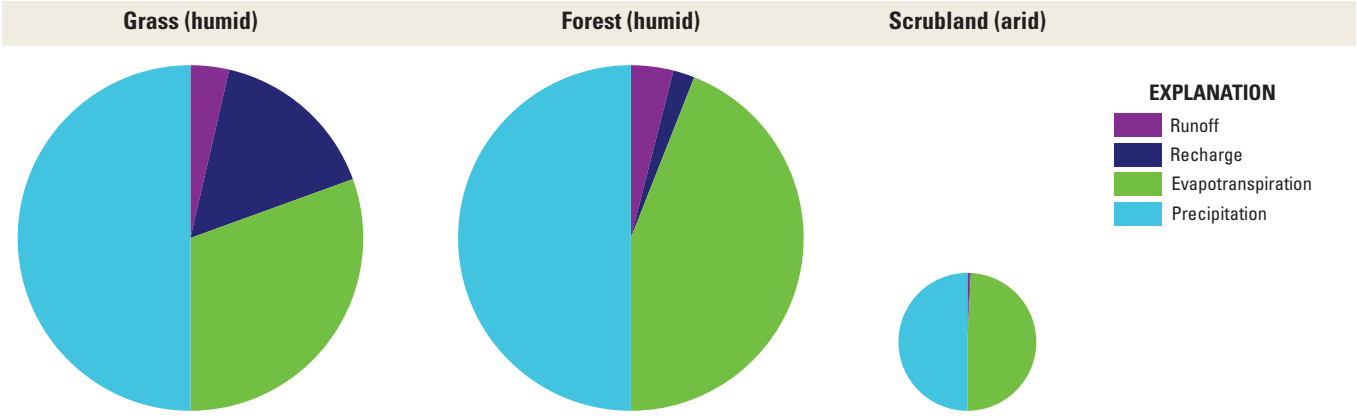


Figure 5.12. Annual inflows (precipitation) are represented by the left half of the pie diagrams, whereas the outflows (runoff, recharge, and evapotranspiration) are represented by the right half of the pie diagrams for three natural landscape types—grass (humid), forest (humid), and scrubland (arid). The area of the pie diagrams are proportional to the annual mean precipitation (108.7 centimeters for the humid climate and 17 centimeters for the arid climate). It is assumed that all water enters as precipitation. The estimates are based on model results (Roth and Capel, 2012a).

Daily water budget values for one or more years can be summed to determine annual water budgets. Multi-year averages for the three landscape types are shown in figure 5.12. Although the amount of water stored in the soil may change from year to year, as mentioned above, the long-term averages for natural landscapes tend to be constant and ΔS is, therefore, zero. Differences in both the magnitude and distribution of daily precipitation for the humid and arid cases are shown in figure 5.11. For the humid case, precipitation is distributed relatively evenly throughout the year. A substantial number of events exceed 10 millimeters per day (mm/d). In contrast, the graph for the arid case shows substantial seasonal variations in precipitation, and relatively few storm events exceed 10 mm/d.

ET is the dominant water outflow process for natural landscapes at both the field scale and in larger watersheds, accounting for nearly two-thirds of the total outflow from humid grassland and nearly all outflow from arid scrubland (fig. 5.12). ET responds to seasonal weather changes and daily precipitation. The immediate increases in ET in both the humid and arid cases as a result of recent precipitation are shown in figure 5.11. In arid landscapes, most ET occurs shortly after precipitation events, when water is readily available in the soil. In humid landscapes, where precipitation is distributed throughout the year, the short spikes in ET following rain events are superimposed on a seasonal trend, with maximum ET during the summer and minimum ET during the winter. ET in humid settings is controlled largely by the growth of vegetation and therefore is strongly related to air temperature. Precipitation that falls during the growing season is more likely to exit the landscape as ET and less likely to exit as RGB or RO (fig. 5.11).

At the field scale, RGB generally occurs over timeframes that are longer than individual precipitation events, because of the relatively slow movement of water within the soil (table 5.2). As a result, the largest daily RGB values typically are associated with multiple, closely spaced precipitation events or events of especially long duration (fig. 5.11). Because groundwater and streams generally are not included in field-scale water budgets, it is commonly assumed that all recharged water reaches the groundwater and eventually flows into the stream that drains the watershed containing the field. In humid grasslands, RGB is most important in the winter when the vegetation is dormant (fig. 5.11). Humid forests have relatively less recharge compared to humid grasslands because ET is greater for forest vegetation because of the deeper, more extensive root systems that develop to support large trees compared to grass.

Although RO accounts for only a small portion of the average annual field-scale water budget, it is the driving force for soil erosion, which is an essential process in natural landscape evolution. Generally, the few largest precipitation events generate most of the runoff and erosion.

At the field scale, stored water is present primarily in the form of soil moisture (see "Soil Properties, Soil Water, and Soil Erosion"). The amount of water stored in the soil changes as a result of precipitation, ET, and recharge to groundwater. Water near the soil surface can evaporate from the pore spaces, whereas water deeper in the soil can be drawn out by plant roots. When the water content of a soil exceeds its field capacity, water flows downward by gravity and enters the RGB flowpath. The magnitudes of short-term fluctuations in stored water are generally greater in humid landscapes than in arid landscapes. For both landscapes, there can be numerous and significant short-term fluctuations in soil-water content (fig. 5.11); the annual changes in soil water content are relatively small (less than a few percent).

Quantifying Water and Sediment Budgets

For a small area, precipitation is relatively easy to measure, but the other water-budget components are much more difficult to quantify. As a result, hydrologic models commonly are used to estimate the magnitudes of the other water-budget components. In these models, the current scientific understanding is captured in mathematical terms and equations that describe and estimate the movement of water and any other materials that it may transport across and through the landscape. One of these models is the Water Erosion Prediction Project (WEPP) model developed by the USDA Agricultural Research Service (Flanagan and others, 1995; U.S. Department of Agriculture, National Soil Erosion Research Laboratory, 2010). WEPP is a process-based model that uses the current understanding of soil erosion to estimate the quantity of sediment delivered to streams—estimates that have shown acceptable agreement with field data across the United States. The WEPP model estimates the water budget (evapotranspiration, recharge, runoff, soil-water storage) and the extent of soil erosion for a given climate, soil type, topography, vegetation, and land management regime. The model computes daily water balances and is capable of generating estimates for multi-decadal periods. Numerical values for parameters quantifying precipitation, temperature, solar radiation, soil type, land slope, and land cover are input to drive a system of equations describing interrelated processes such as infiltration, runoff, soil compaction, erosion, plant growth, and organic matter decomposition. The potential effects of a variety of agricultural management practices—such as tillage, irrigation, and drainage—also can be accounted for.

The WEPP model was used to generate field-scale soil-water budgets in both natural (Chapter 5) and agricultural (Chapter 7) settings for a square field of 16.2 ha (40 acres—a quarter-quarter section) with a loam soil and a uniform slope of 3 percent (Roth and Capel, 2012a) These water budgets were generated using 60 years of climate data from two areas—a humid site in central Indiana and an arid site in central Washington (fig. 1.3). The water that infiltrated below the top 1 m of soil was defined as recharge. For agricultural simulations at the arid site (Washington), the typical daily irrigation was added to the precipitation for the model simulations. Because of the abundance of rainfall and moisture in the humid site (Indiana), no irrigation was applied during the simulations for that site. Although the input parameter values used in the simulations for these two sites were derived from input data from the sites themselves, the results presented have not been compared with observations from either location. Instead, they are presented as examples to illustrate current scientific understanding for determining field-scale soil-water budgets.

Summary

Water moves into, through, and out of natural landscapes along expected flowpaths (for example, P, RO, RGB, and ET) and over expected timeframes. The timeframes of these flowpaths range from minutes to centuries, depending on the flowpath and the distance over which the water moves (through a field, a small catchment, watershed, or basin). The volume of water moving along each flowpath depends on a number of factors including climate (precipitation, solar radiation, and air temperature), topography, soil type, and vegetation type. At the field scale, water can be stored within the soil, and at the watershed scale it can be stored within surface-water bodies (lakes and wetlands) and subsurface environments (soil and aquifers).

In arid landscapes, ET exceeds precipitation, so nearly all water is lost through ET and little is available for either runoff or recharge. As a result, in arid landscapes streams are usually ephemeral because the water table is too far below the land surface to provide baseflow. Precipitation events are seldom large enough to induce runoff from the landscape, but the largest precipitation events can produce appreciable runoff and shape the landscape through soil erosion processes.

In humid landscapes, precipitation generally exceeds ET, but ET is the largest component of outflow of the annual water budget. Both RO (fastflow) and RGB (slowflow) can be important components of the annual water budgets in humid environments. Plentiful recharge keeps the water table shallow, which allows baseflow to sustain perennial streamflow during dry periods. Runoff can cause intense but short-duration increases in streamflow following precipitation events. This runoff can cause soil erosion and deliver sediment and chemicals to the stream, although landscapes that are covered with perennial vegetation are less prone to soil erosion processes.

Streams are integrators of all water flowpaths across and through the landscape. The interactions between the landscape and these various water flowpaths largely determine the quantity and quality of water in the stream. Because it is the water from individual field-scale and catchment outflows that aggregate to form larger streams and regional rivers, it is critical to understand the hydrologic processes at the smaller scales to understand the movement of water, sediment, and chemicals into the broader environment.

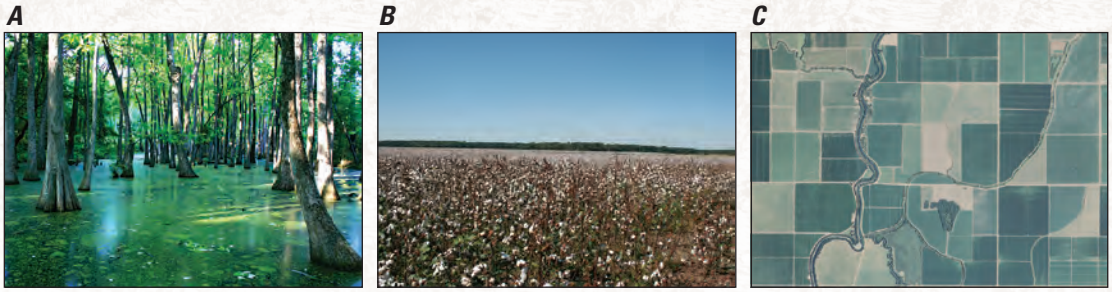
Agriculture in the "Delta" Region of Mississippi

The "Delta" Region in northwest Mississippi (fig. 1.3) is located more than 160 km north of the actual Mississippi River delta. Prior to the arrival of Europeans, the rich alluvial soil of the Delta supported vast expanses of deciduous forests, rivers, bayous, and lakes. This area had fertile soils from annual flooding, a long, frost-free growing season, and plentiful rainfall.

To make agriculture possible in the Delta, the Mississippi River had to be harnessed by levees to reduce and eventually stop the annual flooding. The wetland forests were cleared and drained. Streams were straightened; ditches and canals were constructed to move water quickly and efficiently off of the land. Farmers found cotton to be a high-value product, but also one that required a considerable amount of labor. This labor was first carried out by slaves, and then, after the Civil War, by "sharecroppers" (Zeichner, 1939). In the late 1800s, the railroad reached the Delta region, prompting a major increase in the extent of agriculture because of ease of transportation.

During the Great Depression, the Agricultural Adjustment Administration paid farmers to remove land from production to increase the price of farm products. Anhydrous ammonia was first used here as a soil-applied fertilizer in 1932. A small cylinder of anhydrous ammonia was attached to a "Georgia Stock" plow pulled by a gray mule named Ike (American Society of Agricultural and Biological Engineers, 2011). The crude apparatus and the anhydrous ammonia it applied provided a much needed source of nitrogen for the otherwise rich alluvial soils of the Mississippi Delta. Farming became increasingly mechanized during the 1950s, requiring many farm laborers to seek employment elsewhere. In the 1970s, the increasing price of soybean prompted the clearing of much of the remaining bottomland hardwoods and wetlands to make way for additional cropland. As a result, about one-half of the cropland in the Delta was planted in soybean. The remaining land was used to grow rice, cotton, and a variety of other crops including corn, peanuts, pecans, sugar cane, sweet potatoes, and pond-raised catfish. By 2010, a major increase in corn acreage in the region—driven primarily by demand for corn for the production of ethanol—almost eliminated cotton cultivation.

Because of the uneven seasonal distribution of rain, irrigation was often necessary to meet crop needs, maximize productivity, and to ensure against crop loss because of drought. Starting in the 1960s, irrigation water was drawn from streams and rivers, and eventually from groundwater (Coupe and others, 2012). Irrigation has resulted in lower water levels in the alluvial aquifer and decreased aquifer storage. The decreased storage, in turn, has led to substantially decreased surface-water flows at critical times of the year. Many streams in the Delta are no longer perennial, now flowing only intermittently during the summer in response to rainfall or irrigation. **Intrabasin transfers** or siphoning water from the Mississippi River are being considered as potential strategies to increase the amount of water available for irrigation (Barlow and Clark, 2011). Recent studies by the USGS on the effects of agriculture on water quality have focused on pesticides (Coupe and others, 2012; Rose and others, 2018), nitrogen in shallow groundwater (Welch and others, 2011), and groundwater/surface-water interactions (Barlow and Coupe, 2012).



The landscape of the "Delta" region of Mississippi. (*A*) The bottom-land hardwood swamps typical of the time before agriculture, (*B*) typical cotton field, and (*C*) the view from the air (23 square kilometers). Photographs *A* and *B* by Claire Rose, U.S. Geological Survey, 2011; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010.

Chapter 6—Agricultural Water and Soil Management

How Have Agriculture Modifications Changed the Movement of Water Through Watersheds?

Successful crop agriculture depends on the availability of adequate, but not excessive, water in the plant's root zone at appropriate times of the year. Each crop has its own minimum and maximum water needs and tolerances that change seasonally (fig. 6.1). Natural differences in the landscape and climate across the United States result in areas that have too much water available to crops, as well as areas with too little water and areas with near ideal water conditions. Agricultural activities have altered both directly and indirectly the flowpaths and volumes of water moving through the landscape.

Defined here, "modifications" are all activities in agricultural landscapes that affect water flowpaths, water budgets, wind movement, soil erosion, and sediment yields. Modifications include the implementation of current agricultural **best management practices** (BMPs), but they go beyond these to include the practices of cropping, tillage, infrastructure alterations (including irrigation, drainage), and animal management. Decisions on agricultural modifications to the landscape are made by a broad spectrum of people and organizations including individual farmers, irrigation districts, drainage districts, counties, States, and the Federal Government. The term "modifications" is used here to help avoid the limitations that commonly used terms (such as BMPs) can have on the holistic perspective that virtually all agricultural modifications can have an effect on water, and, therefore, the broader environment.

Agricultural modifications are implemented for a number of purposes (table 6.1). All of the initial modifications to the landscape were implemented to create agricultural land (see "Initial Modification of the Landscape for Agriculture" in Chapter 4). Subsequently, most modifications are implemented to sustain or increase the annual crop productivity. Some modifications are intended to sustain agriculture for the long term by protecting the water and soil resources. In recent decades, many types of modifications have been implemented to protect the environment by decreasing soil and streambed erosion and decreasing the volume and velocity of runoff water, thereby increasing the overall stability of riparian and in-stream habitat, which can further help reduce erosion and protect water quality. As a byproduct, these agricultural modifications can create and enhance aesthetic and recreational benefits. The USDA administers a number of incentive programs that encourage the use of modifications to protect soil and water resources. Some of these programs support the use of BMPs, whereas other programs encourage the removal of vulnerable lands from production (see "U.S. Department of Agriculture Conservation Programs" in Chapter 3).

Agricultural modifications are implemented over different spatial areas (table 6.1). In most cases, these areas are field- or farm-specific. For crops, fields are managed individually. Animal feeding operations also are managed at the site-specific level, whereas rotational grazing operations are managed at the multiple-field scale. Some modifications are focused on restoring stability to streams, wetlands, and fragile portions of agricultural fields that border water bodies. Finally, some modifications, particularly large public irrigation and drainage projects, are implemented at the watershed, county, or regional scale. Within this large infrastructure, farmers make decisions as to how individual fields will be connected by choosing the irrigation delivery method (gravity and sprinkler) or the type of drainage (patterned subsurface drains and **surface inlets**).

A timeframe is associated with each agricultural modification (table 6.1). Infrastructural modifications are designed to be long-term (permanent) features of the landscape. Some modifications have been in place for more than a century (drainage ditches and reservoirs) and are subject to periodic maintenance and expansion. Other modifications have time frames of years to decades, based on contractual obligations (see "U.S. Department of Agriculture Conservation Programs" in Chapter 3) or large investments made for their initial installment (terraces, forested buffers). Yet other modifications (method of tillage and choice of crop) have time frames based on the growing cycle of annual crops (see "A Year with Corn in Central Indiana"). After each growing cycle, the modification can be repeated or changed.

Every agricultural modification can affect the environment by affecting the movement of water and (or) soil through the landscape. When environmental concerns arise from agriculture, the field-based, annually changeable modifications are often targeted for change to help mitigate the concern. However, greater benefits can potentially be gained through changes to the long-term and more spatially expansive landscape modifications.

Some of the important agricultural modifications and their general effect on water budgets and water flowpaths are described in the rest of this chapter. The estimated changes in the water budget and sediment yield of a field with various field-scale modifications compared to that of a field growing corn with reduced tillage are shown in figure 6.2. The direction of changes in water budgets and water flowpaths are largely expected based on the purpose of the modification, however the actual magnitudes of these changes exhibit a high degree of site-to-site variability. The modifications closely related to crops are discussed in four groups: infrastructure, infield/edge of field, tillage, and cropping. Modifications used in animal agriculture are discussed separately.

Table 6.1. Agricultural modifications showing purposes, spatial extents, and durations of common landscape modifications for agriculture.

[**Shaded cells:** Green, crop agriculture; pink, animal agriculture; blank, not applicable. **Purpose:** 1, primary purpose; 2, secondary purposes; YD, to increase yield or other short-term economic incentive; AP, to increase agricultural protection (soil erosion, crop protection) or other long-term sustainability incentives; EP, to increase environmental protection. **Spatial extent:** FD, field scale; ST, stream reach scale; WA, watershed/aquifer scale. **Duration:** PE, permanent, SP, semi-permanent; AN, annual or less than annual]

	Purpose			Spatial extent			Duration		
	YD	AP	EP	FD	ST	WA	PE	SP	AN
Irrigation—Source water									
Groundwater-derived irrigation from annually replenished water[1]									
Groundwater-derived irrigation from "mined" water[1]									
Surface water-derived irrigation from within the watershed									
Surface water-derived irrigation from outside the watershed									
Irrigation—Delivery method									
Flood/furrow irrigation									
Center pivot irrigation									
Sprinkler irrigation									
Drip irrigation	1	2	2						
Sub Irrigation									
Drainage									
Surface (constructed) drainage networks									
Subsurface drain networks									
Field-based subsurface drains									
Surface inlet to subsurface drain									
Horizontal drains through stream berm									
Temporary drainage ditches									
Tillage									
Conventional tillage									
Reduced tillage		1	2						
Conservation tillage (including mulch and ridge)		1	2						
No till		1	2						
Cropping									
Crop rotation	2	1							
Fallow	2	1							
Cover crop		1							
Strip cropping	1	2	2						
Contour farming		1	2						
Naturalization/set aside land									
In-field/edge of field modifications									
Terraces		1	2						
Field (sediment retention) ponds									
Land shaping	1	2							
Field buffers (filter strips)									
Riparian buffers									
Fencing		1	2						
Wind break/shelter belt									
Grassed waterways		1	2						
Watershed-scale modifications									
Reservoirs	1								
Constructed wetlands									
Stream restoration/bank stabilization		2	1						
Stream straightening/channelization									
Animal agriculture									
Confined feeding operations									
Grazing									
Lagoon/waste storage									
Farm ponds									

[1]Irrigation water derived from groundwater are distinguished here between "mined" groundwater and annually replenished groundwater." with "A distinction is made between "mined" groundwater and annually replenished groundwater.

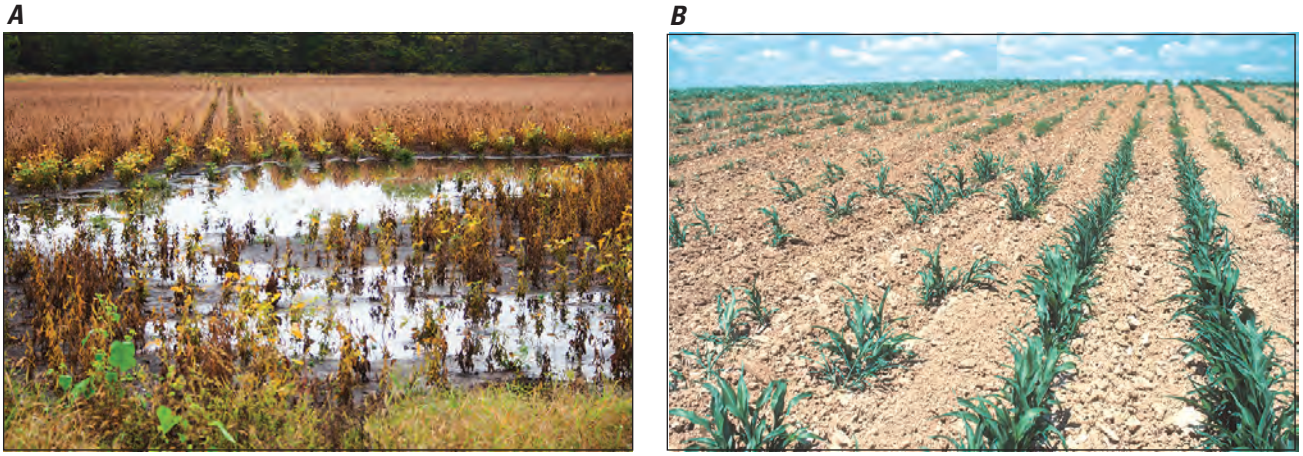


Figure 6.1. Examples of (*A*) too much water or (*B*) too little water during the growing season, which results in crop damage. Photograph *A* by Paul Capel, U.S. Geological Survey; photograph *B* by Tim McCabe, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSAR83004, 1983.

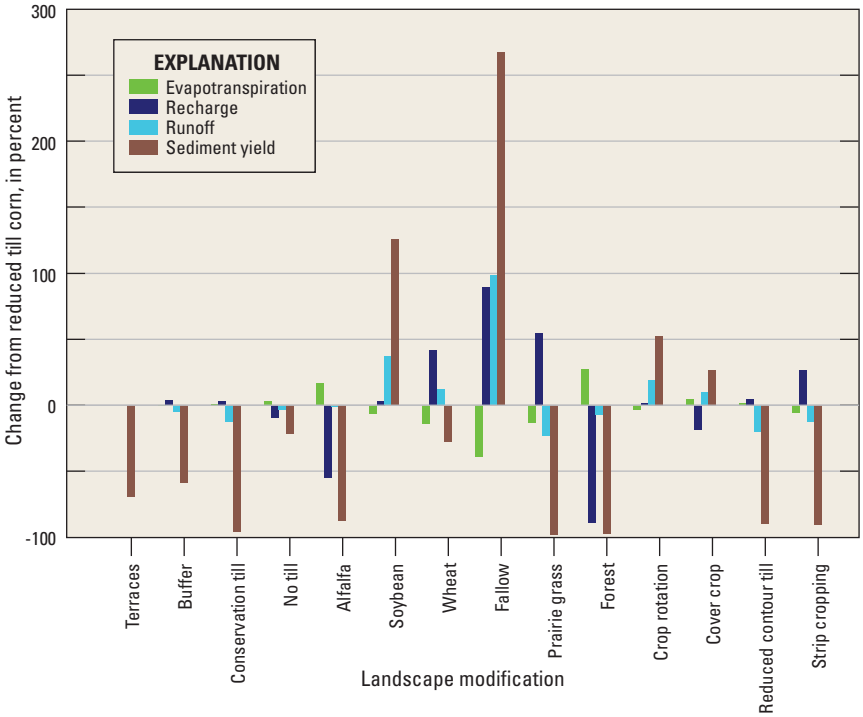
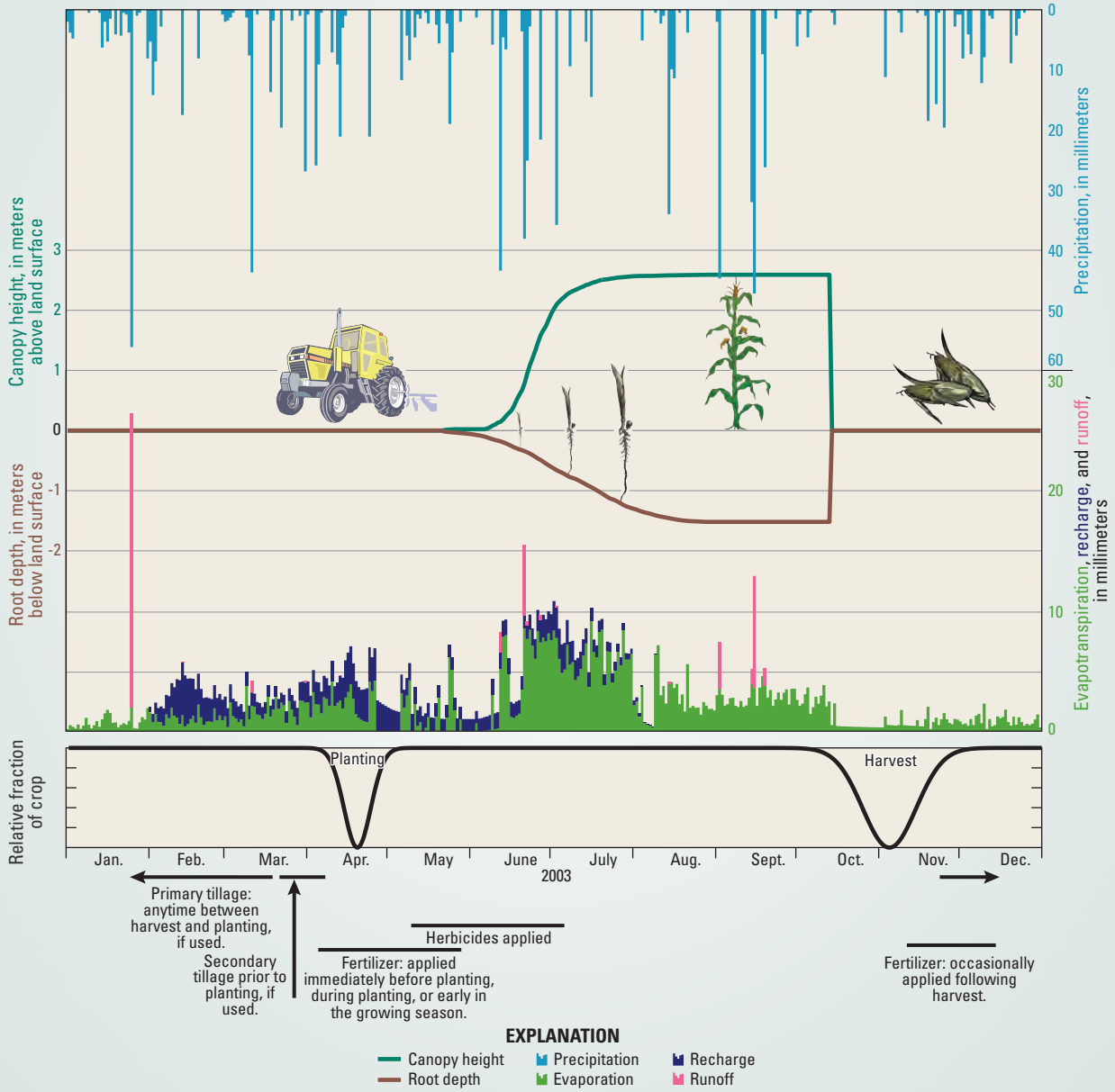


Figure 6.2. Estimated changes in the water budget and sediment yield of an agricultural field for a change in the landscape modification compared to the water budget and sediment yield in a field planted in corn with spring reduced tillage (chisel) (see "Quantifying Water and Sediment Budgets;" in Chapter 5; Roth and Capel, 2012a).

A Year with Corn in Central Indiana

Various agricultural activities, water-budget components, and crop growth are shown for a corn field in central Indiana for a typical year. A similar sequence of events occurs in most areas, although the timing of each activity will be different depending on the climate of the area. The figure illustrates the timing of agricultural management activities, changes in the growth of corn, and changes in selected parts of the water budget for the field, as estimated by the WEPP model (see "Quantifying Water and Sediment Budgets" in Chapter 5; Capel and Hopple, 2018).



Infrastructural Modifications

Irrigation.—When rainfall during the growing season is inadequate for favorable crop production, irrigation water is applied to soil to supplement natural precipitation. Irrigation water can come from many sources, which may be close to or at a distance from the water-deficient area. The choice as to the source of irrigation water is largely dependent on the availability of the water resource, cost of moving the water, legal ownership of the water, and its degree of salinity (fig. 4.4). Depending on the distance of the source and the seasonality of rainfall and snowmelt, the water may be channeled directly to the agricultural fields or stored in reservoirs for later use. Some irrigation water is pumped from shallow or deep aquifers beneath the area of use. Most of the agricultural lands in the Great Plains are irrigated from the High Plains (Ogallala) aquifer system (McGuire, 2009). Other irrigation water is available from surface-water bodies, such as rivers, springs, lakes, and reservoirs (fig. 4.4*A*), and moved through canals. The surface-water bodies may be within the watershed being irrigated or the water may be imported from other watersheds. On an annualized basis, the rate of water used for agricultural irrigation that is derived from surface water and groundwater is 290,000 and 200,000 million liters per day (L/d), respectively (Kenny and others, 2009). Irrigation for agriculture constitutes 62 percent of the total water used in the country (excluding water used for hydropower). Irrigation is particularly important in the West, where rainfall is insufficient for agricultural needs, and in parts of the Southeast, where rainfall during the growing season is insufficient. Although, in 2012, only about 17 percent of cropland in the United States was irrigated, about one-half of the value of all crops sold comes from these areas (U.S. Department of Agriculture, Economic Research Service, 2015).

Irrigation systems are conduits and devices that are used to systematically deliver water to uniformly supply an entire field with enough water to meet plant needs (neither too much nor too little) (fig. 6.3; Dougherty and others, 1995). Most irrigation systems require permanent infrastructure such as pumping wells, piping, center pivots, canals, or reservoirs. Two general types of irrigation—gravity and sprinkler—are used.

In gravity irrigation systems, water is applied directly to the upper slope of the field and moves down slope by the force of gravity. These systems can be designed to cover the whole soil surface (flood irrigation) or just the low areas between the rows (furrow irrigation). Because the systems are designed so that the entire field is irrigated, excess water (**tailwater**) generally accumulates at the downslope end of the field. This excess water becomes runoff that can transport sediment to a stream. At one time, gravity irrigation was the dominant application method, but this method is less efficient compared to sprinkler methods, and therefore is seldom used.

Diverse techniques are used in sprinkler irrigation systems to deliver pumped water to the plants as droplets. Center pivot systems are large-volume sprinklers, consisting of a single arm (joined pipes) mounted on wheels that rotates from a central point to distribute water across the perimeter of a circle. Originally, center pivot systems were designed to operate on square, quarter-section fields (65 ha), but can now cover areas much larger than this (as much as 200 ha; Evans and Sneed, 1996). This type of irrigation is especially popular throughout the Great Plains. One downside to center-pivot systems is that a substantial amount of water is lost to the atmosphere through evaporation. Drip irrigation systems deliver droplets of water, but generally with less evaporation than with sprinklers. Drip systems generally are used on a smaller scale and deliver pressurized water through pipes with perforations, adjustable nozzles, and (or) porous materials, which dispense the water close to the plants. Micro-drip irrigation, in which water is delivered to individual plants, is used to conserve water, especially in areas with limited water resources (Eisenhauer and others, 2006). These modern systems can even include subsurface emitters to limit soil evaporation and ensure that the maximum fraction of applied water possible is transpired through crop plants.

All irrigation practices purposely increase the amount of water that is moving through the agricultural landscape. For irrigation to be successful, it must be managed to control the amount, frequency, and application rate of the water being delivered to the plants yet not lose excessive water to evaporation, infiltration, or tailwater runoff, nor cause soil erosion. Although water is lost to the environment with every irrigation technique, some techniques are more efficient at delivering water to the crops than others (Eisenhauer and others, 2006).

Dams and Reservoirs.—A dam is a structure built across a stream, river, or estuary to slow or stop water movement. A reservoir contains the water impeded by the dam and functions to store water for irrigation (and other uses), control peak discharge of floodwater, improve inland navigation, provide recreation, and (or) produce hydroelectricity. In the arid parts of the United States, reservoirs are extensively used to provide irrigation to agriculture—14 percent of the 8,121 major dams in the United States are used primarily for irrigation. The total normal storage capacity for all dams in the Nation is 130 billion cubic meters (m^3) and the storage capacity for irrigation dams is 220 million m^3 (U.S. Geological Survey, 2006). The distribution of irrigation reservoirs relative to cropland in the United States is shown in figure 6.4. These reservoirs are clustered in areas of the Nation where the irrigation water is needed to support crops.

Figure 6.3. Irrigation systems come in many forms: (*A*) center-pivot arm, (*B*) aerial view of cropland irrigated by center pivots, (*C*) irrigation delivery canal, (*D*) furrow irrigation, (*E*) sprinkler irrigation, and (*F*) micro sprinkler (drip). Photographs *A*, *C*, *D*, and *F* by Paul Capel, U.S. Geological Survey, 2010; photograph *B* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010; photograph *E* by Jeff Vanuga, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSAZ02015, 2002.

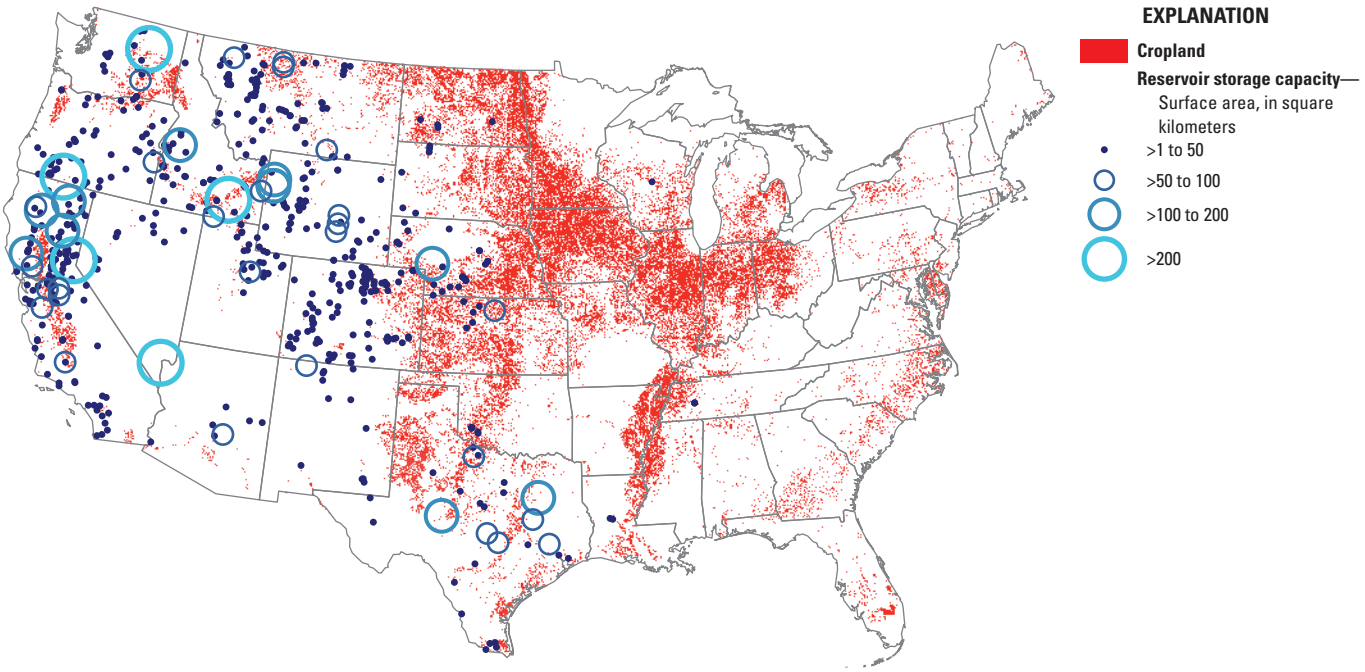


Figure 6.4. Distribution and storage capacity of reservoirs with the primary purpose of irrigation relative to cropland in the United States (U.S. Geological Survey, 2006).

Drainage.—To allow or enhance plant growth, engineered drainage is used to remove excess water in the upper soil layer (root zone). Agricultural areas that benefit from drainage generally have an overabundance of rainfall (or irrigation), slow soil infiltration, and (or) flat topography. These conditions oftentimes result in waterlogged soils and a shallow water table. These areas were wetland environments prior to drainage. In order to convert these areas to land suitable for agriculture, drainage techniques are used to remove excess water (Bos, 1994), aerate the soil, and improve field conditions to allow machinery timely access for tilling, planting, and harvesting. Generally, drainage results in warmer soil temperatures, reduced surface runoff, improved soil structure, and improved root development. Drainage systems generally are installed as permanent, integral parts of agricultural areas.

Surface and subsurface are two main types of drainage systems (fig. 6.5). Surface drainage comprises a network of shallow, open ditches (man-made streams) that convey water to larger and deeper collector ditches and eventually into a natural stream. In many areas of the country, the rural landscape is divided into a grid by the public ditch networks adjacent to the roads. In some areas of the Nation with flat topography and extensive wetlands, such as the upper Midwest, the installation of the surface ditch network was the first step in converting these wetlands into agricultural land.

Subsurface drains control the level of the water table by removing excess water from the upper layer of soil (plant root zone), usually through a network of perforated pipes (plastic or clay tile) placed at a specific depth below the land surface. Subsurface drains can be installed as single pipes running adjacent to topographically low areas or as a network of pipes that are laid parallel to each other. In isolated, topographically low areas of a field, surface inlets (perforated stand pipes) are installed and connected to the horizontal subsurface drains to speed the drainage of temporary ponds that form after storm events (fig. 6.5; Roth and Capel, 2012b). Subsurface drains deliver water to surface ditches or natural streams through infiltration and lateral movement of water along relatively fast flowpaths (hours to weeks). However, areas of the field that are far from the surface drain have slower flowpaths because the distances for lateral movement are greater.

Figure 6.5. Components of agricultural drainage: (*A*) surface ditch, (*B*) subsurface drain outlet, and (*C*) surface inlet. Photographs by Paul Capel, U.S. Geological Survey, 2008.

Engineered subsurface drainage has introduced a completely new type of water flowpath from the field to the stream (fig. 6.6). In watersheds without subsurface drainage, all water reaches the stream through a combination of fastflow, such as runoff, and slowflow, such as recharge to groundwater to baseflow (RGB). Subsurface drainage creates a third source of water (drainflow) to a stream that has both slowflow and fastflow components. The conceptual model of the continuum of two water sources to the stream (fig. 5.9) must be expanded to include an additional end-member for landscapes with subsurface drainage (fig. 6.6*B*). All streams can be located within this conceptual triangle described by the three end-member sources (slowflow, fastflow, drainflow). This is a simplification for many streams, but it is a useful organizing tool in assessing the relative contributions of various sources of water to a stream.

Streams in small agricultural watersheds can be categorized by their characteristic flowpath(s). Figure 6.7 shows rivers and streams in agricultural areas across the Nation that are expected to have slowflow, fastflow, and drainflow as their dominant flowpaths (corresponding to areas near the apexes of the triangle in fig. 6.6*B*), as well as areas that have a mixture of flowpaths (areas in the interior of the triangle in fig. 6.6*B*). Figure 6.7 is based on analysis of watershed properties, probable locations of subsurface drainage, and analysis of streamflow at gaged streams. Although this map is based on limited information, it provides a basis to help understand which flowpaths are important in various areas of the Nation. Caution must be used when using such a map because all flowpaths are affected by local conditions that cannot be depicted on a broad-scale map. The flowpaths leaving even two adjacent fields could be different due to variability in topography, soils, land management, and (or) the presence/absence of sub-surface drainage.

Surface and subsurface drainage reduce the time that infiltrating water remains in the soil (root zone) by promoting rapid transport of the water after rainfall. Many areas in which subsurface drains have been installed are underlain by soils with a high clay content; these soils have numerous macropores that enhance the rate of water movement to subsurface drains (Stone and Wilson, 2006; Smith, 2012).This rapid infiltration decreases the amount of water available for surface runoff, which in turn decreases the amount of runoff and eroded soil (sediment) that is transported to the surface ditch or stream.

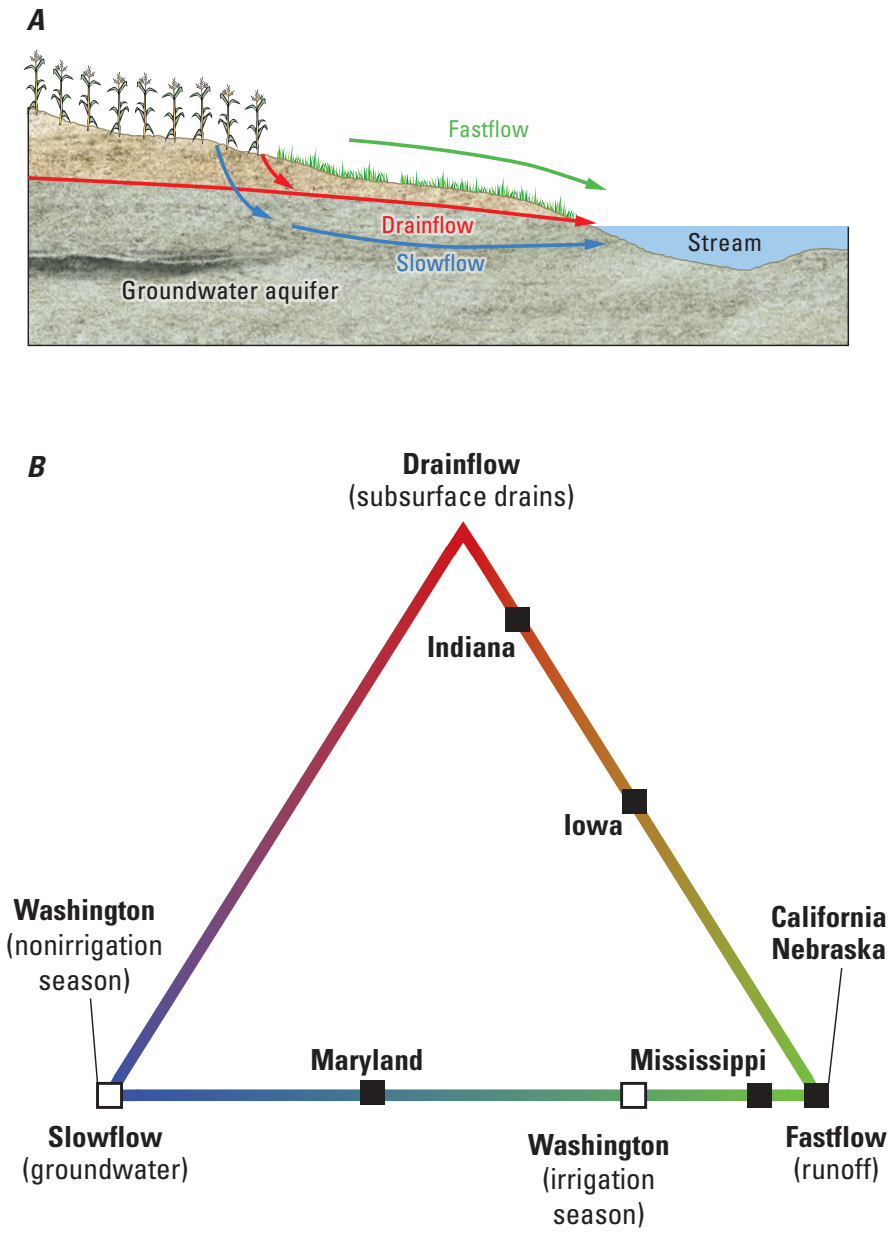


Figure 6.6. Simplified diagrams of *(A)* water flowpaths from the landscape to the stream, including engineered subsurface drainage, and (*B*) continuum of water flowpaths from the landscape and to the stream for watersheds with subsurface drainage. Water flowpaths from catchments are described by a triangular space defined by the three end-members: slowflow, fastflow, and drainflow.

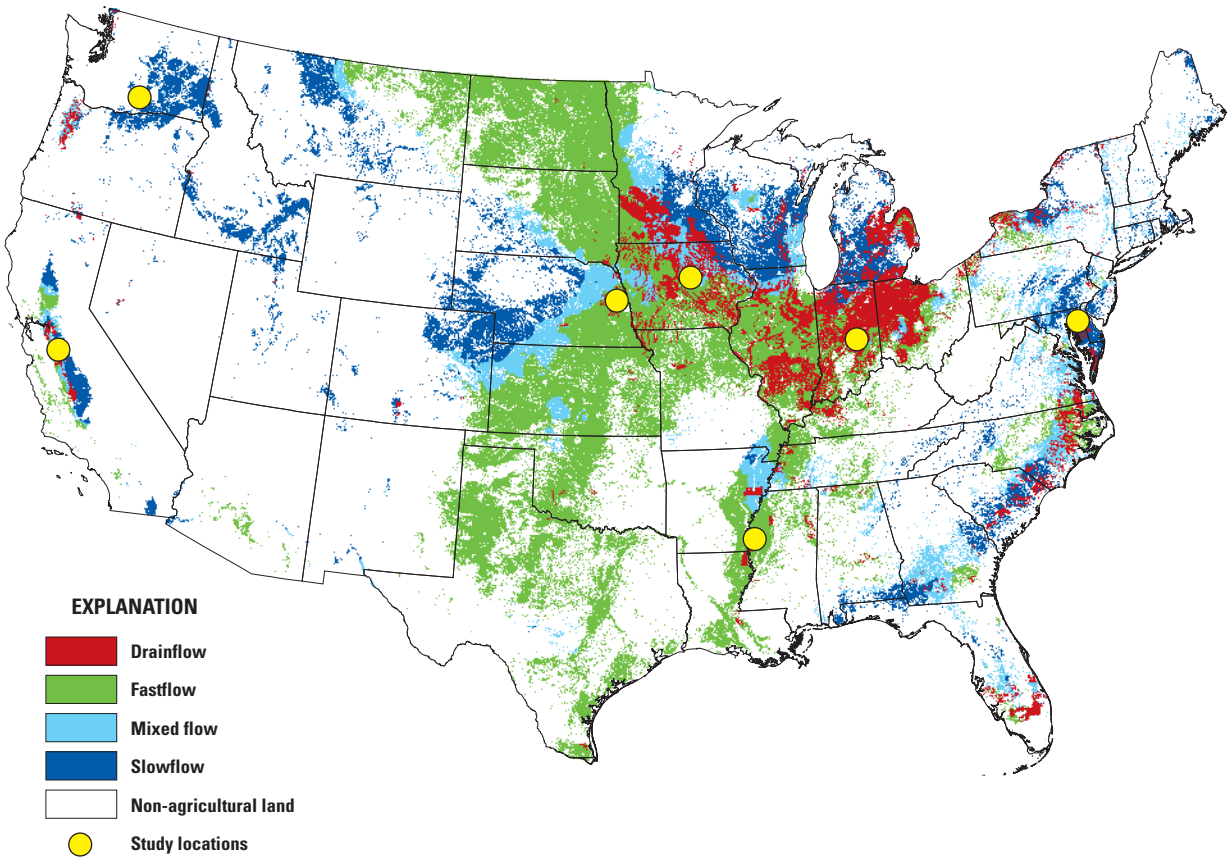


Figure 6.7. Areas in crop agriculture that are expected to have slowflow, fastflow, and drainflow as their important flowpaths (corresponding to areas near the apexes of the triangle in fig. 6.6*B*), and areas that have a mixture of flowpaths (areas in the interior of the triangle in fig. 6.6*B*). (From Capel and others, 2018.)

The topography of the field and the possible location of the drain network outlet largely determines the layout of subsurface drains for each field. In some areas of the country, public drainage districts have installed networks of large-diameter subsurface drains to provide outlets for many fields. The subsurface drainage infrastructure can be modified to partly meet the need for environmental protections (slower water movement into streams and retention of soil water during drought). Controlled drainage, in which a movable gate is installed in the drainage outlet, allows manual control of the water-table elevation (Gilliam and Skaggs, 1986; Evans and others, 1995). When the gate is opened, backed-up subsurface drainage water is released and is rapidly transported to the outlet. When the gates are closed, the water-table elevation is raised, water is stored in the soil, and the rate of subsurface drainage is decreased. Subsurface drains also can be used for irrigation purposes in dry periods (subirrigation), whereby water is pumped into the drainage system to deliver water across the lower part of the root zone.

Stream modifications are physical changes made to the stream channel (channel geometry) or to the stream corridor (in-stream or riparian vegetation). A natural stream corridor encompasses a main stream channel and the land adjacent to the stream (floodplain), as well as any wetlands and (or) tributaries connected to the stream. A natural stream meanders through the landscape, eroding sediment from the outer portion of these meanders (cut banks), where water velocities are greatest, and depositing sediment on the inner portions (point bars), where water velocities are too slow to maintain the sediment in suspension. Peak flows (highest volume) appreciably affect the natural channel's morphology, of which streambank erosion and deposition are integral processes. Over time, a stream will meander across the entire width of the floodplain, redefining the stream channel and redistributing eroded soil and sediment across the adjacent floodplain.

The meandering of a natural stream can be disruptive to row crop agriculture because of the perpetual realignment of the stream channel and the erosion of the adjacent land. To

address this meandering, many streams adjacent to agricultural lands have been channelized. Channelization replaces a natural, meandering segment of a stream with a shorter, straighter engineered segment that imparts less resistance to flowing water. Consequently, flows in the channelized stream have more energy than the natural stream, which can increase flooding and erosion downstream of the engineered segment. In response to the negative downstream effects that channelization of streams has had in some locations, previously channelized stream reaches are being restored. Stream restoration involves restoring the stream channel to its natural, meandering course, reinforcing the streambanks, re-establishing bank vegetation, and adding wetlands to the floodplain to help return the stream's ecosystems to a more natural, sustainable equilibrium, thereby reducing problems downstream (Bernhardt and others, 2005).

Constructed wetlands.—These are engineered areas in which the water levels have been raised to maintain the water table at or above land surface (Hammer and Bastian, 1989; Lowrance and others, 2006). Eventually (usually within a few years) this action results in a vegetated wetland. The wetlands are maintained by movement of water through either surface water- or groundwater-flow systems. Constructed wetlands are designed to mimic and compensate for the loss of natural wetlands. Constructed wetlands can intercept and remove sediment and chemicals from runoff and drain water before the water reaches the stream. These wetlands also can provide flood control by slowing down the velocity of water and storing it on the landscape. Constructed wetlands provide wildlife habitat and create recreational opportunities such as nature watching and hiking. In some cases, constructed wetlands are used for production of food (for example, rice and cranberries).

The water level and flow in constructed wetlands can be controlled. The rate of water delivered to the wetland combined with its storage volume determines the transit time of the water in the wetland. Often a holding pond is intentionally located upstream of the wetland to help maintain the water level during dry periods, serve as an additional settling basin for sediment, and protect wetland vegetation from water surges during storms. The water level in the constructed wetland can vary diurnally (because of evapotranspiration) and seasonally (because of rainfall patterns).

In-Field and Edge-of-Field Modifications

Landscape modifications in or at the edge of agricultural fields are usually used to reduce water runoff, which also reduces soil erosion and the amount of sediment delivered to streams (fig. 6.8).

Terraces (fig. 6.8*A*) are leveled sections of a hillslope that are designed to slow surface runoff, reduce soil erosion, and retain soil moisture (Baker, Helmers, and Laflen, 2006). Terraces can substantially decrease water runoff and sediment yield, and increase infiltration and evapotranspiration. The slower water velocity provides a longer time for resulting infiltration and evapotranspiration; therefore, terraces are used for water conservation in addition to erosion control in semi-arid areas. The slower moving water also has lower energy, which allows the eroded sediment to settle. Often, a field is formed into multiple terraces, giving a stepped appearance. The construction of terraces can increase cultivated area and allow better access for farm machinery. Different designs can be used for releasing excess water from the terraces. Some terraces route excess water through grassed waterways or surface ditches, whereas others have subsurface drains. For those terraces without engineered drainage, excess water is lost through infiltration and evapotranspiration. The effects of terraces on water-budget components and sediment yield of a corn field are illustrated in figure 6.2.

Buffers and filter strips (figs. 6.8*B* and 6.8*C*) are areas of perennial vegetation (grasses and (or) trees adjacent to agricultural fields) that provides benefits to the environment (Baker, Helmers, and Laflen, 2006). Riparian buffers, often wooded, are left between a field and a stream to protect the stream, whereas strips of vegetation within fields or just along field borders are filter strips. In both, the perennial vegetation decreases the amount and velocity of runoff, traps sediment, and increases infiltration and evapotranspiration. Vegetative buffers also provide habitat for many species of animals and plants. The effects of buffer strips on water-budget components and sediment yield of a corn field are illustrated in figure 6.2.

Grassed waterways (fig. 6.8*D*) are areas of perennial grass vegetation that are placed along ephemeral drainage ways within agricultural fields. The thick grass vegetation reduces water velocity and protects the soil surface to prevent gully formation (Baker, Helmers, and Laflen, 2006). On steeply sloping fields, the crop rows run perpendicular to the grassed waterway. In particularly wet areas or where the slope is steep, the waterways can be lined with concrete or other permanent material, rather than grass, to decrease soil erosion. Waterways are commonly used as outlets for runoff from terraces.

Land shaping is the movement of soil to shape, grade, and smooth the landscape for agricultural purposes (Baker, Helmers, and Laflen, 2006). Land shaping is frequently practiced to provide a constant slope to the land to improve for gravity irrigation. Land shaping also is used to remove surface irregularities for more effective use of water by crops, more uniform planting depths, and ease of use of farm machinery during tilling, planting, and harvesting. This practice can be used to improve terrace alignment and field contours and to reduce the ponding of water in the field. If land shaping is done incorrectly, soil structure can be damaged (compaction and clumping in wet soils) or topsoil can be lost (buried), resulting in poor crop emergence and (or) water penetration.

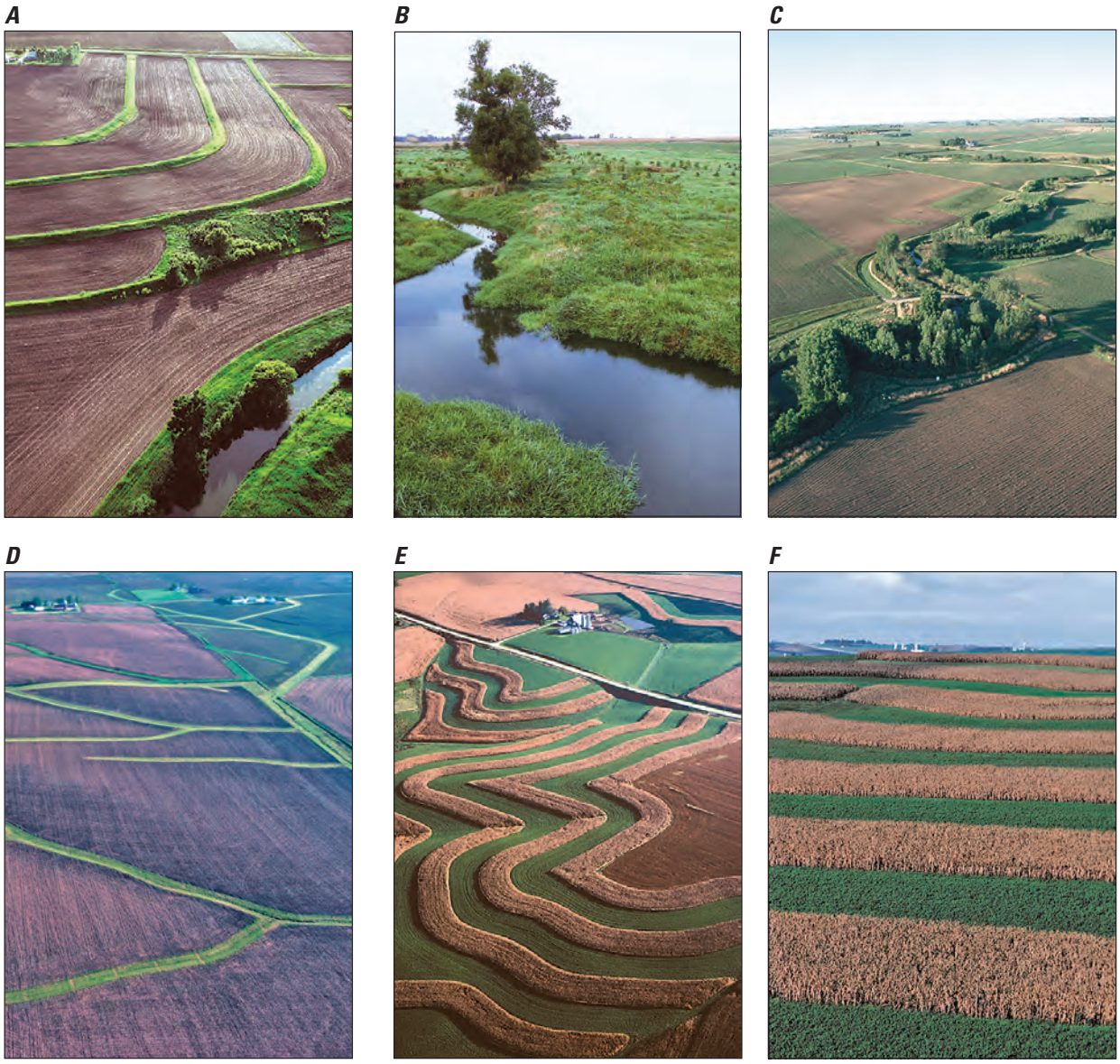


Figure 6.8. In-field landscape modifications include (*A*) terraces, (*B*) grass buffer strips, (*C*) forested buffer strips, (*D*) grassed waterways, (*E*) contour cropping, and (F) strip cropping. Photographs from U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, *A*, Lynn Betts, NRCSIA99090, 1999; *B*, Lynn Betts, NRCSIA03023, 2002; *C*, Lynn Betts, NRCSIA00041, 2000; *D*, Lynn Betts, NRCSIA99446, 1999; *E*, Tim McCabe, NRCSIA99358, 1999; *F*, Tim McCabe, NRCSIA99355, 1999

Windbreaks are linear plantings of trees and shrubs on the edges of agricultural fields or farmsteads. Windbreaks protect crops and reduce wind erosion of soils. The reduced exposure of crops to wind reduces their evaporative demand, and, hence, reduces crop water stress. Windbreaks, especially in combination with conservation tillage, help trap snow to increase soil moisture in spring in semi-arid areas. When planted around livestock areas, windbreaks help minimize animal stress and mortality, reduce feed consumption, and reduce visual impacts and odors. Windbreaks also help to reduce or prevent snow drifts and to spread the snow and, thus, spring soil moisture more evenly.

Field ponds are permanent or semi-permanent structures, such as dug basins or impoundments, that fill with water. Field ponds are used to capture storm-water runoff from fields, decrease the transport of eroded sediment to streams, and make water available for irrigation and (or) livestock needs. The water-storage capacity of the ponds helps slow down and decrease the delivery of water and sediment to the stream.

Tillage

Tillage (plowing) is the mechanical manipulation of soil and plant residue in preparation for planting seeds. Tillage mixes soil, crop residue, or applied manure throughout the plant root zone. Tillage also destroys weeds before planting, and loosens soil to facilitate deeper root penetration. Primary tillage breaks up the soil to depths of 30–55 cm and leaves a rough soil surface with many clods (U.S. Department of Agriculture, Natural Resources Conservation Service, 2010). The main primary tillage tools are the moldboard, chisel, and disk plows (see "Glossary of Farm Implements"). In many areas, primary tillage is not done every year to minimize the disturbance of the soil. Secondary tillage follows primary tillage to break up the clods and level the soil for planting. Secondary tillage is done at a shallower depth (15–30 cm). The common secondary-tillage tools include the disk harrow, spring-tooth harrow, wire-tooth harrow, and spike-tooth harrow, packer-roller, and rolling basket. From a soil conservation perspective, tillage practices are grouped by percentage of soil surface covered with plant residue after tillage (fig. 6.9). As the percentage of plant residue left on the surface increases, less bare soil is exposed to the erosive forces of water and wind.

Conventional tillage removes most of the plant residue from the surface of the soil—less than 15 percent of crop residue cover is left on the land surface. Conventional tillage can include primary or secondary tillage techniques. Primary tillage is most disruptive and results in a minimum residue cover.

Conservation tillage encompasses many different tillage practices, all of which maintain a crop residue cover of 30 percent or greater. This relatively large residue cover slows the movement of water across the land surface and reduces soil erosion. In mulch tillage, the entire field is plowed, and the crop residue is mulched (chopped) and evenly distributed across the surface.

No till is the conservation tillage practice that results in the least soil disturbance. The soil is left almost undisturbed during the period between harvesting and planting. When the crop is planted, the seeds are planted (mechanically drilled) into the soil through the remaining residue. In the no till practice, weeds are controlled by herbicides rather than by mechanical methods.

The estimated water budgets and sediment yields for a field of corn with reduced till, ridge till (conservation tillage), and no till (conservation tillage) are compared to their yields under conventional tillage in figure 6.2. In comparison to conventional tillage (using a chisel plow), all conservation tillage practices increased water infiltration, reduced water runoff, and reduced sediment yield (see "Effects of Tillage on Runoff and Recharge").

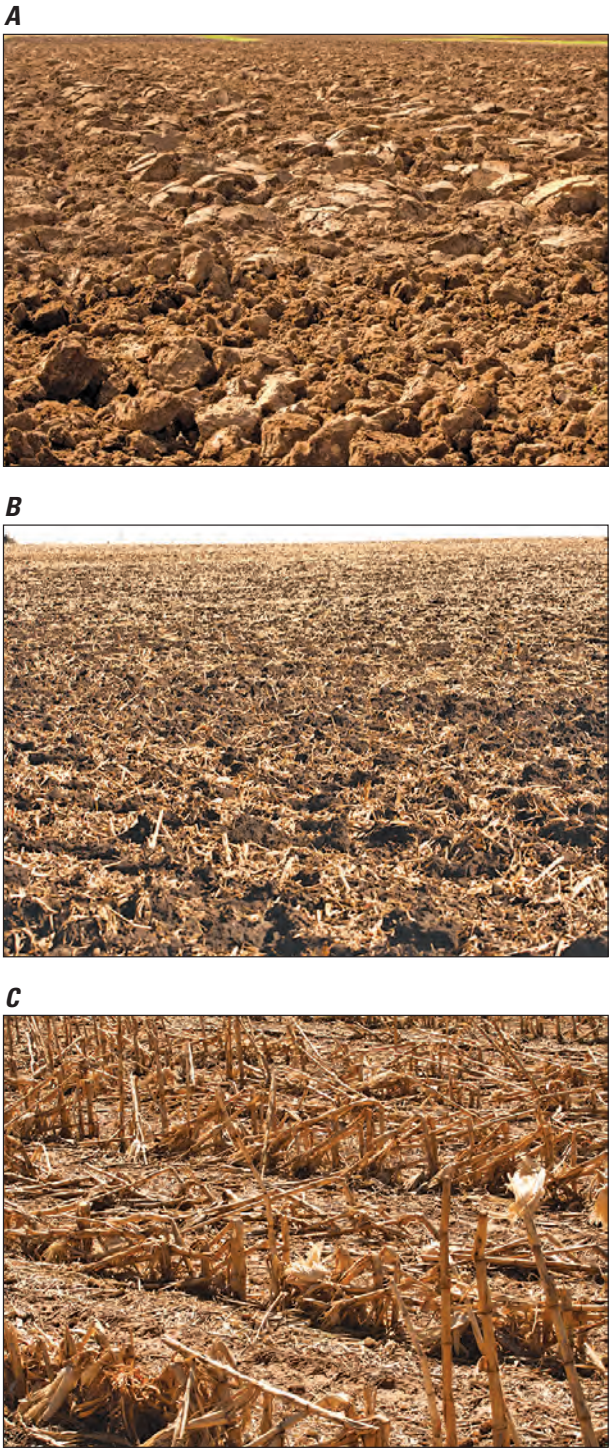


Figure 6.9. Corn residue on the land surface after (*A*) conventional tillage (<15 percent residue), (*B*) conservation tillage (>30 percent residue), and (*C*) no tillage (no-till). Photographs by Paul Capel, U.S. Geological Survey, 2009.

Effects of Tillage on Runoff and Recharge

Surface runoff from a field happens when the rate of rainfall or applied irrigation water is higher than the rate of infiltration into the soil. Water enters the soil through the network of pores that connects the surface to the deeper layers of soil (see "Soil Properties, Soil Water, and Soil Erosion" in Chapter 5). Land-use and soil-management activities can alter the pore-size distribution and continuity of the pore system, and, consequently, change important hydrological processes, such as water infiltration and runoff. The presence, size, and effectiveness of soil macropores are especially sensitive to soil-management operations, such as tillage and the weight of agricultural equipment (such as tractors and combines). Each time the soil is tilled, the numbers and sizes of soil macropores are increased (Arshad and others, 1999). Over time, however, the volume of these pores is reduced because of compaction from agricultural equipment and rainfall effects. The impact of raindrops reduces the macropores near the soil surface, whereas farm machinery reduces the soil macropores deeper in the subsurface.

After soil is tilled, the surface is poorly protected (no living plants and little crop residue). Falling raindrops collide with the soil surface, destroying some of the surface aggregates. The smaller primary particles, which comprise the soil aggregate, are initially dispersed, and then are rearranged to form a surface crust (0.5–2.0 mm thick) that becomes dense and hard upon drying. This process is called "surface sealing" (Bissonnais and others, 1989). This crust, which can form in all types of soils, reduces water infiltration and impedes the emergence of seedlings (fig. 6.10). Poor residue cover, high sodium concentration, and the presence of aggregates of low stability are important contributors to crust formation. Agricultural practices that include intensified (that is, frequent primary) tillage can accelerate decomposition of soil organic matter that maintains soil aggregation. Loss of soil organic matter leads to soil that is prone to crusting. Soil crusting often indicates a history of excessive tillage (except in arid and semi-arid areas where naturally high soil sodium concentrations can lead to soil crusting).

Figure 6.10. Lettuce plants sprouting through a dry soil crust.

Soils with crust formation are more susceptible to erosion and, consequently, the transference of excess water, eroded soil, and agricultural chemicals to the stream because of higher runoff volumes. Conservation tillage and no till are among the practices that can increase surface-soil organic matter and decrease surface sealing, reduce soil erosion, and protect the soil against the impacts of raindrops.

Cropping

The different kinds of crops and the sequence of crops grown in a given field over a period of time is termed a cropping system. Variations in cropping systems include choice of crop and crop rotation, cover cropping, contour farming, and strip cropping (Reeder and Westermann, 2006).

Corn, soybean, wheat, cotton, and sorghum are the most prevalent crops grown in the United States (Chapter 4), but many dozens of other crops are grown. Each crop has its own specific effect on the environment because of its water and nutrient needs, length of growing season, and extent of ground cover by the leaves. At times, some fields are removed from production and not planted for a short period (for example, left fallow for a growing season) or converted to native grasses or trees for conservation purposes. The estimated water budgets and sediment yields for a field of corn are compared to those for alfalfa, soybean, wheat, fallow, prairie grass, and forest in figure 6.2. Each land cover has a different water budget and a different sediment yield. Prairie grass, forests, and fields of alfalfa all act to decrease runoff and reduce sediment yield because these areas are not plowed annually and the continuous presence of perennial plant cover protects the soil.

Crop rotation is the practice of planting different crop types (grains, legumes, and grasses) in the same field in a seasonal succession to promote long-term improvement of soil quality. Crop rotation increases soil organic matter and improves soil structure and aggregation, which aid in plant root heath (Reeder and Westermann, 2006). Crop rotation also improves crop yield (Bullock, 1992). In the Midwest, corn-soybean (2-year cycle) or corn-corn-soybean (3-year cycle) are common rotations. When soybean or other nitrogen-producing plants (peas, clover, and alfalfa) are used as part of the crop rotation, they reduce nitrogen fertilizer needs.

Cover cropping involves planting fast growing grasses, legumes, or small grains (rye, clover, and oats) after the harvest of the regular cash crop. The presence of the cover crop provides shorter exposure of bare soil, which helps to decrease water runoff and protects the surface soil from water and wind erosion. The cover crop is plowed back into the soil rather than harvested, which increases the organic matter and soil fertility.

Contour cropping involves planting rows of crops at equal elevations along the contours of the landscape (fig. 6.8*E*). The crop rows planted on the contour create rows of furrowed structures across the field, which act like many small dams to slow water flow and increase opportunity for infiltration. Contour cropping is most effective on long, uniform, low-angle slopes, and aids in reducing water runoff and soil erosion, which decreases the formation of rills and gullies that can form wherever soil erosion is a problem. In addition, contour cropping can allow better farm-machine access and make planting and harvesting easier.

Strip cropping is a systematic arrangement of different crops (such as corn alternating with soybean) across a field (fig. 6.8*F*). Strip cropping is often used to decrease runoff and soil erosion on sloping terrain, where the strips are placed parallel to the contours (as in contour cropping). Strip cropping also can be used to decrease wind damage and wind erosion by planting crops with different heights in rows that are perpendicular to the direction of the prevailing wind.

Animal Agriculture

Animals are an important component of our Nation's agriculture, accounting for more than one-half of the value of agricultural products (U.S. Department of Agriculture, Economic Research Service, 2016d). Beef and dairy cattle, hogs, turkeys, and chickens (broilers and layers) are the major products (fig. 2.1*B*). Each animal requires its own unique set of agricultural activities and resources—including space, water, food, protection (from pests and weather), and disposal of the wastes. Animals are usually raised under conditions where they forage for food (pasture and grassland lands) or where they are fed (animal feeding operations). Much of animal agriculture, outside of arid areas, is interspersed in the areas of crop agriculture.

Grazing occurs on farms, grasslands, or rangelands, where animals (dairy cows, beef cattle, horses, sheep, goats, and others) are allowed to roam freely, feeding on grasses and other vegetation (fig. 2.2*B*). Commonly, grazed land is unsuitable for crop production (insufficient rainfall or too steep for machinery) and thereby generates higher profits through livestock conversion of forage into meat, milk, and other products. Overgrazing—livestock feeding that exceeds plant growth rate—can lead to soil compaction, loss of vegetative cover, and increased water and wind erosion. To guard against overgrazing, animals are moved from field to field (similar to crop rotations) allowing the most recently grazed areas time to recover (rotational grazing).

Fencing of pastures and range areas excludes livestock from unwanted areas, including streams and areas adjacent to streams. Fencing can help reduce bank erosion and eliminate the direct input of animal waste into streams. In some places, the construction of fences designed to hold livestock is mandated by law.

Animal feeding operations are agricultural practices in which the feed is brought to the animals (typically dairy cows, beef cattle, hogs, chickens, or turkeys) rather than having the animals forage (fig. 2.2). The animal feeding operations are facilities, either indoor or outdoor, where the animals are concentrated (with no available grass or other vegetation) for 45 or more days in a 12-month period (U.S. Environmental Protection Agency, 2011). There are about 450,000 concentrated animal feeding operations distributed across the United States (U.S. Environmental Protection Agency, 2011). Although the spatial footprint (overall area) of animal feeding operations is relatively small compared to that of crop agriculture, the amount of animal waste generated at a facility can have a substantial effect on the surrounding air and water quality. Animal waste can be managed in many different ways, including on-site treatment, land application (manure spreading), and long-term storage (in arid areas).

Lagoons are pond-like water treatment structures designed for temporary storage and treatment of liquid animal waste until it is used on cropland (fig. 6.11*A*). The lagoon bottom is generally sealed to protect groundwater and surface water from contamination by the waste. Most lagoons are designed to treat the waste without added oxygen (anaerobic decomposition), although other lagoons add oxygen (aerobic decomposition). Because the anaerobic lagoons are not dependent on maintaining a minimum dissolved oxygen concentration, they can be much deeper (usually from 2 to 5 m) and require less surface area than do aerobic lagoons. Aerobic lagoons are designed to provide a higher degree of treatment with fewer odors, but anaerobic lagoons can decompose more organic matter per unit volume.

Manure spreading is both a method for disposing of animal waste and for returning the beneficial components (organic material, nutrients) of the waste back to the soil (fig. 6.11*B*) (see "Manure"). The use of manure to enhance soil structure and provide nutrients to crops has been a common practice throughout the world for centuries. Manure can be spread on fields in liquid and solid forms (see "Glossary of Farm Implements"). Manure is usually applied in the fall after harvest or in the spring before planting. Manure spreading on frozen soil is prohibited in some States to protect surface water from contamination by runoff water during snow melt (fig. 6.11*C*).

Figure 6.11. Manure can be stored and treated in (*A*) on-site lagoons or (*B*) spread on fields. (*C*) Manure spreading on frozen soil is prohibited in many states, but has been done as part of a Valentine's Day message. Photographs *A* and *B* from U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery. *A*, Jeff Vanuga, NRCSGA02036, 2002; *B*, Tim McCabe, NRCSIA99216, 1999; photograph *C* from Albert Lea Tribune, Albert Lea, Minnesota.

Manure

The use of manure as a nutrient supplement for agriculture is a common practice throughout the world and is an important part of modern agriculture. About 5 percent of the Nation's crop area receives an application of manure annually (MacDonald and others, 2009). Agricultural crops benefit greatly when manure is used as a fertilizer or soil amendment. Manure adds important nutrients (nitrogen, phosphorus, and potassium), minerals (calcium and magnesium), and organic matter to the soil. When added to the soil, organic matter can increase water infiltration rates and increase moisture retention. Applying manure to fields also is a practical method for disposing of animal waste, but manure typically contains metals, antimicrobials, hormones, bacteria, and **pathogens** (Boxall and others, 2003; Hanselman and others, 2003; Martínez-Carballo and others, 2007; Andaluri and others, 2012). The use of proper storage and application techniques can help to alleviate many of the contamination issues associated with manure applications.

Many animals produce manure that is suitable for use as agricultural fertilizer. Cattle, swine, and poultry are the most common livestock animals, but these animals are not evenly distributed throughout the United States (fig. 2.1*B*). This uneven distribution leads to differences in the type of manure that is available for application at any specific location. The chemical and physical composition of manure varies dramatically with different animals (fig. 6.12), and that composition is to some extent dependent on age, health, diet, and location (climate). Manure from certain animals may be more beneficial for a particular crop or soil type than other animals. Excess of a specific nutrient, for example phosphorus, in some manure may require alteration of the animal's diet or addition of dietary supplements, for example phytase, to produce manure with the desired characteristics to fulfill crop requirements (Smith and Joern, 2012).

The improper storage and application of manure can be detrimental to the environment. Typically, liquid or slurry manures are held in storage lagoons (fig. 6.11) or in-barn pits, and dry, solid manure is stored in large piles. Liquid manures typically are sprayed on the field (see "Glossary of Farm Implements"), injected into the soil, or pumped through irrigation systems. The injection methods have the benefits of increased nutrient retention, lower runoff potentials, and reduced odors. Solid manure is applied by spreading on the surface of the field. Afterwards, the soil is sometimes tilled to mix the manure into the soil to preserve nutrients.

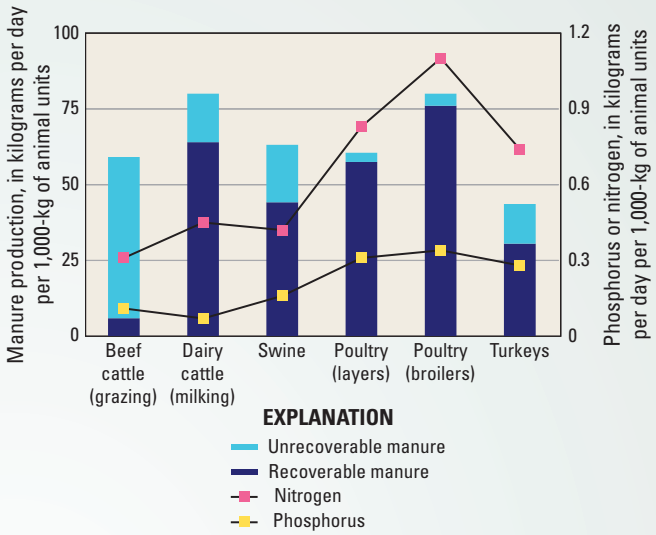


Figure 6.12. Manure and its nitrogen and phosphorus content produced by various farm animals. Recoverable manure is the manure that can be economically retrieved by the producer (Capel and Hopple, 2018).

Differences in animal distributions throughout the United States and in the composition of manure can lead to unique environmental issues in different areas. For example, the application of manure to fields in arid regions can cause a buildup of salts from the manure, thereby decreasing soil fertility if adequate rainfall or irrigation water is not available to wash the salts from the soil. Loss of manure from fields in runoff after excess irrigation or a strong storm can degrade water quality of runoff-receiving streams through the addition of organic matter, nutrients, and bacteria. In areas where there is a high density of animal feeding operations, the local production of manure may be greater than is needed by the crops; over application of manure as a way to dispose of it results in excess nutrients (see "Nutrient Management Plans" in Chapter 8). This can lead to a build-up of soil phosphorus and contamination of surface water, or leaching of excess nitrogen as nitrate.

Agricultural Landscapes

Each of the agricultural modifications discussed above has its own unique effect on the environment, affecting movement of wind and water and, ultimately, the transport of sediment and agricultural chemicals to the broader environment. Many agricultural modifications affect individual fields. Some of the modifications, however, also can affect surrounding fields and nearby areas. The combined effect of all modifications defines the agricultural landscape. The combination of the many modifications determines the water budget and water flowpaths of the local stream and the impacts on the broader environment. An aerial photograph of an 11-km^2 agricultural area in north-central Iowa with many of the agricultural modifications of the area identified is shown in figure 6.13. The next chapter discusses the water budgets and local water flowpaths of agricultural-dominated watersheds that result from combinations of these modifications.

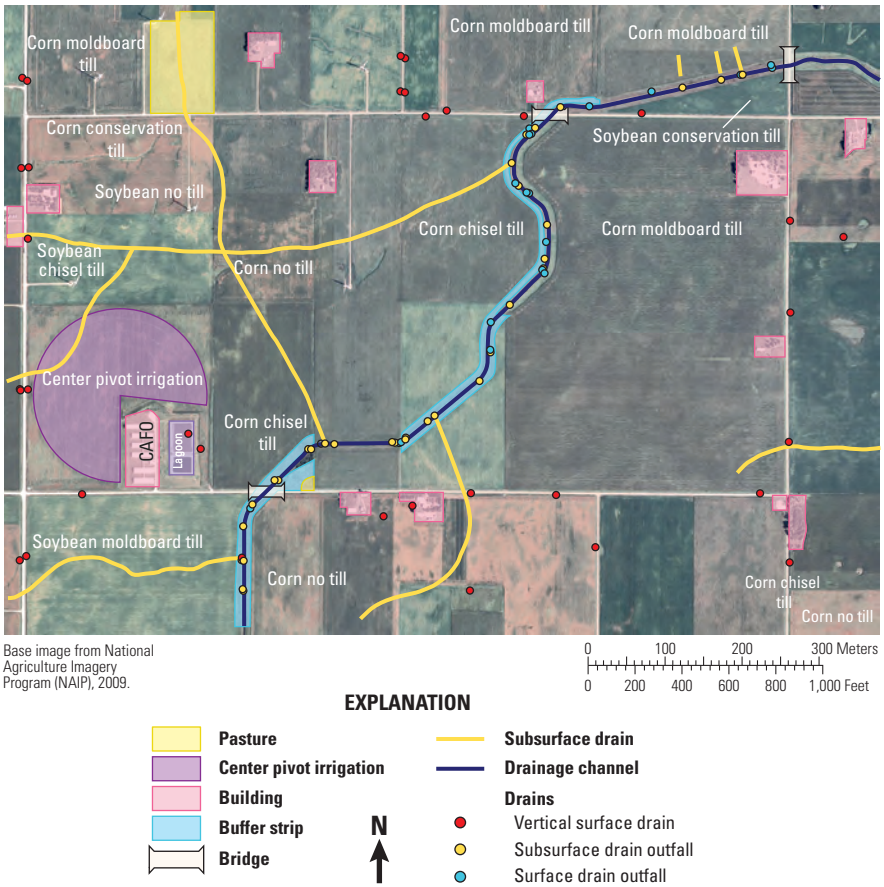


Figure 6.13. Aerial photograph of an 11-square kilometer agricultural area in north-central Iowa with many of its agricultural modifications identified (CAFO, concentrated animal feeding operation.)

Summary

Crops and animals need water in the proper amount and at the proper time to survive and thrive. To meet the changing needs of agriculture over time, modifications have been made to alter water budgets, water flowpaths, wind movement, soil erosion, and sediment yields. Agricultural modifications include irrigation, reservoirs, drainage, tillage, cropping, in-field and edge-of-field management practices, and accommodations for grazing and feeding operations. Crop agriculture is more spatially extensive than animal agriculture, so the effects of its modifications are seen across a larger area. Modifications for animal agriculture have great variability, however, because of the type and density of animals raised.

The primary goal of most agricultural modifications is to increase productivity. Other modifications have goals of protecting and sustaining the soil and water resources and (or) protecting the broader environment. These protective/preventive practices are often referred to as conservation practices. Some modifications are annually renewable, whereas others last for years to decades, and some have become permanent features of the landscape. Whereas most of the modifications are implemented at the field or farm scale, some are implemented along stream reaches or at the county or regional scale.

Landscape modifications can be changed, as needed, for the benefit of agriculture and (or) to benefit the environment. Changes are determined by an number of factors, including Federal, State, and local policy and management decisions, as well as farmer decisions on profitability, sustainability, and need for operational maintenance. Landscape modifications of short duration (annual) or small scale (field) are often the easiest (and least expensive) to make, but these changes may not be as effective in protecting the environment as changes to the long-term (years and decades) and more spatially expansive modifications.

Each agricultural modification has its own unique effect on the environment, affecting movement of wind and water and ultimately the transport of sediment and agricultural chemicals to the broader environment. Many agricultural modifications affect individual fields. Some of the modifications, however, also affect surrounding fields and nearby areas. The combined effect of all modifications defines the agricultural landscape. The combination of the many modifications determines the water budget and water flowpaths of the local stream and the impacts on the broader environment.

Agriculture in Central Washington

The floor of the Yakima River Valley lies in the rain shadow of the Cascade Mountains (fig. 1.3) and receives only about 18 cm of precipitation each year. When settlers first arrived in the mid-1800s, the area was covered with grass, primarily bunchgrasses, and other small desert shrubs. Snowmelt from the upper elevations provided seasonal flow in streams, but most of the region was arid and not suitable for crop agriculture.

The first settlers, mostly cattle or sheep ranchers, built small ditches to route river water to their land. They found fertile soils and a climate with long hot days and cool nights throughout summer that was well suited for the growth of certain crops like apples. As the population grew, so did the demand for water to supply irrigation needs. In the 1880s, work began on a system of irrigation canals to deliver water from the Yakima River to cultivated fields. The largest, Sunnyside Canal, was completed in 1980. By the early 1900s, the irrigation system supported thriving agriculture including alfalfa, clover, hay, hops, vegetables, and orchard fruits. With substantial quantities of irrigation water being applied, standing water occurred in the low-lying areas, creating seasonal wetlands, and concentrating alkali in the soils. By 1902, rises in the water table of as much as 23 m were reported (Jayne, 1907), and the need for engineered drainage became apparent. Drainage Irrigation Districts were established and construction of a system of drainage canals was begun.

The farms in the Sunnyside Canal area of the Yakima Valley typically are small, ranging in size from 1 to dozens of hectares that produce a large diversity of crops including corn (both grain and silage), tree fruits, juice and wine grapes, asparagus, and alfalfa. Land use also includes dairy and cattle feeding operations. Approximately 10 percent of the land is used as pasture (Payne and others, 2007). High-technology drip-irrigation systems, capable of sensing water and nutrient needs of individual plants, are being used for high-value crops such as “designer” apples. Drip irrigation systems require high initial installation costs but low long-term operation costs.

Recent studies on the effects of agricultural on water quality in the Yakima River watershed have focused on nutrient contamination in surface water (Wise and others, 2009; Wise and Johnson, 2011), nutrient contamination in shallow ground water (Domagalski and Johnson, 2011; U.S. Environmental Protections Agency, 2012g), and water temperature (Voss and others, 2008).

The landscape of central Washington. (*A*) The small desert shrubs typical of the time before agriculture, (*B*) typical cropped fields with the Sunnyside irrigation canal, and (*C*) view from the air (23 square kilometers). Photographs *A* and *B* by Paul Capel, U.S. Geological Survey, 2010; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agriculture Imagery Program, 2010.

Chapter 7—Water on the Modified Agricultural Landscape

How Has Agriculture Changed the Movement of Water Through Watersheds?

Approximately 13 percent of the land in the United States is used to grow crops (not including hay, fig. 2.1*A*) (Baker and Capel, 2011). When these natural lands were converted from natural to agricultural use, the natural water cycle was altered. Ongoing agricultural modifications continue to alter the water flowpaths through the landscape. Although many agricultural modifications are field based, their combined effects have an appreciable effect on the water budget and the local flowpaths. These modifications also affect how the agricultural landscape interacts with the broader environment. An understanding of how agricultural modifications have changed and continue to change the water cycle and water flowpaths is an important foundation for effective policy and management decisions.

Crops thrive where the soil is fertile and well drained, land slope is gentle, and the right amount of water is available during the growing season. Where these factors are part of the natural landscape, only minor changes were necessary to convert the natural landscape to productive agriculture. However, where the natural landscape was not well suited for agriculture, extreme changes were needed for agriculture to succeed.

Generally, modifications to the natural landscape to support agriculture have proven successful throughout the United States. However, the modifications to the natural landscape have, in some cases, negatively impacted the environment. Whereas many of these consequences of agricultural modifications were intended—increased water input in arid areas, optimization of soil moisture, altered runoff patterns—some were unintentional and their long-term effects unforeseen.

One of the important ways that agricultural landscape modifications have changed the environment is by altering water flowpaths. Water moves through catchments along expected flowpaths that connect the various components of the hydrologic systems—atmosphere, soil, groundwater, and surface water. For a particular catchment, each flowpath starts at a specific location where water from precipitation or irrigation enters the catchment and ends at the point where the water leaves the catchment. For example, a flowpath may start at a point in a field where irrigation water contacts the land surface and end at a point where the local stream flows out of the catchment. At the catchment scale, streams are considered as the primary integrators of water landscapes, and shallow groundwater is considered largely as a conduit through which water flows toward streams. In some locations around the country, some of the water that infiltrates into the soil recharges deep groundwater systems that eventually discharges to distant streams, lakes, or the ocean. In general, this deep, regional groundwater system is not relevant to the catchment scale.

Depending on its route between the starting and ending points, each flowpath has a characteristic transit time. Transit times range from short (minutes and hours) to long (decades and centuries) periods of time (table 7.1). The degree to which agricultural modifications change water movement depends on which flowpaths were important before agricultural development and which flowpaths are important as a result of the agricultural modifications. (The transit times associated with natural water flowpaths are summarized in table 5.1.)

The effects of agricultural modifications on water budgets and water flowpaths for three typical pre-agricultural settings are discussed in the following sections. Specific location examples show that a combined understanding of the underlying natural hydrology and the local effects of various agricultural modifications provide the basis for understanding the manner by which water moves through agricultural areas.

Table 7.1. Potential flow paths and associated transit times in an agricultural catchment.

[Red cells indicate the typical time ranges for each flowpath for agricultural catchments. Blank cells indicate that these flowpaths or time scales are not important for this type of catchment]

Flowpath	Transit time						
	Minutes	Hours	Days	Months	Years	Decades	Centuries
Evaporation							
Plant transpiration							
Macropore flow through soil							
Matrix flow through soil							
Seepage from wetlands							
Local groundwater flow							
Subsurface drain flow							
Runoff							
Macropore flow through soil to stream							
Regional groundwater flow							

Where the Natural Landscape is Well Suited to Agriculture

Where sunlight and rainfall during the growing season are adequate, the soil is fertile and well drained, and the topography is gentle, only slight modifications are necessary to adapt natural landscapes to agricultural production. As agriculture was developed and expanded across the country, the areas that were naturally well suited to agriculture typically were the first to be cultivated. Although these areas required relatively little modification to become agriculturally productive, some fundamental changes that were necessary have had important hydrologic and environmental consequences.

When natural land was converted to cropland, the first fundamental change to the landscape was preparation of the land surface by clearing native vegetation and plowing the soil (see "Initial Modification of the Landscape for Agriculture" in Chapter 4). Plowing and other tillage practices removed vegetation, broke the soil surface, and loosened the soil in preparation for planting crops. Sometimes, the land surface was altered by leveling, smoothing, or grading in order to reduce surface ponding or to reroute runoff. These land-shaping modifications typically increase the rate at which water is routed from fields to streams and, therefore, can increase peak streamflow during storm events.

The second fundamental change to the landscape resulted when land was converted to cropland; the native vegetation was replaced with crops. The amount of water used by seasonal crops typically is less than that used by native perennial vegetation, and the decrease in evapotranspiration means that additional water is available (Scanlon and others, 2005; Zhang and Schilling, 2006; Schilling and others, 2008). This additional water can either run off to a nearby stream, or move through the soil surface, recharge the shallow groundwater, and eventually enter the stream as baseflow. The increased groundwater recharge can result in a rise in the water table and increased baseflow to the stream.

Typically, when a watershed that is well suited to agriculture is developed, the overall effect on the water budget is to decrease the volume of water that leaves as evapotranspiration, increase the volume that flows to the stream, and increase the overall streamflow that leaves the watershed (fig. 7.1). In most of these watersheds, the water flowpaths are the same or similar to those present prior to agriculture. Morgan Creek, Maryland, provides a specific example of a watershed that is naturally well suited to agriculture (see "Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Well Suited to Agriculture" in Chapter 7).

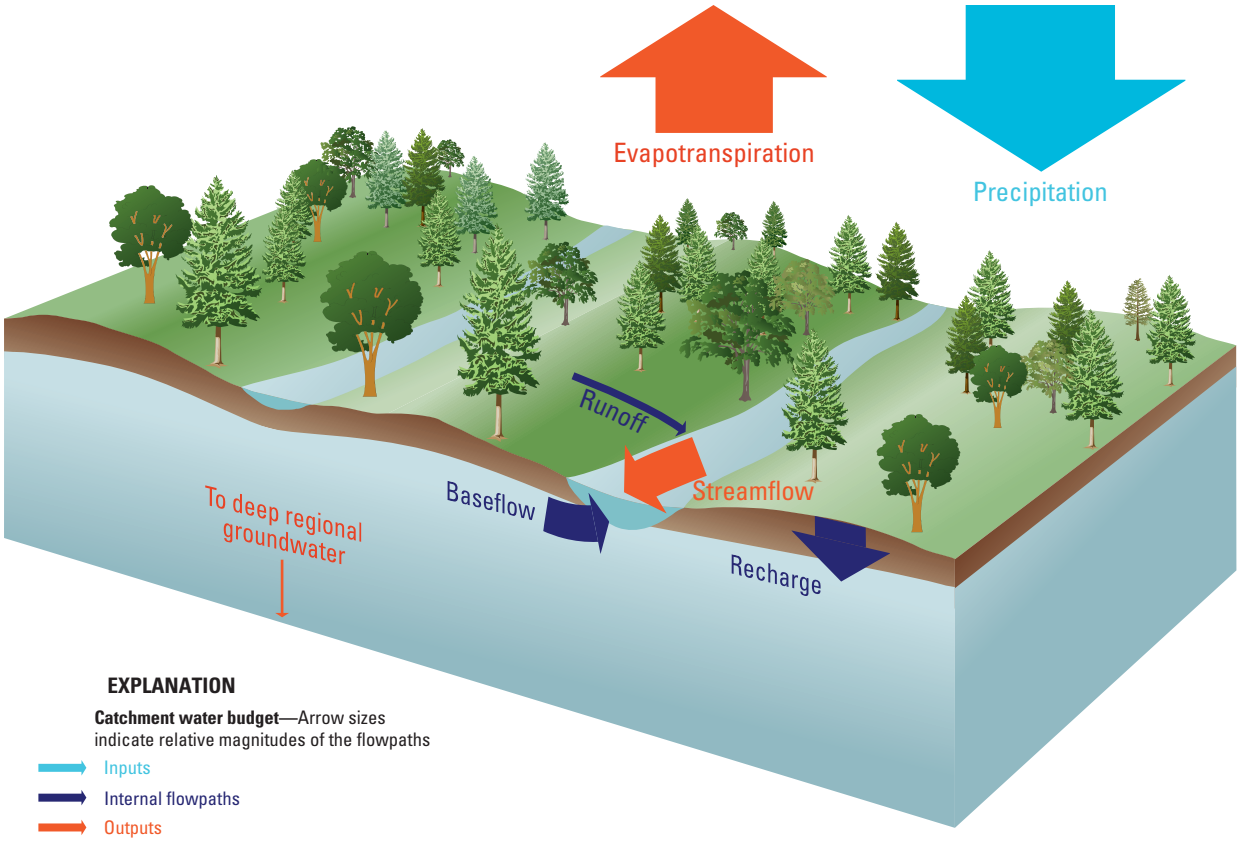


Figure 7.1. The natural water cycle in a setting that is well suited to agriculture. Under natural conditions, a large amount of the precipitation in the catchment is consumed by evapotranspiration, a small amount of the excess precipitation is moved to the stream by overland flow paths, and the remainder moves through the soil surface, recharges the groundwater, and enters the stream as baseflow.

Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Well Suited to Agriculture

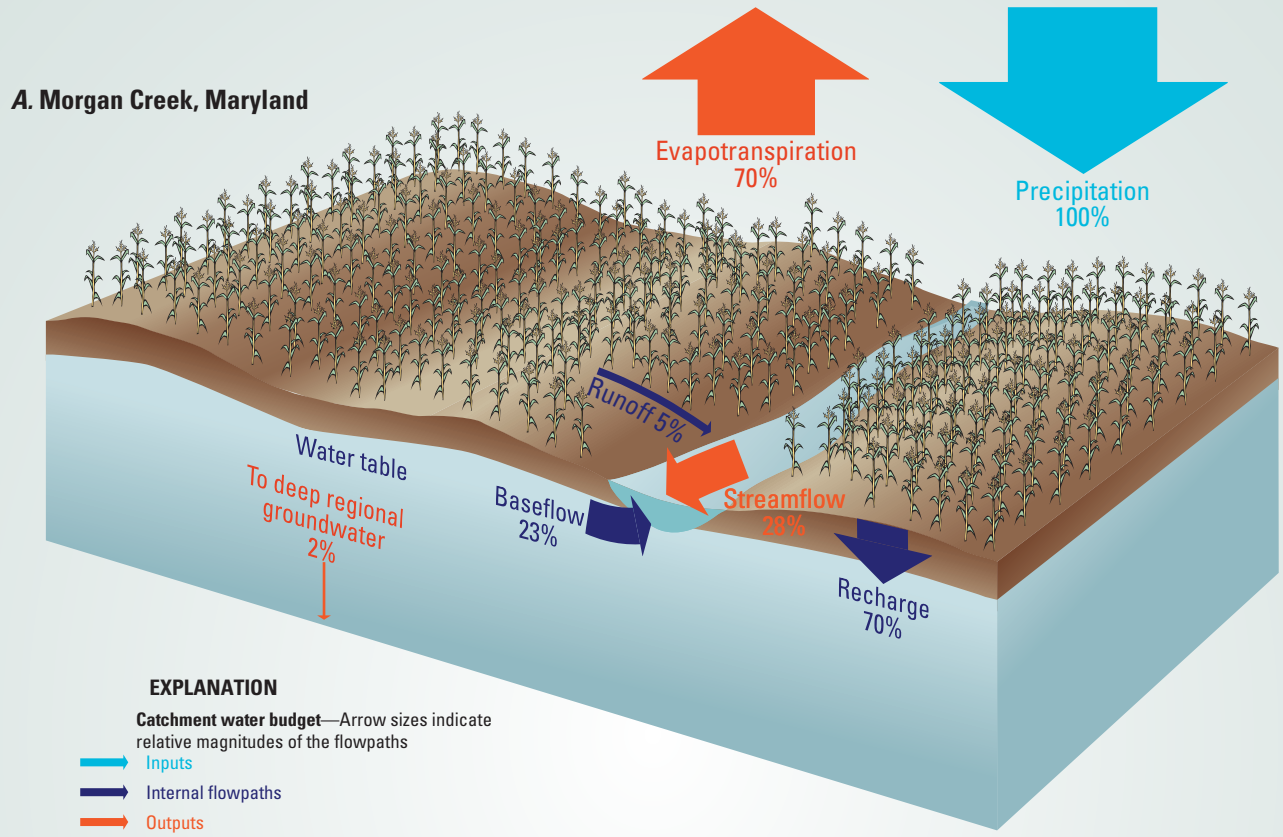
The Morgan Creek watershed covers about 31 km^2 on the Delmarva Peninsula in eastern Maryland (see "Agriculture in Maryland's Eastern Shore" in Chapter 4; Hancock and Brayton, 2006). The topography of the watershed is nearly level with some gently rolling relief. The soils are porous and well drained. The climate is humid subtropical, with an annual average precipitation of approximately 1.1 m that falls throughout the year (fig. 5.12). Groundwater seeps in the floodplain adjacent to Morgan Creek form small tributaries that sustain a substantial baseflow in Morgan Creek throughout the year.

The topography, soils, and climate of the Morgan Creek watershed make it well suited to agriculture. The region has been agriculturally productive since the mid-17th century, when tobacco was a key crop. Today, more than 70 percent of the land in the watershed is used for agriculture. The major crops are corn and soybean.

Agricultural practices in the watershed include a variety of conservation tillage practices, cover crops, grassed waterways that direct overland runoff and route it to Morgan Creek or its tributaries, the construction of small retention ponds on many farms to control erosion and trap sediment, and small amounts of irrigation. Forested buffer zones along streams are common in the area.

About 70 percent of the precipitation that falls in the Morgan Creek watershed is consumed by evapotranspiration (fig. 7.2). The remainder of the precipitation either infiltrates to the subsurface, flows into retention ponds, or follows overland flowpaths to Morgan Creek or its tributaries. Water that infiltrates to the subsurface travels from the land surface through the soil layers to recharge groundwater, eventually discharging as baseflow in Morgan Creek. Water that flows into retention ponds is mostly returned to the atmosphere as evaporation because these ponds are designed to minimize seepage to the subsurface and typically do not overflow except during large storm events. About 30 percent of the precipitation falling in the watershed eventually flows out of the watershed as streamflow in Morgan Creek, and about 60 percent of the total flow enters the creek as baseflow from groundwater. Surface runoff accounts for the remainder of the total streamflow. A small amount of water flows out of the watershed as regional groundwater (fig. 7.2).

Because the natural landscape and climate conditions of the Morgan Creek watershed were so well-suited to agriculture, successful farming in the area required only minor changes to the landscape. As a result, agriculture has had a minor effect on the watershed's water cycle. One of the key effects of agricultural development here—a decrease in evapotranspiration when native forest and other perennial vegetation was cleared and replaced with annual crops—has been counterbalanced by increased evaporation from the retention ponds scattered throughout the watershed. Although the amounts of water are likely distributed differently among the various flowpaths compared to pre-agricultural times, most water follows the same major flowpaths (table 7.2).



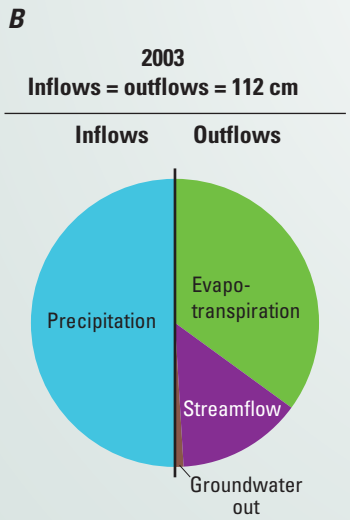


Figure 7.2. Diagrams showing (*A*) important water flowpaths and (*B*) estimated water budget for the Morgan Creek, Maryland, watershed, 2003. The relation between precipitation and streamflow is shown in figure 5.9 (Capel and Hopple, 2018).

Table 7.2. Potential flowpaths and associated transit times in Morgan Creek, Maryland.

[**Shading:** Blue cells indicate natural conditions; **red** cells indicate conditions after agricultural development; blank cells indicate that these flowpaths or time scales are not important for this type of catchment]

Flowpath	Transit time						
	Minutes	Hours	Days	Months	Years	Decades	Centuries
Flowpaths to the atmosphere							
Evaporation							
Plant transpiration							
Flowpaths to shallow groundwater							
Macropore flow through soil							
Matrix flow through soil							
Seepage from wetlands							
Flowpaths to streams							
Local groundwater flow							
Subsurface drain flow							
Runoff							
Macropore flow through soil to stream							
Flowpaths to rivers and oceans							
Regional groundwater flow							

Where the Natural Landscape is Not Well Suited to Agriculture

As the Nation's population grew and expanded across the country during the late 1800s and early 1900s, agriculture expanded into many places that were not necessarily well suited to farming (fig. 2.1). Natural conditions in these areas were less ideal for agriculture as compared to the prime lands previously farmed. Substantial modifications were necessary for agriculture to succeed in these non-ideal areas.

Of all the environmental factors (physical determinants) that govern whether or not a location is suitable for agriculture—climate, soils, slope, and rainfall—the right amount of water at the right time is one of the most important (Chapter 4). Because the amount of water is one of the few factors that is feasible to modify at a large scale, the water budgets and water flowpaths of large areas across the country have been changed to yield productive farmland by removing the constraints of either too much water or too little water.

Where There is Too Much Water.—In many locations, especially in the East and Midwest, precipitation exceeds the water needs of vegetation. Under natural conditions, water tables are shallow and wetlands and (or) waterlogged soils develop in low-lying areas if the topography is fairly flat and soils are fine grained (fig. 7.3). In order to convert these areas to productive agriculture, engineered drainage systems were necessary to remove water ponded on the land surface and to drain the waterlogged soil. Prior to European settlement, there were about 1 million km^2 of wetlands in the conterminous United States (Dahl and Allord, 1996). Less than one-half of this wetland area remained by the mid-1980s, and most of the drained areas had been converted to agricultural use (Dahl and Johnson, 1991; Gollehon and Quinby, 2006). In 2010, about 25 percent of the cropland in the country was drained (fig. 4.8). Wetlands and ponds generally serve to store water, at least temporarily, and, thus, slow the rate of movement and increase the transit time of water. When engineered drainage systems are installed, ponds and wetlands may be partly or completely drained and water storage within the watershed is reduced. In most cases, the draining of ponds and (or) wetlands is intentional and these drained areas become available for growing crops. However, wide-scale drainage systems have far-reaching effects, and, in some cases, wetlands or ponds are unintentionally drained.

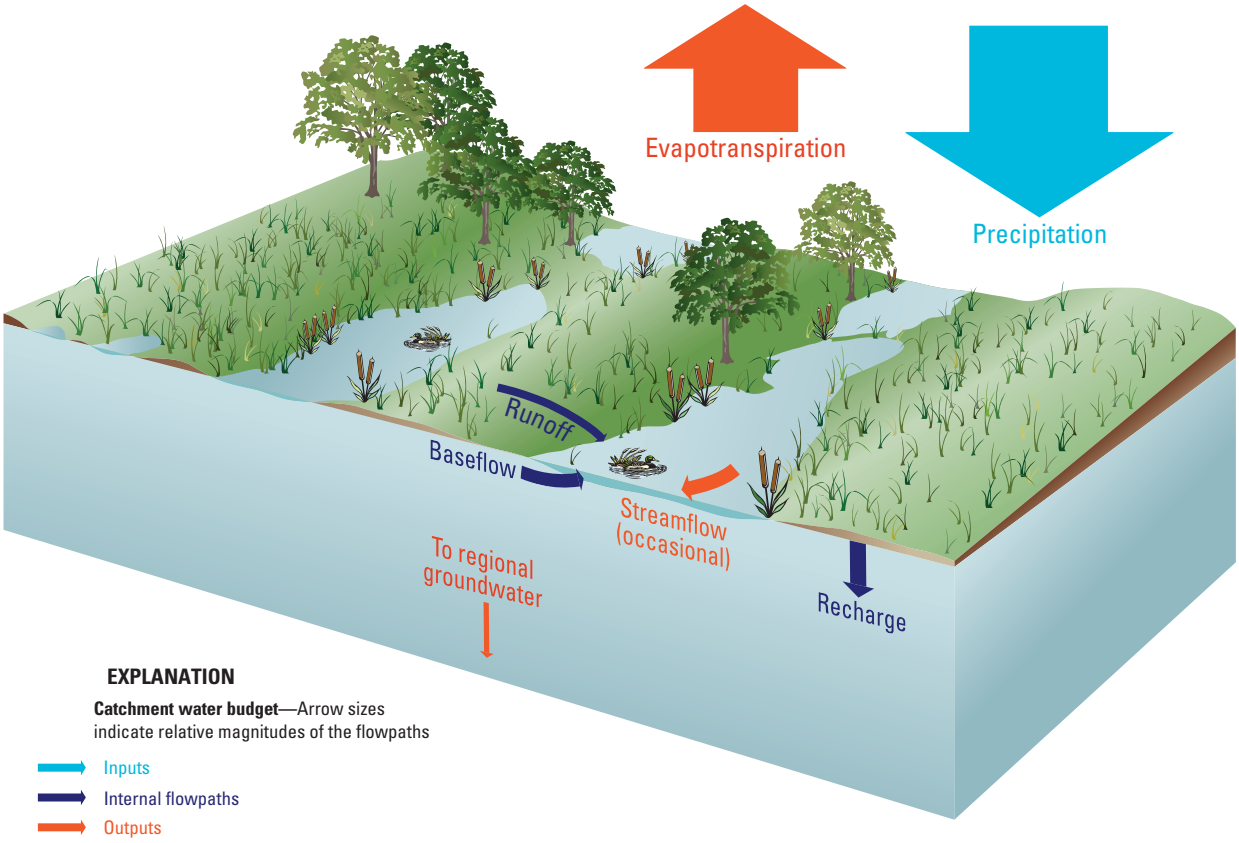


Figure 7.3. Natural water cycle in a catchment too wet for agriculture. In a catchment a with shallow water table and fine-grained soils, infiltration of rainfall is precluded by the limited capacity of the waterlogged subsurface to accept more water. Much of the rainfall reaching the land surface therefore follows overland flowpaths to local topographic lows including ponds and streams. This added zone of temporary water storage slows the delivery of storm event water to streams, and, thus spreads the stream response over time and decreases peak outflows. In addition, for small storm events, soil storage may be sufficient to store all event water and there may be no outflow.

The purpose of drainage is to move water quickly and efficiently off the landscape. Subsurface drainage removes moisture from the soil and prevents the water table from rising above the drain level for long periods of time. The water from the subsurface drains generally empties into a surface drain (ditch) that carries the water to a natural stream. Catchments in these areas are defined by the spatial network of connected surface and subsurface drains rather than by topographical divides. Prior to agricultural drainage, many of these areas did not contain perennial streams; many were wetlands that released surface water only during particularly wet periods.

Streamflow at the outlet of artificially drained catchments is the composite of flow from all drains. Individual fields within the catchment respond differently to rainfall on the basis of their topography, soil texture, and extent of soil macropores. The distance that water travels from individual drain outlets to the catchment outlet varies depending on the distance of the field from the outlet and the characteristics of the surface channels that carry water from the drain outlet to the watershed outlet. If discharge from multiple drains takes approximately the same time to reach the catchment outlet, these discharges will be additive, leading to relatively high peak flows. By contrast, discharge from various zones of the catchment can reach the outlet at different times, which will result in a lower peak but a greater duration of streamflow.

The large-scale effect of cropping and agricultural drainage in the Mississippi River Basin have increased streamflow as a function of the percentage of land in row crops (fig. 7.4; Raymond and others, 2008). The increased streamflow is the result of numerous landscape modifications that allow crop production in naturally wet areas. Overall, these modifications substantially change water budgets and water flowpaths by reducing evapotranspiration (replacing perennial vegetation with seasonal crops), decreasing water storage in wetlands and shallow soil, and increasing the volume and velocity of runoff (through surface and subsurface drainage). Leary-Weber Ditch, Indiana, provides a specific example of a watershed that is not naturally well suited to agriculture because of the abundance of water (see "Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Too Wet for Agriculture").

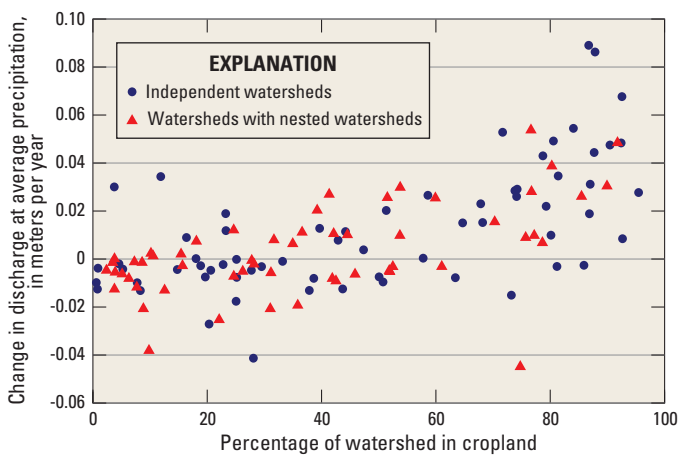


Figure 7.4. As the percentage of cropland increases in the sub-watersheds within the Mississippi River Basin, there is a trend toward increases in streamflow at average precipitation. The change was calculated by averaging the time periods before 1966 and after 1987 (modified from Raymond and others, 2008).

Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Too Wet for Agriculture

The Leary-Weber Ditch watershed covers about 7.1 km^2 in the Sugar Creek watershed in east-central Indiana (see "Agriculture in Central Indiana" in Chapter 8; Lathrop, 2006). The topography in the area is flat and the soils are poorly drained. The area has a humid continental climate and receives about 90 cm of precipitation each year.

Prior to the establishment of farms in the area in the early 1800s, wetlands covered much of the land surface. When rain fell on this landscape, a diffuse system of overland flow rivulets likely formed to carry water to local depressions and, when these overflowed, water flowed into Sugar Creek. The earliest farmsteads were established on the highest land to avoid the waterlogged soils. Gradually, however, an extensive network of subsurface drains and surface drainage ditches, such as Leary Weber Ditch, were dug to carry the water to nearby streams such as Sugar Creek. In recent years, nearly 90 percent of the Leary-Weber Ditch watershed is used to grow corn and soybean and all of this land is drained by engineered surface and subsurface drainage systems (fig. 4.9).

About 60 percent of the precipitation in the Leary-Weber Ditch watershed is consumed by evapotranspiration (fig. 7.5). Much of the surplus water infiltrates the soil and is intercepted by the subsurface drain network that carries it to Leary-Weber Ditch. A small part of the excess precipitation falls on areas adjacent to the ditch and follows overland flowpaths directly into the ditch. Under certain hydrologic conditions, the predominant flowpaths carrying water to the ditch can change markedly. For example, during intense storm events (greater than 2 cm/h), and when soil conditions are wet prior to rainfall, it is estimated that overland flow comprises about 40 percent of the flow in the ditch (Baker, Stone, and others, 2006). The contribution to subsurface drain flow from water quickly moving through soil macropores may be 50 percent or higher during high-intensity storm events (Kumar and others, 1997; Stone and Wilson, 2006).

Flow in Leary-Weber Ditch is usually continuous during winter and spring, when rainfall is plentiful and crops are small or not present (fig. 7.5). From mid-summer to early autumn, however, streamflow often ceases because no water is available after crop requirements are met. As a result of the large changes to the natural hydrologic system, agricultural development in the Leary-Weber watershed has greatly affected the watershed's water cycle (table 7.3). Overall, the predominant flowpaths are much faster after agricultural development than under natural conditions, which can enhance chemical transport and streambank erosion.

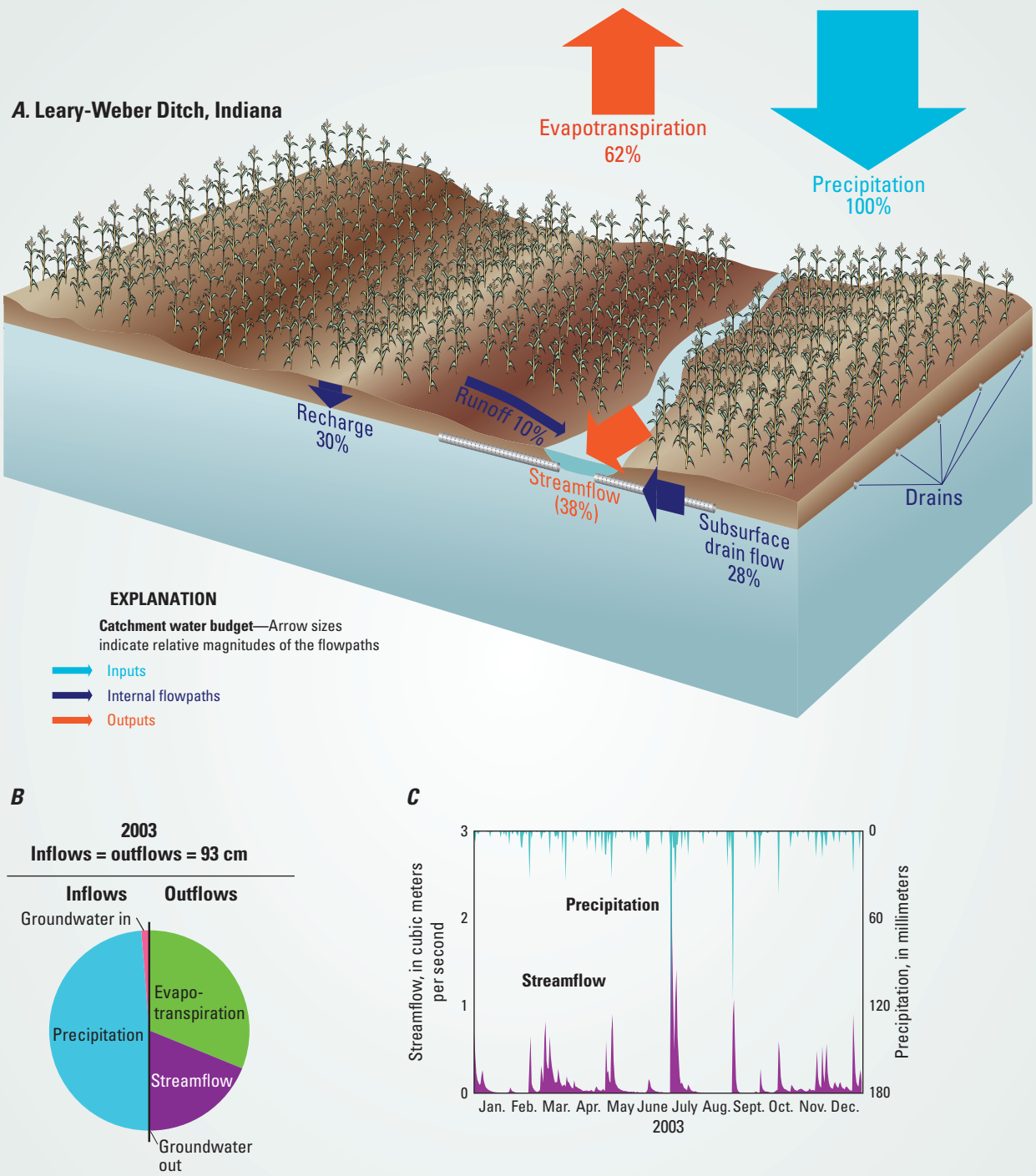


Figure 7.5 Diagrams and graph showing (*A*) important hydrologic flowpaths, (*B*) estimated water budget, and (*C*) relation between precipitation and streamflow for the Leary-Weber Ditch, Indiana, watershed, 2003 (Capel and Hopple, 2018).

Table 7.3. Predominant flowpaths and associated transit times in Leary-Weber Ditch, Indiana.

[**Shading;** **Blue** cells indicate natural conditions; **red** cells indicate conditions after agricultural development; blank cells indicate that these flowpaths or time scales are not important for this type of catchment]

Flowpath	Transit time						
	Minutes	Hours	Days	Months	Years	Decades	Centuries
Flowpaths to the atmosphere							
Evaporation							
Plant transpiration							
Flowpaths to shallow groundwater							
Macropore flow through soil							
Matrix flow through soil							
Seepage from wetlands							
Flowpaths to streams							
Local groundwater flow							
Subsurface drain flow							
Runoff							
Macropore flow through soil to stream							
Flowpaths to rivers and oceans							
Regional groundwater flow							

Where There is Not Enough Water.—Large regions in the Western United States have temperatures, soils, and topography that are well suited to agriculture, but have too little precipitation during the growing season to support crops (fig. 4.3). Under natural conditions, virtually all of the small amount of precipitation that falls on arid landscapes either evaporates or is used by native plants that are adapted to low-moisture conditions. Often there is not enough precipitation to sustain perennial streams at the catchment scale (fig. 7.6). Occasionally, however, rain or snowmelt events produce enough water to exceed the infiltration capacity of the soil. The result is surface runoff to temporary (ephemeral) streams in low-lying areas. Although the water infiltrates and seeps into the soil matrix during these events, most of this water is eventually consumed by evapotranspiration before reaching the water table. The water table tends to be quite deep in arid regions.

Various sources of irrigation water are used and the methods used to apply this water to cropland and pasture varies widely. Where surface water is the source of irrigation, practices range from occasionally rerouting local stream water onto nearby fields to importing large volumes of water from distant areas by extensive pipeline or canal systems. Where groundwater is the source of irrigation water, practices range from occasionally pumping that water to supplement precipitation to regularly pumping large volumes to supply virtually all crop needs.

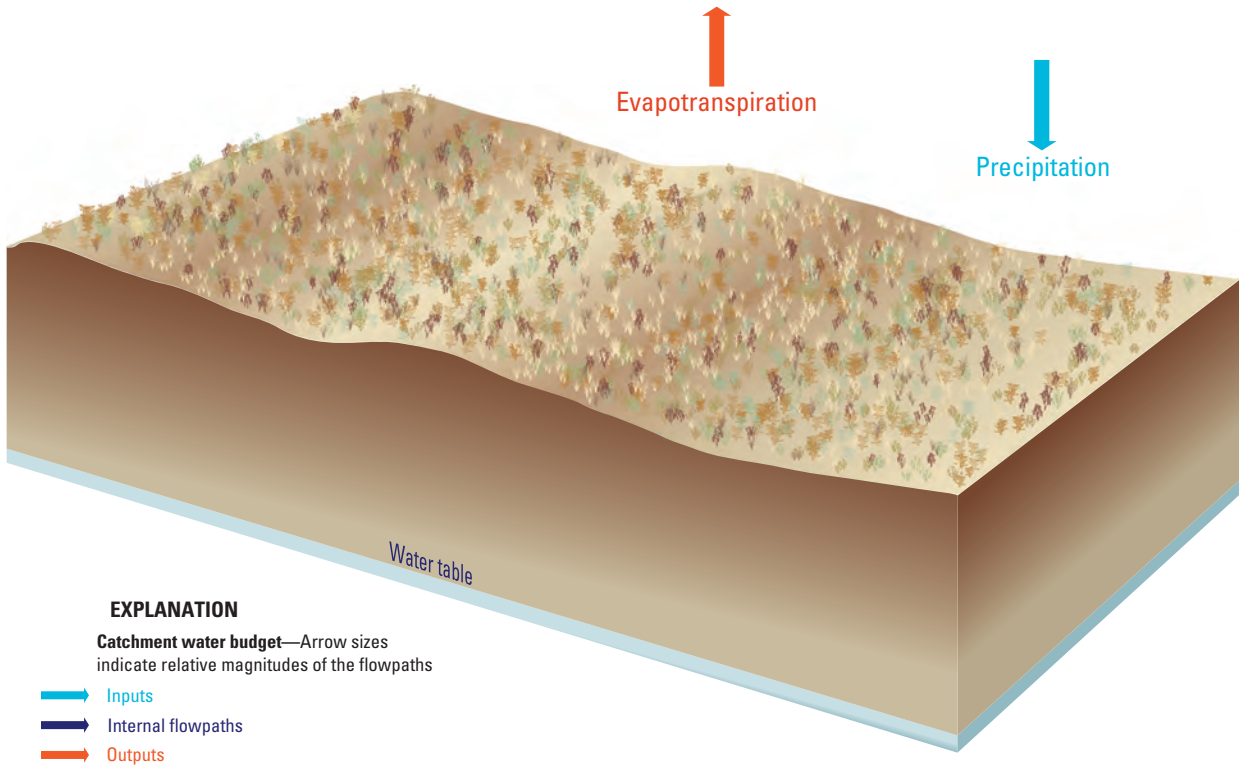


Figure 7.6. Natural water cycle in a catchment too dry for agriculture. Under natural conditions, almost all of the small amount of precipitation that falls in arid and semi-arid landscapes either evaporates or is used by native plants that are adapted to low-moisture conditions. Often there is not enough precipitation to sustain perennial streams at the small-catchment scale. Occasionally, however, rain or snowmelt produces enough water to exceed the infiltration capacity of the soil and the resulting overland flow forms temporary streams in topographic lows. Although the water that infiltrates and seeps through the soil matrix during these events is often greater than the short-term evapotranspiration potential, the water table tends to be quite deep in arid regions and, in most cases, excess moisture is eventually consumed by evapotranspiration before reaching the water table.

In all cases, irrigation increases the volume of water delivered to the land surface during the growing season. Much of this added water is consumed by the plants and lost through evapotranspiration, but commonly more water is applied than can be used by crops. Consequently, flowpaths across the land surface or into the subsurface carry more water than under natural conditions. To carry the increased volume of water, man-made flowpaths, such as drainage ditches, have been developed in some locations. In other locations, the response of natural flowpaths to extreme rainfall storm events in the natural (pre-agriculture) landscape has become more important and sometimes perennial. The large amounts of irrigation water applied frequently and over the long term markedly change the water budget and water flowpaths.

Furrow and flood irrigation purposely deliver water at a rate faster than it can infiltrate the soil and be used by the plants. This water delivery results in surface runoff (tailwater) that is typically routed away from cropped areas by drainage ditches. These field-scale ditches carry water to natural streams. If no natural streams were present, a network of ditches was excavated to collect and route the water to a natural stream.

Irrigation water that infiltrates the soil, but is not consumed by plants, moves downward and recharges groundwater. This increased recharge, relative to natural conditions, can raise the water table (fig. 7.7). Under these conditions, the water table can intersect topographically low-lying areas of the catchment and discharge as surface water. Perennial streams and surface ditches, supported by baseflow and irrigation runoff, can form where previously not present. The surface channels have flow characteristics that can be appreciably different than those of natural streams (fig. 7.8). In some cases, the water table rises so close to land surface that waterlogging of near-surface soil is extensive and artificial drainage systems must be installed to allow agriculture to continue.

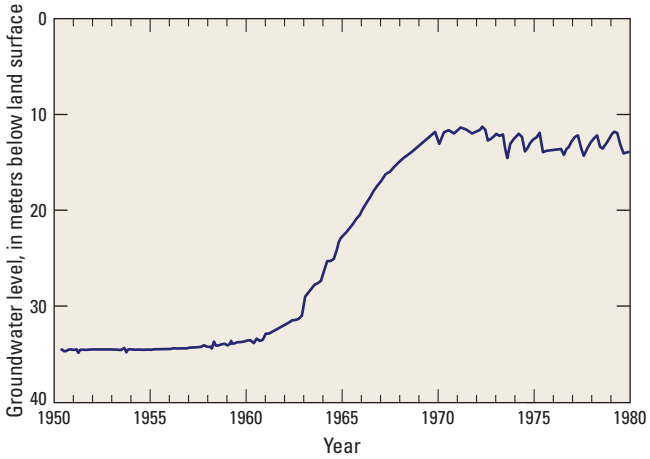


Figure 7.7. Rise in the water-table elevation resulting from long-term irrigation with surface water in the Columbia Plateau, Washington. The rise began when the Columbia Basin Irrigation Project was implemented in the late 1950s. The water table rose approximately 20 meters over a period of less than 10 years. Installation of a drainage system in the 1970s—primarily surface ditches—prevented further rise of the water table (Capel and Hopple, 2018) .

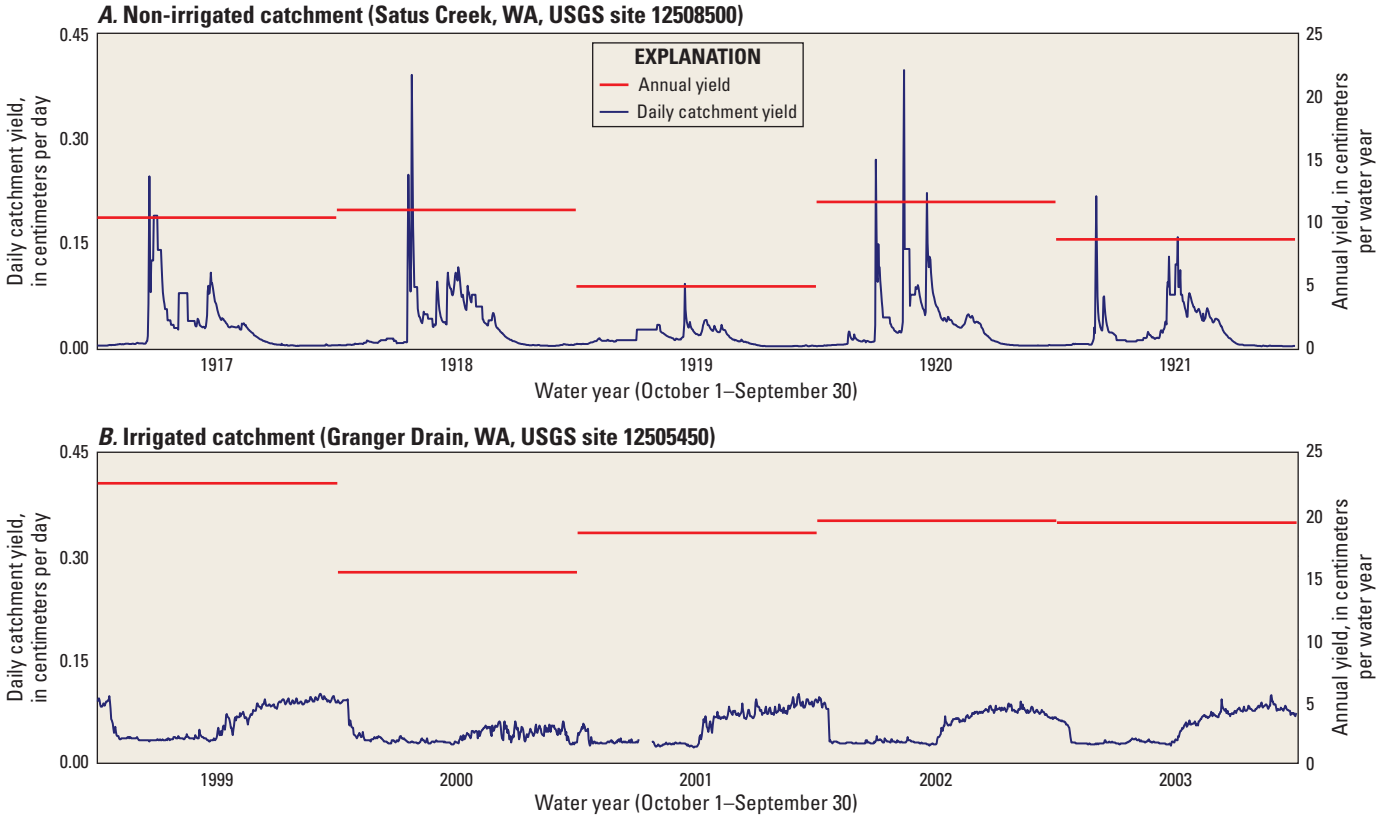


Figure 7.8. Effect of imported irrigation water on catchment water yield. (Catchment water yield is the streamflow divided by catchment area.) The peak yields in (*A*) the non-irrigated catchment (Satus Creek, Washington) are substantially higher than in (*B*) the irrigated catchment (Granger Drain, Washington). The substantial amount of sustained baseflow in the irrigated catchment leads to a higher annual water yield compared to the non-irrigated catchment and can contribute to a greater transport of agricultural chemicals (Capel and Hopple, 2018).

As more efficient methods for delivery and application of irrigation water have been developed and implemented (U.S. Department of Agriculture, 2010), the changes to the water cycle caused by irrigation have been substantially reduced. Although these more efficient methods are increasingly used, conversion is proceeding slowly because they are expensive and, at this time, are economically feasible only for a few crops and environmental conditions (Schuck and others, 2005). Another confounding factor is the nature of water rights in the Western States, where "prior appropriation" water rights generally prevail. These rights are contingent on the holder putting the water to beneficial use (Anderson and Woolsey, 2005). All or parts of these water allocations may be lost if the water is not regularly used. Because of the non-use clause in the language, water users have a legitimate concern about losing some of their water rights by using less water in the interest of conservation. In the Eastern States, "riparian water rights" generally prevail. These rights are granted based on ownership of the land that physically touches the stream, lake, or other water body, and cannot be lost through non-use of the water.

In addition to the effects of irrigation on the catchment in which the irrigation is applied, extensive, long-term irrigation can deplete the stream or aquifer that serves as the source reservoir from which irrigation water is withdrawn. When surface water is withdrawn for irrigation, the flow in the source stream declines. Although excess irrigation water is eventually returned to the stream in most cases, the volume of water has been appreciably reduced by evapotranspiration and the net effect is reduced flow in the source stream (fig. 7.9).

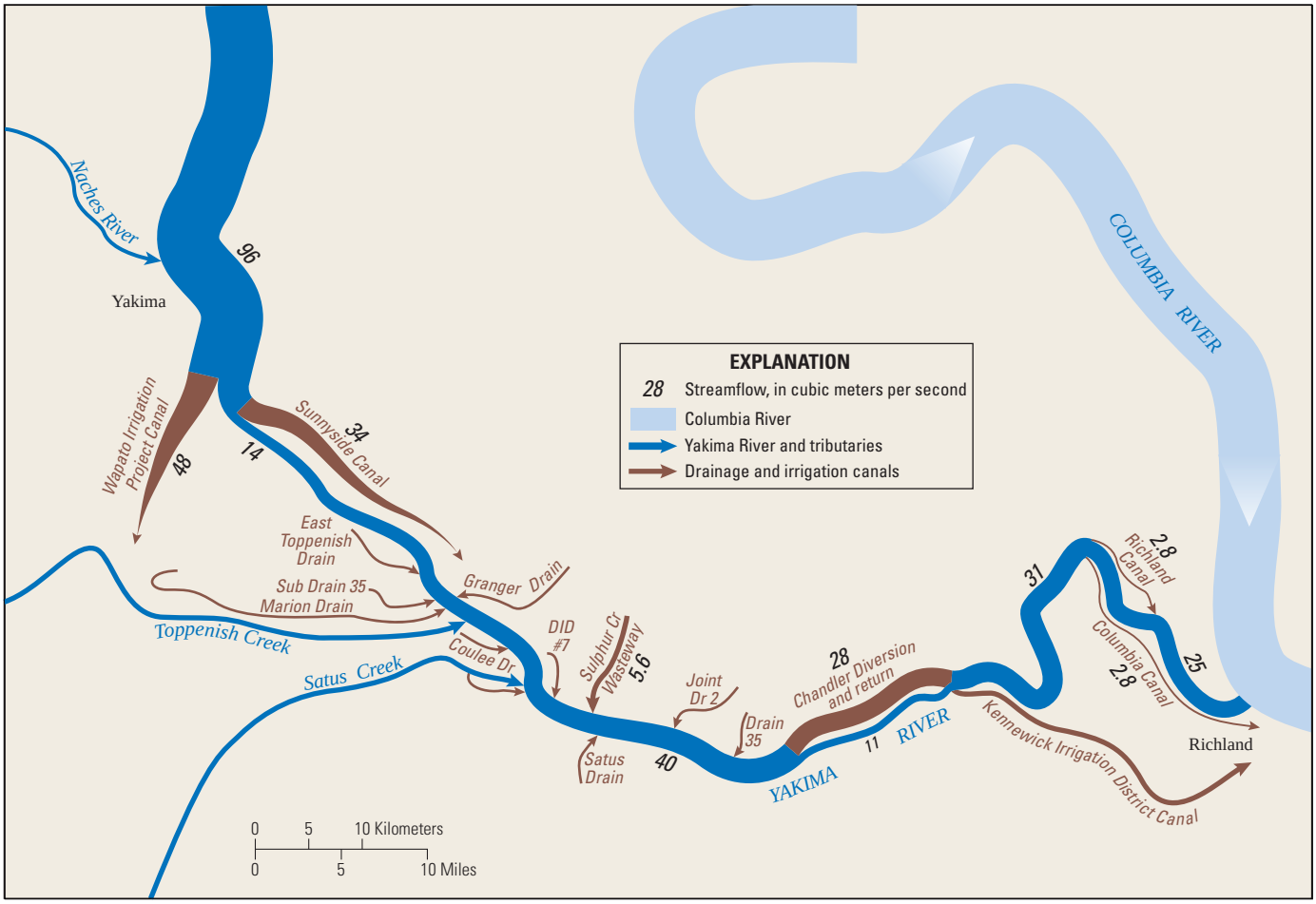


Figure 7.9. Typical irrigation-season streamflow and irrigation canal flow for the lower part of the Yakima River Basin, Washington. The widths of flow lines, which are proportional to flow rate, show that irrigation withdrawals from surface water have appreciable effects on streamflow (Modified from Wise and others, 2009).

When groundwater serves as the source of irrigation water, long-term pumping can lower the water table. When the water table is lowered, baseflow resulting from groundwater discharge to streams can decrease, or losses from stream channels to groundwater can increase. Under either of these scenarios, streamflow is reduced and can change the stream habitat. The DR2 Drain watershed in Washington provides a specific example of a watershed that is not naturally suited to agriculture because there is not enough available water (see "Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Too Dry for Agriculture").

In many areas of the United States, the water-table decline is substantial, extensive, and long term (fig. 7.10). In a 2004 compilation, groundwater withdrawals for irrigation accounted for about two-thirds of total groundwater withdrawals in the United States (Hutson and others, 2004). In California's Central Valley, both surface water and groundwater are used extensively for irrigated agriculture, and declines in groundwater levels up to 120 m have resulted (Faunt, 2009). These water-level declines have resulted in considerable land subsidence because of compaction of aquifer materials (Galloway and others, 2000; Reilly and others, 2008). On the Columbia Plateau, pumping has removed water from storage in the aquifers and resulted in water-level declines of up to 100 m locally and declines of more than 30 m over extensive areas (Morgan and others, 2008). In the High Plains aquifer of the Central United States, groundwater-level changes from predevelopment to 2007 ranged from a rise of 26 m in Nebraska to a decline of 71 m in Texas, and the total water in storage in the aquifer declined by more than 300 billion m^3 over that period (McGuire, 2009).

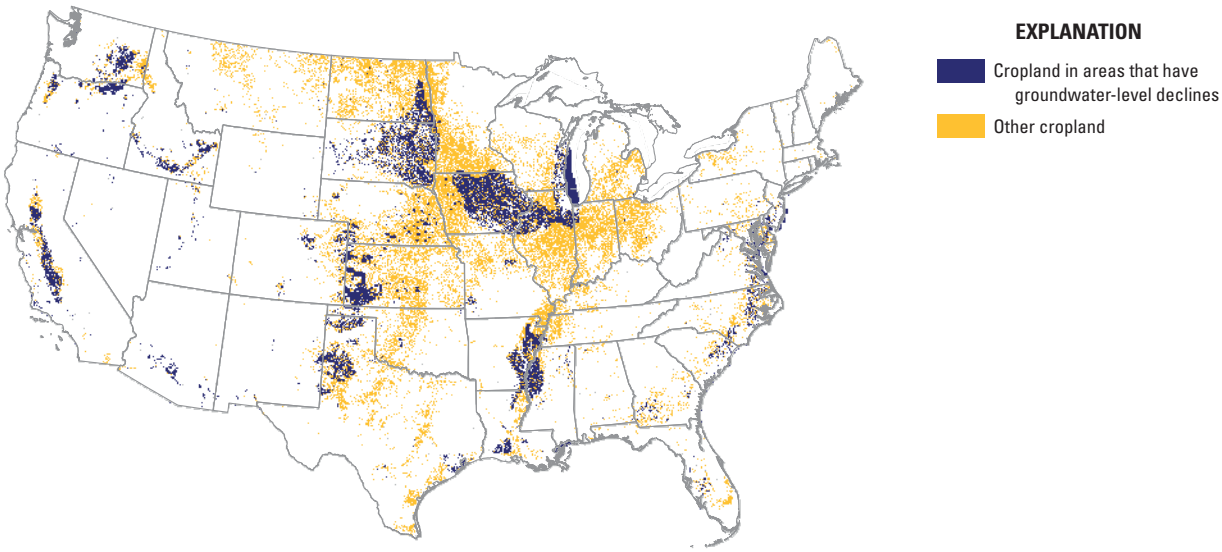


Figure 7.10. Areas of groundwater-level decline relative to the extent of cropland. The areas of cropland in which groundwater levels have declined does not necessarily mean that irrigated agriculture is the principal cause of the decline. Crops that are irrigated with water from sources in decline may be vulnerable (Reilly and others, 2008).

Summary

Water movement through an agricultural watershed is governed by the combination of natural hydrological factors and the various agricultural modifications. The collective effects of the modifications change the natural, pre-agricultural water budgets and water flowpaths. The extent of this change depends largely on how suitable the natural landscape of the watershed was for agriculture. Areas with fertile soil, adequate drainage, and adequate rainfall during the growing season require relatively few modifications to become agriculturally productive. Generally in these areas, conversion of the natural landscape to agricultural use results in a decrease in the volume of water that leaves the watershed as evapotranspiration, an increase in runoff and (or) recharge, and an increase in the annual streamflow that exits the watershed. Despite these water budget changes, the flowpaths that water follows are the same or similar to flowpaths present prior to agricultural modifications.

In areas where there is too much water in the soil for agriculture (wetland areas), engineered drainage systems are used. The drainage systems have become a permanent component of the landscape and have substantially altered the water budget and water flowpaths. The purpose of drainage is to move water quickly and efficiently off the landscape. Subsurface drainage removes moisture from the soil and prevents the water table from rising above the drain level for long time periods. The water from subsurface drains generally empties into surface drains (ditches), which carry the water to a natural stream. Overall, these modifications substantially change the water budgets and water flowpaths by reducing evapotranspiration (replacing perennial vegetation with seasonal crops), decreasing water storage in wetlands and shallow soil, and increasing the volume and velocity of runoff (through surface and subsurface drainage).

In some areas, precipitation during the growing season is inadequate to meet crop requirements, even though other climatic and landscape factors are suitable for agriculture. In these areas, water for agriculture is supplied by irrigation. Irrigation increases the input of water to the catchment and creates new water flowpaths or expands the flowpaths that were present before agricultural uses began. The source of the irrigation water can be either surface water or groundwater. Surface-water sources can be either within or outside of the watershed where it is used. Long-term pumping from groundwater sources for irrigation can lower the water table. The decline can be substantial and affect the sustainability of the groundwater resource. If groundwater is pumped from a shallow aquifer that is hydraulically connected to a stream, streamflow can decrease due to the reduction or cessation of baseflow. Irrigation imported from external surface-water sources can increase groundwater recharge and cause the water table to rise to the extent that subsurface drainage is needed to drain the soil. Large amounts of irrigation water applied frequently and over the long term (years and decades) can markedly change the water cycle in an area.

Water moves through catchments along largely expected flowpaths that connect the various components of the hydrologic systems—atmosphere, soil, groundwater, and surface water. For a particular catchment, each flowpath starts at the specific location where water from precipitation or irrigation enters the catchment and ends at a specific location where the water leaves the catchment. Different flowpaths predominate in different fields, and, depending on the route followed between the starting and ending points, each flowpath has a characteristic transit time, ranging from minutes to centuries.

Some fraction of the water that enters an agricultural landscape moves into the broader environment through runoff or recharge. This water that moves through surface and subsurface flowpaths can transport sediment and agricultural chemicals. The movement of these chemicals off farms and into the broader environment is largely governed by the movement of the water.

Hydrologic Consequences of Agriculture in a Watershed Where Natural Conditions Were Too Dry for Agriculture

The DR2 watershed covers approximately 5.5 km^2 in the Granger Drain watershed in south-central Washington (see "Agriculture in Central Washington" in Chapter 6; Payne and others, 2007). The watershed is arid, receiving an average of only about 17 cm of precipitation annually. Most of the precipitation falls during November through January. The driest months are during the summer growing season (fig. 7.11).

Land use in the DR2 watershed is approximately 90 percent agricultural—orchards, vineyards, pasture, corn, and vegetable crops and dairy feeding operations. All agricultural operations are dependent on irrigation. The large demand for irrigation water throughout the region is met by withdrawals from the Yakima River that are transported by an extensive system of canals. At the individual field scale, water is applied to crops by various methods, including rill, drip, and sprinkler irrigation systems.

By 1902, substantial quantities of irrigation water were being regularly applied throughout the region. The water table rose more than 20 m (Jayne, 1907). Construction of a system of drainage ditches, such as DR2, began in 1907, as well as installation of subsurface drainage. The regular application of irrigation water since this time has maintained a water table that is high enough to sustain year-round flow in the lower reaches of many drainage ditches. Thus, more than a century of irrigated agriculture has created surface-water and shallow groundwater-flow systems that were not present prior to development.

Relative to natural conditions, irrigation has increased water input to the DR2 watershed approximately tenfold (fig. 7.11; McCarthy and Johnson, 2009). This increased input results from irrigation applied directly to the fields within the watershed as well as from excess irrigation water applied elsewhere that flows as groundwater into the watershed. Leakage alone from the irrigation water delivery canal equals precipitation. About one-half (45 percent) of the total water input to the watershed is consumed by evapotranspiration. A small amount of water leaves the watershed as regional groundwater flow, and the remainder—about 40 percent—leaves the watershed as streamflow in DR2.

During the non-irrigation season (typically from mid-October to mid-March), flow is sustained in DR2 by baseflow. During the irrigation season, approximately one-third of the flow in DR2 is from baseflow. The remaining two-thirds consists of a mixture of spill from the irrigation system (water transported directly from the irrigation delivery system to the stream without being released to the landscape), overland flow such as tailwater ditches, and applied irrigation water that infiltrates and then travels through shallow subsurface flowpaths, such as subsurface drains, without being part of the groundwater system. As a result of the large changes to the natural hydrologic system, agricultural development in the DR2 watershed has had a large effect on the watershed's water cycle (table 7.4).

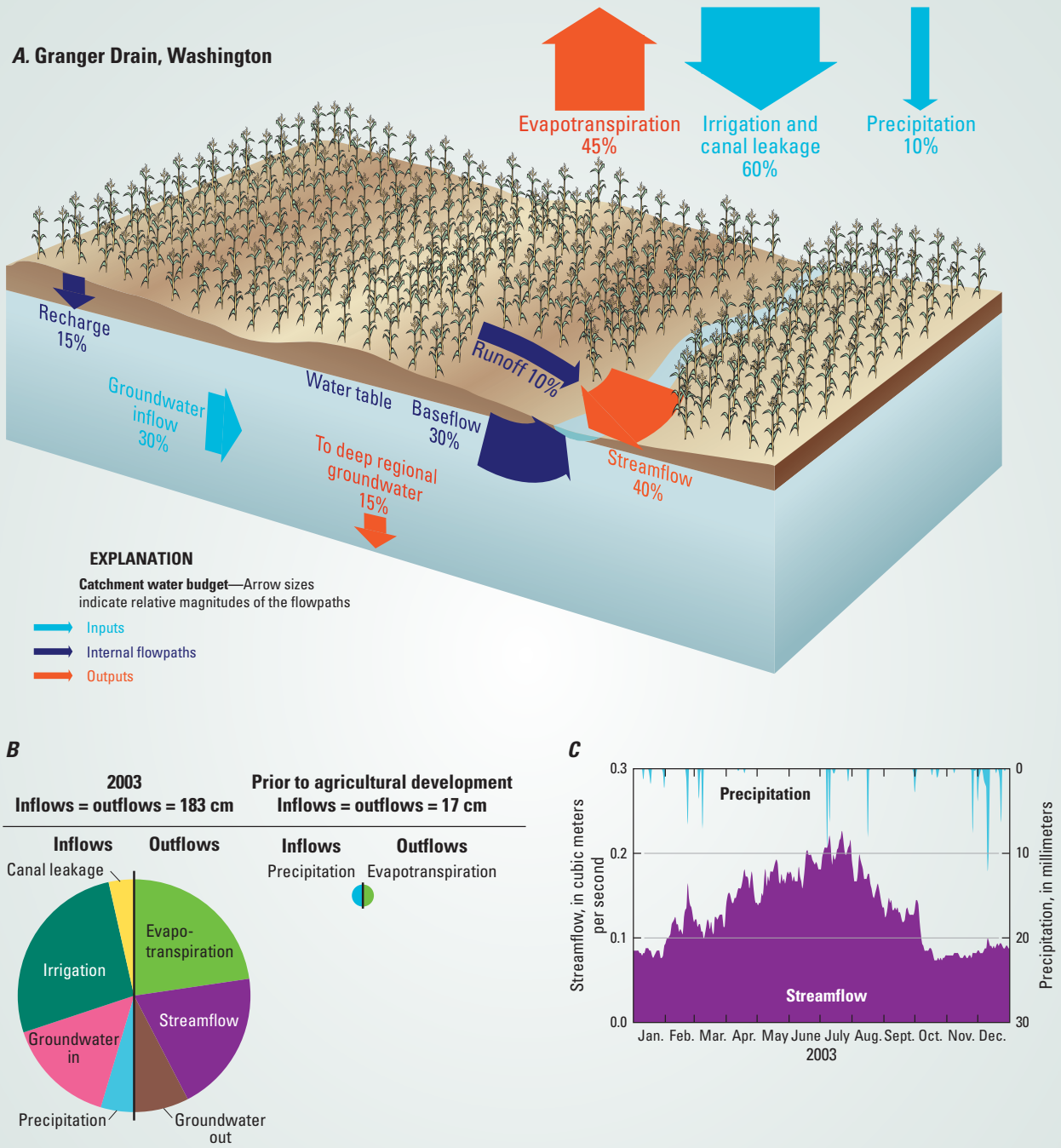


Figure 7.11. Diagrams and graph showing (*A*) catchment water budget with important hydrologic flowpaths, (*B*) estimated water budget after and before agricultural development, and (*C*) relation between precipitation and streamflow for the DR2 watershed, Washington, 2003 (Capel and Hopple, 2018).

Table 7.4. Predominant flowpaths and associated transit times in DR2 watershed, Washington.

[**Shading:** Blue cells indicate natural conditions; red cells indicate conditions after agricultural development; blank cells indicate that these flowpaths or time scales are not important for this type of catchment]

Flowpath	Transit time						
	Minutes	Hours	Days	Months	Years	Decades	Centuries
Flowpaths to the atmosphere							
Evaporation							
Plant transpiration							
Flowpaths to shallow groundwater							
Macropore flow through soil							
Matrix flow through soil							
Seepage from wetlands							
Flowpaths to streams							
Local groundwater flow							
Subsurface drain flow							
Runoff							
Macropore flow through soil to stream							
Flowpaths to rivers and oceans							
Regional groundwater flow							

Agriculture in the Central Valley of California

The San Joaquin River Valley in central California (fig. 1.3) is bounded by the Sierra Nevada to the east, the Coast Ranges to the west, the Tehachapi Mountains to the south, and the Sacramento–San Joaquin Delta to the north. The topography of the region is a gently sloping plain, with rivers and their seasonal tributaries carrying flow from the surrounding mountains. Pre-settlement vegetation included extensive stands of saltbush scrub, desert grassland, alkali scrub, and wetlands. Annual rainfall ranges from 46 (north) to 25 cm (south), and the climate is characterized by warm dry summers and moist winters.

In the early 1800s, a Spanish expedition arrived in Merced County and found the grass plains ideal for grazing livestock. The Spanish Army officer in charge of the expedition named the river Rio de Nuestra Señora de la Merced (The River of our Lady of Mercy), from which the county derives its name. By 1855, about 500 pioneers raised cattle in the area. Settlers arrived rapidly and cereal production became important; soon managing livestock was no longer profitable. In 1870, the Central Pacific Railroad constructed tracks down the San Joaquin Valley, providing transportation for agricultural products.

In 1919, the Merced Irrigation District was formed. The Exchequer Dam on the Merced River was selected as the District's first project and was completed in 1926 to provide flood control and water for irrigation and power generation. In 1967, New Exchequer Dam was completed to expand Lake McClure Reservoir capacity. In the same year, McSwain Dam was completed downstream as a regulating reservoir. The addition of canals and irrigation appreciably changed the crops farmers were able to produce. Crop diversification included orchards, vineyards, fruits, almonds, corn, and grains. The Merced Irrigation District operates most of the irrigation infrastructure, which supplies water to about 625 km^2 of farmland with about 4,000 sets of control gates and 1,300 km of canals (Merced Irrigation District, 2013).

In the 1990s, Merced County saw a reorganization of irrigation practices, providing better service to growers while managing water more efficiently and cost effectively. Flow management projects in the upper watershed, where surface water is unavailable, developed drip irrigation and automated micro-sprinkler irrigation systems to increase efficiency. In the lower watershed, where surface water is plentiful, flood systems and permanent sprinklers dominate. Dairy accounts for about one-third of the total value of agricultural production, almond orchards account for 45 percent of agricultural land, followed by corn and grain at 16 percent, and vineyards at 12 percent. A variety of fruits are grown in Merced County including peaches, figs, and wine and raisin grapes.

Nitrate in groundwater is one of the greatest water-quality issues of concern in the California's Central Valley watershed (Burow and others, 2008; van der Schans and others, 2009; Landon and others, 2011). Because of a shallow water table, attributable in part to irrigation with surface water, and a high percentage of sandy soils, the shallow groundwater of the eastern San Joaquin Valley has elevated concentrations of nitrate (greater than 10 milligrams per liter [mg/L] as nitrogen). Much of the aquifer contains enough dissolved oxygen to prevent significant transformation of nitrate to other forms of nitrogen and allow the mobilization of naturally occurring trace elements into recharge from excess irrigation (Jurgens and others, 2010).

The landscape of the Central Valley of California. (*A*) The grasslands typical of the time before agriculture, (*B*) an almond orchard, and (*C*) the view from the air (23 square kilometers). Photograph *A* from Bureau of Land Management, BLM CA160, Seeds of Success, 2012; photograph *B* from U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSCA06014; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agricultural Imagery Program, 2010.

Chapter 8—Chemicals in Crop and Animal Agriculture

How Do Agricultural Chemicals Affect Water Quality?

Agricultural activities are defined here as all farming procedures that fulfill the requirements for the production of crops or animals—space, soil, water, nutrients (for plants), food (for animals), protection (from pests and weather), and disposal of the wastes. Many of these agricultural activities are accomplished through modifications to the landscape or applications of chemicals. Landscape modifications affect the water flowpaths (Chapter 6). Some fraction of the water that is introduced into the agricultural landscape can carry agricultural chemicals, sediment, and microorganisms into the environment. (Even though sediment and microorganisms are not chemicals, they share many of the same source, transport, and fate processes.) The water, sediment, chemicals, and microorganisms can give rise to a number of environmental concerns (table 2.2). Water-quality concerns related to agriculture usually result from elevated levels of chemicals, sediment, and (or) microorganisms as compared to the natural condition. Any level of a man-made (synthetic) chemical is an elevated level compared to the natural condition.

More than 7,000 chemicals are associated with plant and animal agriculture (Capel and others, 2017). Some of the important chemicals or chemical groups and their source(s) are presented in table 8.1. Many chemicals are purposely used in agricultural activities because they directly benefit crop or animal production. These chemicals include the active ingredients in fertilizers, lime, pesticides, hormones, and antimicrobials. Other chemicals are produced by the crops or animals as waste by-products, such as methane and manure. Some are produced by chemical or microbiological reactions in the soil and water. These chemicals include pesticide transformation products, nitrogen oxides (see "Nitrogen" in Chapter 2), and dissolved organic carbon. Some chemicals are naturally stored in the soil and water, such as selenium, arsenic, and salts, and can be mobilized by agricultural activities, such as irrigation. Finally, some chemicals are introduced into the agricultural landscape through "piggy-backing" on purposely applied chemicals. Animal manure, used as a fertilizer on crops and as a soil amendment, can contain chemicals used for the animals (hormones, antimicrobials) and microorganisms like coliform bacteria (*E. coli*) (see "Manure" in Chapter 6).

Some chemicals are predominantly used in or produced from plant agriculture and others predominantly in animal agriculture. Some chemicals are common to both activities (table 8.1). In the case of manure, it is a by-product of animal agriculture and purposely used as a fertilizer and soil amendment in plant agriculture. For those chemicals that are purposely used, their reasons for use is generally to increase yield, to protect crops or animals, to increase soil quality, to dispose of waste, to facilitate the effectiveness of another chemical with a purposeful use, or to protect the environment (table 8.1).

Agricultural Chemicals

There are two broad categories of chemicals that are important to agriculture—those that provide nutrients (fertilizers and manure) and those that protect the crops and (or) animals from pests (pesticides). The water-quality concerns from these categories are due in part to their effects on the environment, and in part to their quantity of use and (or) release in agriculture.

Fertilizers provide the necessary nutrients for plants to grow. Nutrients are the essential elemental building blocks of the plant cells. Three major nutrients with limited natural supply—nitrogen, phosphorus, and potassium—are often added to crops either as synthetic fertilizers or as manure (table 8.2). As many as seven other essential plant nutrients, mainly trace metals that are needed by plants in small amounts (micronutrients), are added to fertilizer as needed: manganese, boron, copper, iron, chlorine, molybdenum, and zinc. The other elemental building blocks of plants (carbon, oxygen, hydrogen, and sulfur) generally are abundant in the air, water, and soil. If one of these plant nutrients is in short supply, plant growth will be limited and yield will be reduced. The techniques, timing, and rates of fertilizer application depend on the nutrient content of the fertilizer, the crop and yield goal, soil type and texture, climate, and the equipment available to the applicator (see "Glossary of Farm Implements"). Nitrogen and phosphorus can have adverse water-quality impacts upon entering the broader hydrologic environment (see "Nitrogen" in Chapter 2).

Nitrogen is involved in protein synthesis and chlorophyll formation. Nitrogen is a component of DNA. Plants with adequate nitrogen show healthy vigorous growth, strong root development, dark green foliage, and substantial seed and fruit formation. The use of synthetic nitrogen fertilizers has increased steadily in the last 50 years, rising to the current rate of 1 billion metric tons of nitrogen per year (fig. 3.8). The spatial distribution of nitrogen use on cropland in the United States is shown in figure 8.1*A*.

Table 8.1. Selected common chemicals used in and produced by crop and animal agriculture.

[**Shaded cells:** Green, chemicals primarily associated with crop agriculture; pink, chemicals primarily associated with animal agriculture; blue, chemicals associated with both crop and animal agriculture; blank, not applicable. **Source(s) into the agricultural system:** PU, purposeful use; PB, "piggy-backed" on something with a purposeful use; IS, *in situ* production; MN, mobilized naturally occurring substance; WP, waste product of agriculture. **Benefit(s) from purposeful use:** YD, increases yield; AP, increases agricultural protection (for example, soil erosion, crop production); SQ, improves soil quality; FP, facilitates the effectiveness of another purposeful chemical; WD, disposes of waste; EP, increases environmental protection. **Abbreviations:** MSMA, monosodium methyl arsenate; DDT, dichlorodiphenyltrichloroethane; DDE, dichlorodiphenyldichloroethylene]

	Source(s) into the agricultural system					Benefit(s) from purposeful use						Brief description, examples
	PU	PB	IS	MN	WP	YD	AP	SQ	FP	WD	EP	
Antibiotics, antimicrobials												Protects animals from bacteria that cause disease (at therapeutic dose). Improves animal health, which translates to more rapid and efficient growth (at subtherapeutic dose). Oxytetracycline, Penicillin G, lincomycin.
Arsenic												Used in herbicides: Used in herbicides, such as MSMA. Used in livestock growth promoters, such as roxarsone.
Bacteria, viruses	A	A		A								Microorganisms are abundant in all agricultural environments, only a few are pathogens. *Escherichia coli*, *Bacillus thuringiensis*.
Dust												Fine particulate matter that can become airborne.
Fungicides												Provides crops protection from fungal diseases. Azoxystroban, captan, metalaxyl.
Gypsum												Supplies sulfur and calcium for plant nutrition. Improves poor soil structure caused by high sodium in the soil.
Herbicides												Provides crop protection from weeds that compete for space, sunlight, and nutrients. Atrazine, metolachlor, gylphosate.
Hormones												Promotes growth and increases meat and milk production. Bovine somatotropin (bST) for dairy. Testosterone, trenbolone for beef.
Inert ingredients in pesticide formulations												Chemicals added to the active ingredient in pesticide formulations to improve handling and application. Surfactants, gums, clay, oils, pheromones.
Insecticides												Provides crop and animal protection from insects. Carbaryl, chlorpyrofos, DDT, permethrin.
Lime												Adjusts the pH of the soil to make phosphorus more accessible to plants. Calcium oxide.
Manure												Waste from livestock that can be used as fertilizer and soil amendment.
Methane												By-product of digestion by cattle and decomposition of manure.
Nematicides												Provides crop protection from soil nematodes (roundworms). 1,3-Dichloropropene, metam sodium.
Nitrogen												Essential nutrient for crop and animal growth. Nitrate, ammonia, urea, nitrous oxide.
Organic matter												From plant and animal wastes, oftentimes used as a soil amendment. Manure, compost, sludge.
Polyacrylamide (PAM)												Erosion control agent for furrow irrigation.
Phosphorus												Essential nutrient for crop and animal growth. Total phosphorus, orthophosphate.
Potassium												Essential nutrient for crop and animal growth. Potash.
Salinity												Ions dissolved from rocks and minerals. Dissolved solids, salt.
Sediment												Mobilized soil particles in surface waters. Sand, silt, clay, turbidity.
Trace elements	B	B		B								Elements that are found in low abundance in the Earth's surface. Some can be required for growth (micronutrients), some are toxic. Selenium, mercury, copper, zinc, boron, uranium.
Transformation products of pesticides and other organic chemicals												Chemicals formed by the transformation of a chemical. Metolachlor sulfonic acid, deethyl atrazine, DDE.
Volatile organic compounds (VOCs)	C		C		C							A class of chemicals with a tendency to exist in the vapor phase. Methyl bromide, propane, carbon tetrachloride, methane.

A Some current-use pesticides are active or inactive bacteria. There are bacteria and viruses in animal manure that are applied to the fields. There are bacteria and viruses naturally occurring in soils.

B Some current-use pesticides contain arsenic, manganese, zinc, and other trace elements. Historically, pesticides also contained mercury. Selenium, cobalt, boron, and others are micro-nutrients for both plants and animals. Many different trace elements can be found in manure. Mobilization of naturally occurring trace elements is due to the dissolution of soils and rocks, often dependent on the level of dissolved oxygen in the water. This is of particular importance for arsenic, selenium, iron, and manganese.

C Many different volatile organic compounds (VOCs) are included as inert ingredients in pesticide formulations. Some pesticides, called fumigants, are VOCs (methyl bromide). Many different VOCs are created during the storage and treatment of animal waste (including odor-causing chemicals). Many different VOCs are produced by animals (including methane in cows).

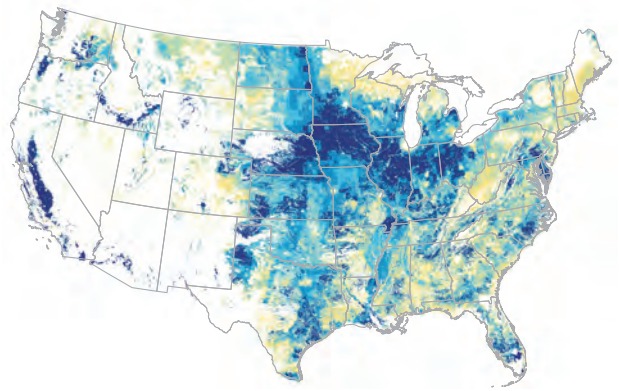
Table 8.2. Mass of selected chemicals (active ingredients) used in crop and animal agriculture in the United States, 2009.

[From U.S. Food and Drug Administration, 2010; Grey and others, 2012. **Abbreviations:** Mg, megagram (1 Mg = 1 metric ton); –, not applicable]

	Mass used (Mg)	Percent of group total	Percent of individual pesticide categories
Crop agriculture			
Nutrients	**17,427,000**	**100.0**	–
Nitrogen (as N)	10,372,000	59.5	–
Phosphorous (as P)	1,264,000	7.3	–
Potassium (as K)	2,327,000	13.4	–
Micronutrients	3,464,000	19.9	–
Soil Amendments	–	–	–
Gypsum (as Ca_2SO_4)	1,267,000	–	–
Manure	594,000	–	–
Total Conventional Pesticides	**301,000**	**100.0**	–
Fungicides	**22,000**	**7.3**	–
Chlorothalonil	3,780	1.3	17.2
Hydrated lime	2,530	0.8	11.8
Mancozeb	2,500	0.8	11.3
79 other fungicides	13,200	4.4	60.1
Herbicides[1]	**242,000**	**80.2**	–
Glyphosate	99,500	33.0	41.1
Atrazine	29,200	9.7	12.1
Metam	15,900	5.9	6.6
154 other herbicides[1]	97,000	32.2	40.1
Insecticides	**12,100**	**4.0**	–
Chlorpyrifos	3,180	1.1	26.4
Acephate	1,360	0.5	11.3
Clothianidin	570	0.2	4.7
80 other insecticides	6,950	2.1	57.6
Nematicides and fumigants	**25,400**	**8.4**	–
Dichloropropene	14,400	4.8	56.9
Chloropicrin	5,060	1.7	19.9
Methyl bromide	3,120	1.0	12.3
7 other nematicides and fumigants	2,760	0.9	10.9
Other Pesticidal Agents			
Petroleum oil	30,800	–	–
Sulfur	26,200	–	–
Animal agriculture			
Antimicrobial Agents	**13,100**	**100.0**	–
Tetracyclines (for example, tetracycline)	4,610	35.3	–
Ionophores (for example, laidlomycin)	3,740	28.6	–
Others (for example, bacitracin)	2,230	17.0	–
Macrolides (for example, erythromycin)	862	6.6	–
Penicillins (for example, penicillin)	611	4.7	–
Sulfas (for example, sulfadimethoxine)	518	4.0	–
Aminoglycosides (for example, streptomycin)	340	2.6	–
Lincosamides (for example, lincomycin)	116	0.9	–
Cephalosporins (for example, cephapirin)	41	0.3	–

[1]Includes plant growth regulators.

A. **Nitrogen**

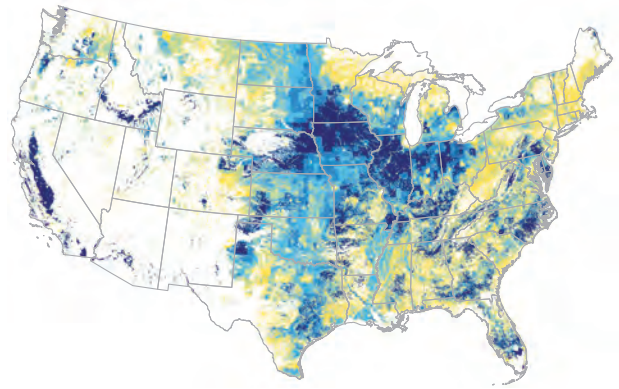


EXPLANATION

Estimated 2002 nitrogen (as N) inputs from fertilizer, manure, and atmosphere, in kilograms per square kilometer

- >0 to 1,000
- >1,000 to 2,500
- >2,500 to 5,000
- >5,000 to 7,500
- >7,500
- Not agricultural land

B. **Phosphorus**

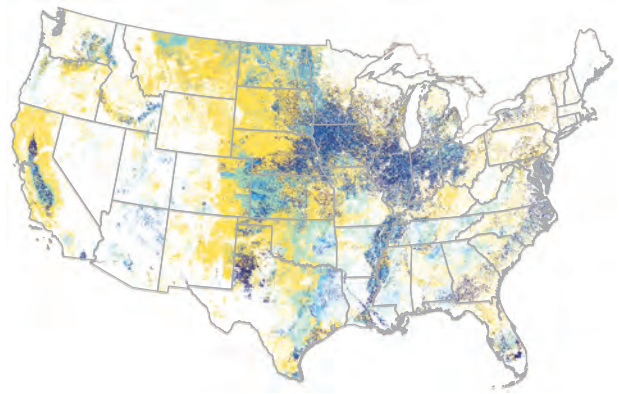


EXPLANATION

Estimated 2002 phosphorus (as P) inputs from fertilizer, and manure, in kilograms per square kilometer

- >0 to 300
- >300 to 500
- >500 to 1,000
- >1,000 to 1,500
- >1,500
- Not agricultural land

C. **Herbicides**



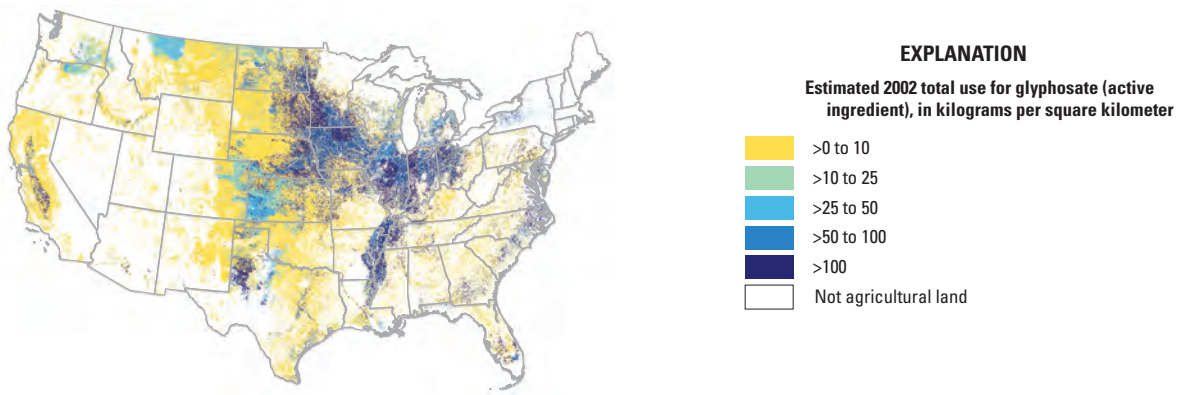
EXPLANATION

Estimated 2002 total use for 110 herbicides (active ingredients, glyphosate not included), in kilograms per square kilometer

- >0 to 10
- >10 to 25
- >25 to 50
- >50 to 100
- >100
- Not agricultural land

Figure 8.1. Application of (*A*) nitrogen fertilizer, (*B*) phosphorus fertilizer, (*C*) herbicides (excluding glyphosate), (*D*) glyphosate, and (*E*) insecticides for the United States.

***D.* Glyphosate**



***E.* Insecticides**

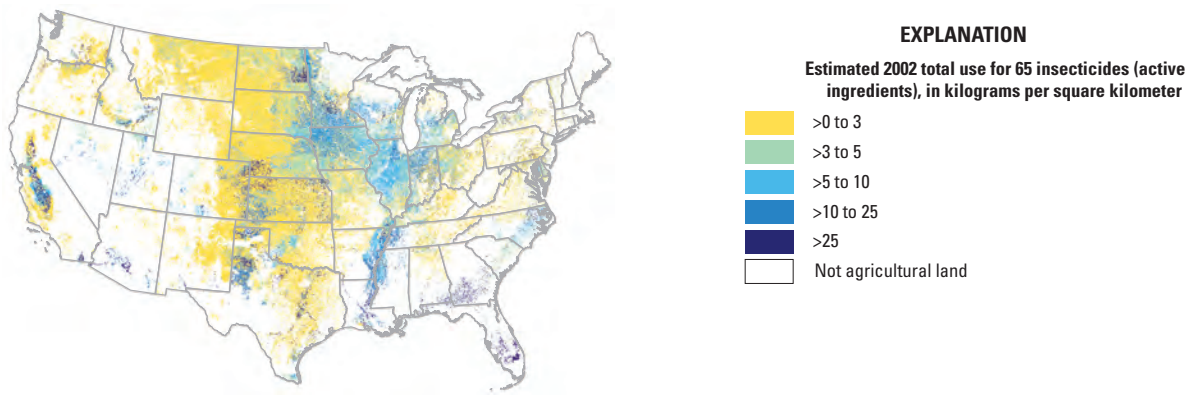


Figure 8.1.——Continued

Many different chemical forms of inorganic nitrogen (N) are used in crop agriculture. Anhydrous ammonia (82 percent N) is a liquid stored under pressure. Anhydrous ammonia becomes a gas when exposed to air and, therefore, must be injected into the soil. Ammonium nitrate (34 percent N) is a solid typically applied in granular form to pasture lands and specialty crops such as citrus. Urea (46 percent N) also is a solid applied in granular form. It can be combined with ammonium nitrate in water to make a urea ammonium nitrate (UAN) solution. It usually takes less than 2 weeks for urea to be transformed to ammonia. In contrast to these inorganic fertilizers, the nitrogen content of manure is much less (see "Manure" in Chapter 6).

Phosphorus (P) is an essential component of DNA and proteins and is essential in energy production within plant cells. Abundant phosphorus stimulates early root growth in plants and hastens maturity by stimulating flower blooming and seed formation. There are three common phosphorus fertilizer products: mono-ammonium phosphate (MAP) (11 percent N, 52 percent P), di-ammonium phosphate (DAP) (18 percent N, 46 percent P) (together called ammoniated phosphates), and triple superphosphate (46 percent P), a highly concentrated form. The spatial distribution of phosphorus fertilizer use on cropland in the United States is shown in figure 8.1*B*.

Potassium (K) is involved in photosynthesis, protein synthesis, regulation of plant stomata, and numerous other critical cell functions. Potassium also increases plant resistance to drought and disease. Muriate of potash (from 60 to 62 percent K) is the most common potassium fertilizer.

Broadcasting, the uniform application of chemicals to the surface of fields, can be done either by a ground rig or by airplane. The fertilizer infiltrates into the soil with water or is plowed into the soil. Broadcast applications generally are used for large field areas, when time and (or) labor are limiting, or when it is important to obtain a uniform distribution across the field. Banding applications are narrow bands of fertilizer applied in furrows between the rows. This type of application is often used to stimulate early plant growth and increase yield. Banding is especially important in no-till cropping systems where crop residues or winter cover result in lower soil temperatures and higher moisture levels that can reduce plant heartiness. A sidedressing fertilizer, usually supplemental nitrogen, is applied after the crop has emerged (early to mid-growth period of the crop). Sidedressed fertilizer is commonly used in sandy, wet, and irrigated soils where nitrogen loss from the root zone can be high. In irrigated areas, nitrogen and potassium can be added to the irrigation water (chemigation). Phosphorus is not normally applied in this manner because it forms insoluble compounds that tend to clog the irrigation system. Finally, nutrients can be applied directly to the leaves of the maturing plant (foliar application). These nutrients are absorbed and used by the plant within minutes after application. Foliar application can supplement nutrient needs at a critical time for the plant, but it is not a substitute for the normal fertilizer application to soil.

For the major crops, fertilizer application can take place before planting in the spring, at the time of planting, or after planting. In addition, manure is commonly applied to fields in the fall in many parts of the country. Nutrient management plans are developed so that the amount applied is based on the crop's nutritional needs minus the nutrients already available in the soil (see "Nutrient Management Plans"). Nitrogen is added at least once a year to most crops, although lesser amount are applied to legumes, which fix nitrogen from the atmosphere. In many vegetable and corn cropping systems, a split application of nitrogen is often used. In areas where the loss of nitrogen from the field is potentially high, multiple applications may be needed. Phosphorus and potassium are stored in the soil longer than nitrogen and generally are applied on a less frequent basis than nitrogen. The micronutrients are applied, when needed, at the time of planting. Agricultural lime is applied any time prior to crop emergence to adjust the soil pH and aid in the uptake of phosphorus by the plants.

Pesticides are a diverse group of chemicals that provide protection to crops and animals from various pests. Some pesticides are used to protect the crops and (or) animals from weeds (herbicides and plant growth regulators), insects (insecticides), fungi (fungicides), soil nematodes (nematicides), and bacteria (antibiotics and antimicrobials) (table 8.2). These compounds generally are thought to provide a wide range of benefits, including increased production and quality and a reduction in losses from infestations and diseases. Pesticides can have adverse water-quality impacts upon entering the broader hydrologic environment (Gilliom and others, 2006; see "Human and Ecosystem Health Effects of Agricultural Chemicals" in Chapter 2).

About 350 million kilograms (kg) of conventional pesticides (active ingredients) have been used in the United States each year over the past several decades with use leveling off at about 300 million kilograms per year (kg/yr) since the late 1990s (fig. 3.8, table 8.2). In 1997, about 900 pesticidal active ingredients in more than 20,000 different pesticide products were registered for use in the United States (Aspelin and Grube, 1999). Each year some new pesticides are introduced and old pesticides are withdrawn from use. In the mid-1990s, the introduction of genetically modified (GM) crops caused a substantial change in the use of conventional pesticides, both insecticides and herbicides, on agricultural crops. Use of many conventional insecticides in cotton and corn has decreased due to the increased use of genetically modified varieties of these crops with the inclusion of the B_t gene. The use of conventional herbicides on soybean, corn, and cotton also has changed because of the introduction of plants that are genetically resistant to a specific herbicide, such as glyphosate (see "Changes in Conventional Pesticide Use Due to Development of Genetically Modified Crops"). The use of herbicides, glyphosate, and insecticides on cropland is shown in figure 8.1.

Pesticides can be applied using a wide variety of methods. As with fertilizers, the appropriate application method depends on the kind of pesticide being used, the formulation type (granular, emulsified, aqueous, or other), the crop and type of planting system, and the equipment used by the applicator. Herbicides are commonly applied to either the soil or the weed foliage (depending on the mode of action), but insecticides and fungicides are often directed at microhabitats within the foliage canopy. Preventive use of herbicides, insecticides, and fungicides require that the entire plant or soil area be treated. The foliage density and crop spacing often dictate which application method will offer the best coverage. Pesticide application methods include broadcast (from tractor or airplane), incorporation (injection), chemigation (mixed with irrigation water), directed/banded application, and treatment of the seed (see "Glossary of Farm Implements"). Precision application of pesticides provides a technology that targets areas so that the minimum effective amount of the chemical can be applied.

Nutrient Management Plans

Nutrients are important to both crop and animal agriculture. In crop agriculture, nutrients are essential for optimum production of food, feed, fiber, and fuel, and must be replenished. In animal agriculture, nutrients are contained in the animal feed, and an appreciable amount of these nutrients is passed through the animal as waste (manure). Since at least the early 1980s, the term "nutrient management" has been commonly used in agriculture, and has developed into a system of practices to ensure the appropriate use of nutrients for production while minimizing impacts on water quality.

The USDA Natural Resources Conservation Service (NRCS) developed a Conservation Practice Standard for nutrient management. This standard defines nutrient management as "managing the amount, source, placement, form, and timing of the application of nutrients and soil amendments" (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011). The standard also outlines five elements of purpose behind nutrient management: (1) budget and supply nutrients for plant production; (2) properly utilize manure or organic by-products as a plant nutrient source; (3) minimize agricultural non-point-source pollution of surface and groundwater resources; (4) protect air quality by reducing nitrogen emissions (ammonia and nitrogen oxides compounds) and the formation of atmospheric particulates; and (5) maintain or improve the physical, chemical and biological condition of soil. The NRCS standard "…applies to all lands where nutrients and soil amendments are applied." The NRCS is a non-regulatory agency, so any involvement by farmers in nutrient management is done without regulatory concern (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011). The standard was designed as technical guidance for implementing a nutrient management plan. Even so, there are many reasons that farmers elect to manage nutrients on their farms, for environmental benefits, risk management, or economic advantages.

According to the NRCS, a nutrient management plan should: (1) create a nutrient budget for nitrogen, phosphorus, and potassium, considering all potential sources of nutrients; (2) establish realistic crop yield goals; (3) minimize the movement of chemicals to surface and groundwater by including in a plan the source, amount, timing, and method of application; and (4) avoid the application of nutrients to areas with established minimum application setbacks (for example, sensitive areas like sinkholes, wells, gullies, ditches, and inlets to surface drains).

The USDA has set the goal that all animal feeding operations have a voluntary manure management plan—a Comprehensive Nutrient Management Plan (CNMP)—that includes agricultural best management practices to help manage manure and other animal by-products and to control soil erosion. A CNMP includes both the production area (where the animals are concentrated and fed and the storage areas for manure and feed) and the land where manure is applied.

A nutrient management plan can be seen as a "nutrient budget" for a given field or farm. Even though not required by law, nutrient management plans are beneficial to producers and the environment to properly manage nutrients on the farm, reduce nutrient loss to the environment, reduce the nutrient inputs required for a cropped field, and improve long-term soil quality.

Changes in Conventional Pesticide Use Due to Development of Genetically Modified Crops

Genetically modified (GM) varieties of corn, soybean, and cotton have largely replaced conventional varieties of these crops (see "Genetically Modified Crops" in Chapter 3). By far the most widely used application of GM technology has been the development of crops that are tolerant to a specific herbicide, or that produce insecticidal properties within the plant itself, or both (stacked GM crops). GM crops have the potential to save the grower time and money by reducing the amount and variety of conventional pesticides used. Over the past two decades, the use of conventional pesticides in the United States has been strongly affected by the use of GM crops (Coupe and Capel, 2015). This change in pesticide use for soybean and corn is illustrated in figure 8.2

Herbicide-tolerant GM crops are made to tolerate a single, broad-spectrum herbicide, primarily glyphosate, but more recent technologies include resistance to glufosinate and imazethapyr. For insect-resistant GM crops, the whole plant has been made to produce a toxin to certain classes of insects.

For soybean, there has been a substantial increase (about 9-fold) in the use of glyphosate since the introduction of the herbicide-tolerant GM crop in 1996. Over the same period, the mass of all conventional herbicides used on soybean has decreased (about 6-fold). Soybean has minimal problems with insecticides, however, so no insect-resistant GM soybean have been developed. The use of conventional insecticides on soybean is small, but may be on the rise in recent years (Coupe and Capel, 2015).

Since glyphosate-tolerant GM corn was introduced in 1996, herbicide use has only decreased about by one-half. The amount of glyphosate used has increased substantially and continually, but is still only one-half of the total amount of conventional herbicides—even though about 90 percent of the corn planted is of the glyphosate-tolerant GM varieties. The use of conventional herbicides on GM corn is still substantial and has not been reduced to nearly the same extent as for soybean. The use of conventional insecticides on corn has substantially decreased (about 8-fold) since the introduction of the *Bt* corn.

Changes in the use of insecticides and herbicides on cotton have been similar to that for corn since the introduction of the GM cotton crop in 1995. The use of total conventional insecticides used has decreased about 5-fold and the use of total conventional herbicides has decreased by about one-half, but the combined herbicide mass is still greater than the mass of glyphosate use, even though about 90 percent of the cotton crop has GM herbicide tolerance (Coupe and Capel, 2015).

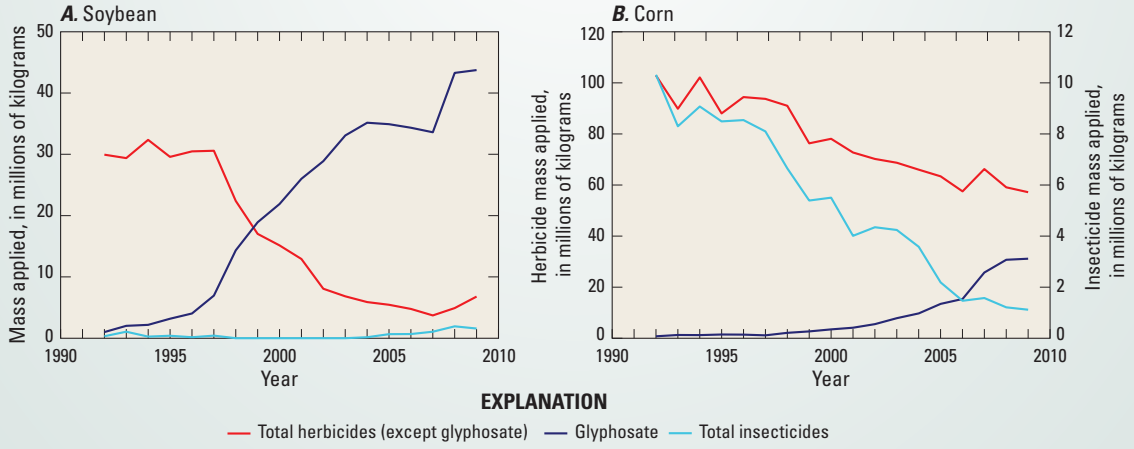


Figure 8.2. Application of total conventional insecticides, total conventional herbicides (except glyphosate), and glyphosate on (*A*) soybean and (*B*) corn in the United States, 1992–2009 (Coupe and Capel, 2015).

Most pesticides are not applied in their pure form, but rather are formulated with carriers (inert ingredients) that allow for a uniform application at a specific dose. Water is the most common diluent, but various solvents, mineral oils, and vegetable oils also are used. Pesticides also can be adsorbed to solid materials, such as chalk, clays, rice hulls, and nut shells. These liquid formulations and solid carriers are all designed to add stability to the pesticide mixture, make them easier to handle, easier to apply, and maximize their efficacy. A variety of inert chemicals (about 1,500 different chemicals; Capel and others, 2017) are used in the formulations of pesticides for specific purposes. Included among these inert chemicals are wetting and sticking agents (surfactants and gums) added to help the pesticide formulation produce the optimum droplet size and to help make contact with the plant surface. Other inert ingredients are attractants (pheromones and syrups) added to attract insects to the pesticides, thickeners (polymers and clays), and defoaming agents (silicones) added to create the correct consistency for application. For some insecticides, a synergist (piperonyl butoxide) is added to increase effectiveness of the active ingredient.

Chemicals in animal agriculture are both consumed to simulate growth and protect against pests and disease, and produced as waste by-products. The essential nutrients for growth (carbon, nitrogen, phosphorus, potassium, and micronutrients) come from feed and other supplements, all of which are largely derived from plant materials. Animal feed largely comes from natural grasslands or agricultural crops. Grazing animals (largely cattle) obtain most of their food from grasslands. Other animals, which are concentrated in feeding operations (fig. 8.3), obtain all or part of their nutrition from feed that is derived from crops, such as corn, soybean, sorghum, and hay. The animal feed is sometimes supplemented with additional nutrients (particularly phosphorus), micronutrients, and vitamins. Agricultural animals, particularly those in concentrated feeding operations, also receive chemicals to protect them from pests (insecticides) and disease (antimicrobials; table 8.2). Some animals also receive hormones and low-level antimicrobials to promote faster growth (U.S. Food and Drug Administration, 2002, 2010).

Animals produce waste. A number of environmental concerns arise from the handling, storage, utilization, and disposal of animal waste (table 2.2; see "Manure" in Chapter 6). When applied to agricultural land appropriately, manure adds organic matter and nutrients to the soil. However, manure also can be over applied and supply excess nutrients that can affect water quality. Manure also can contain trace elements, antimicrobials, hormones, bacteria, and pathogens (Boxall and others, 2003; Hanselman and others, 2003; Martínez-Carballo and others, 2007; Andaluri and others, 2012). These substances can be distributed throughout the fields on which the manure is applied. For the most part, the pathogens die in the soil and the chemicals are transformed, but some small fraction persists and can move into the environment. Improper manure handling and application have resulted in contamination of streams and human food supplies. The contamination of streams by manure can lead to low dissolved oxygen concentrations that can result in fish kills.

Figure 8.3. Antimicrobials are widely used in concentrated animal feeding operations to improve health and growth rates (Wisconsin). Photograph by Bob Nichols, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSWI00015, 2000.

Animal agriculture also generates waste gases directly from the animals or from off-gassing of the manure. These waste gases cause two distinct types of environmental concerns. Methane (directly from cattle) and nitrous oxide (from the decomposition of manure) are greenhouse gases that can contribute to global climate change. Hundreds of other gaseous chemicals from animal agriculture (including hydrogen sulfide, ammonia, and volatile fatty acids) have a strong odor and some are irritants when breathed. These chemicals can cause substantial local concerns for human health and aesthetics.

Environmental Behavior of Agricultural Chemicals

Each agricultural chemical behaves uniquely in the environment, but all are subject to common chemical, biological, and hydrological processes. Upon entering the environment, a chemical can undergo three different types of change processes. A chemical can undergo a change as to its local, molecular-scale environment (distribution processes), its location (transport processes), or its chemical form (transformation processes). These processes, taken together, can be used to help interpret and predict the environmental behavior and fate of a chemical.

Distribution processes determine the extent to which an agricultural chemical is distributed among various environmental phases—water, air, sediment, and (or) biota. The distribution of an individual chemical is based on the characteristics of the chemical, the characteristics of the environmental phases, such as water and soil, and the relative volumes of the different environmental phases. The water solubility of a chemical largely controls the distribution between water and biota and between water and sediment. (Sediment is used herein as a general term to describe all environmental particles such as suspended sediment, stream-bottom sediment, soil, and aquifer solids). The vapor pressure of a chemical largely controls the distribution between air and sediment, whereas Henry's Law constant (vapor pressure divided by water solubility) largely controls the distribution between air and water. The equilibrium distribution of a variety of agricultural chemicals among air, water, and sediment is shown in figure 8.4. These results are simple generalizations, but are useful in helping to make the connections between a chemical's properties, phase distribution, and environmental transport. Environmental characteristics, such as pH, redox, temperature, salinity, and type of soil surface, also affect the phase distribution of chemicals. As an example, the solution pH has an important effect on the distribution of chemicals and chemical compounds with acid/base properties, such as ammonia and glyphosate.

Transport processes move chemicals from one location to another—from the soil surface, through the layers of soil to a subsurface drain, to an agricultural ditch, to a major river, and ultimately to the ocean. Chemical (and particle) transport is accomplished through the energy provided by the movement of water or wind. Most of the material presented in Chapters 4 through 7 has focused on the movement of water through and out of agricultural areas and serves as the foundation for understanding chemical transport into and through the environment.

The environmental phase in which a specific chemical accumulates is important to its environmental behavior and transport. Chemicals that are strongly distributed toward sediment (upper left part of fig. 8.4) are largely transported in the environment with the soils and sediment, and accumulate

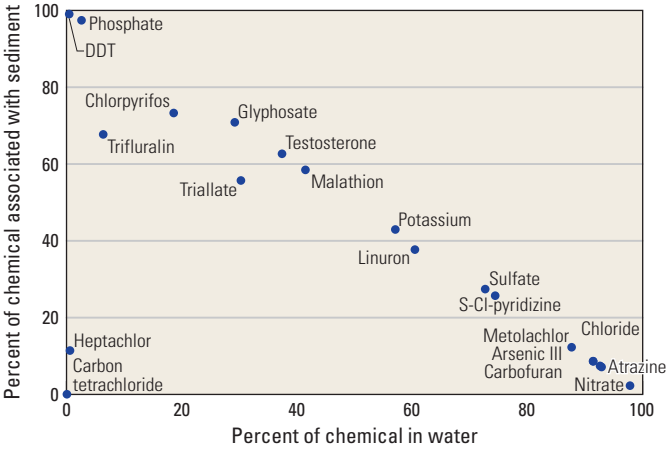


Figure 8.4. Estimated equilibrium distribution of various agricultural chemicals among air, water, and sediment in and above a stream. The chemicals at the origin of the graph (0 percent in the water, 0 percent associated with sediment) are gases with high vapor pressures and predominantly are present in the environment in the gas phase. Most chemicals settle along the line that connects 100 percent in the water with 100 percent associated with sediment. These chemicals are distributed between water and sediment, and do not readily move into the air. A few chemicals, such as the herbicide trifluralin, settle below this line, indicating that some of the chemical in the air, so all three phases are important in their environmental distribution (Capel and others, 2018).

in soils, streambed sediments, and suspended sediments. This group of chemicals includes phosphorus, some pesticides (DDT, chlordane, permethrin, and chlorpyrifos), and some trace elements (lead and copper). A subset of these chemicals also accumulate in biotic tissues (DDT and chlordane). Some chemicals are present predominantly in water (lower right part of fig. 8.4) and, generally, are moved by the flow or movement of water. This group of chemicals includes chloride, nitrate, atrazine, and metolachlor. The environmental movement of the permanent gases and other chemicals with high vapor pressures is generally controlled by the movement of the air.

Transformation processes change the structural form of a chemical to produce a new chemical(s). Every chemical has a unique three-dimensional arrangement of atoms. Chemical structure can range from simple, such as that of molecular nitrogen (N≡N), to complex structures like proteins. A change in this three-dimensional arrangement of elements creates a different chemical(s) with different environmental behavior, and oftentimes different environmental concerns. Chemical transformations are induced by external forces (energy from the environment) acting on the chemical, including biological (plants, animals, or microorganisms), chemical (reactions with other chemicals), and physical (sunlight and heat) forces.

Many elements combine with other elements to form a large number of different chemicals. As an example, some of the various forms of nitrogen are shown in figure 2.4 (see "Nitrogen" in Chapter 2). Each of these forms of nitrogen is a different chemical, but the element nitrogen is always the same, regardless of whether it is in the form of ammonia, nitrate, nitrous oxide, or urea. Natural processes can transform one form of nitrogen into all its other forms. Together, these processes allow nitrogen to cycle among its various forms and guarantee that no single form becomes a "dead end" that accumulates in the environment. The important nitrogen forms (boxes) in the agricultural environment and the transformations that connect them (arrows) are illustrated in figure 8.5.

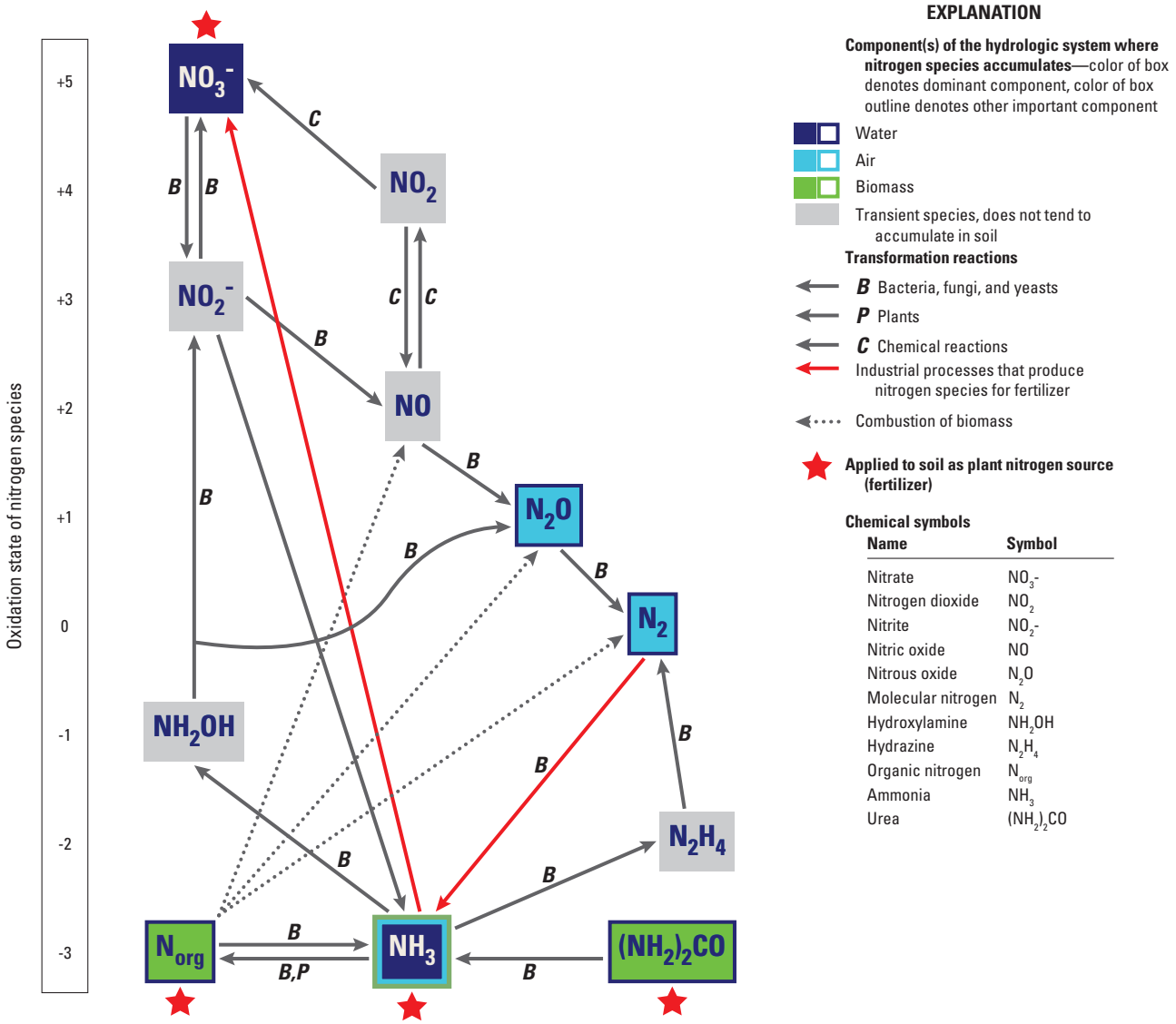


Figure 8.5. Cycle of nitrogen in the agricultural environment showing the transformations between the various chemical forms of nitrogen, arranged in rows by their oxidation state. (Capel and Hopple, 2018.)

Carbon forms strong bonds with itself and many other elements. This bonding provides the possibility of creating new synthetic carbon-containing chemicals. When one of these carbon-containing chemicals is transformed, the carbon remains as carbon, but the complex, three-dimensional structure generally becomes simpler until it is eventually transformed to carbon dioxide or methane. The transformation of the herbicide glyphosate is illustrated in figure 8.6. The complex chemical structure of glyphosate is produced industrially. After glyphosate is released in the environment, it is transformed through a series of intermediate chemicals (transformation products or degradates) until the carbon dioxide endpoint is reached. Some of the transformation products have short (hours and weeks) environmental lifetimes, whereas others persist much longer (months and decades). For example, glyphosate has an environment lifetime of about 7 months in water, but aminomethylphosphonic acid (AMPA), its first transformation product, has a longer lifetime and has been observed to accumulate in some of the hydrologic components (Coupe and others, 2011). Because there are no natural processes that produce synthetic chemicals, such as glyphosate, transformations are always in the direction from complex synthetic chemicals to carbon dioxide. Many intermediate chemicals can be formed and transformed in the process.

The range of environmental lifetimes for some common agricultural chemicals is illustrated in figure 8.7. For chemical elements, this range is the lifetime of a certain specific chemical form (for example, nitrate being transformed into other nitrogen forms, fig. 8.5). For carbon-based molecules, this is the lifetime of the specific chemical being transformed into another chemical (for example, glyphosate transformed to AMPA, fig. 8.6). The extent and rate of the transformation is oftentimes dependent on the chemical and biological characteristics of the environment. As an example, nitrate is shown twice in figure 8.7. Nitrate has a relatively short lifetime in environmental settings with little or no oxygen (such as many groundwater environments), but a comparatively long lifetime in environments that are rich in dissolved oxygen (such as groundwater containing dissolved oxygen).

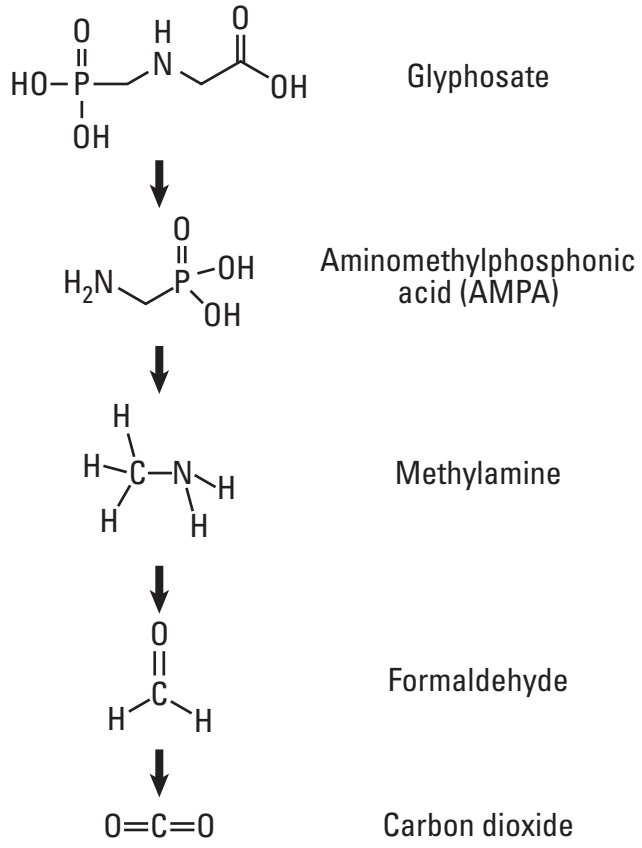


Figure 8.6. Transformations of glyphosate in the environment (Wiersema and others, 2012).

Legacy chemicals have long environmental lifetimes (years and decades) and are observed long after their sources have decreased in concentration or been eliminated. The legacy chemicals detected in groundwater generally are long-lived compounds that are largely dissolved in water and move with water through the groundwater system. The legacy chemicals detected in surface water generally are long-lived compounds that strongly bind to sediment and accumulate in bottom sediments or are taken up by living organisms and accumulate in their tissues. Sediments, from eroded soil and streambanks, that have accumulated in stream channels and streambeds are also a legacy concern.

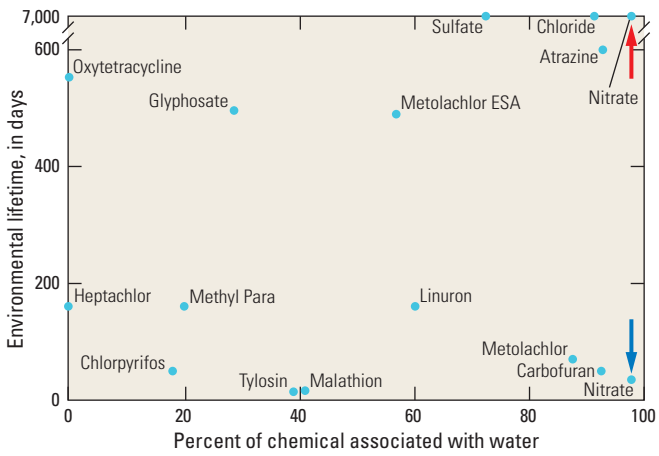


Figure 8.7. Environmental lifetime and the percentage of the chemical in the water for various agricultural chemicals. Legacy chemicals (those with long environmental lifetimes) typically found in surface water are grouped on the upper left side of the graph (minimally in the dissolved phase) and legacy chemicals typically detected in groundwater are grouped on the upper right side of the graph (largely in the dissolved phase). Nitrate is readily removed in subsurface environments with no or low dissolved oxygen (reduced conditions, blue arrow), but has a long lifetime in subsurface environments with higher dissolved oxygen concentrations (oxic conditions, red arrow) (Capel and others, 2018).

DDT, chlordane, and other organochlorine insecticides were widely used in agriculture from the 1940s through the 1970s. Many of these chemicals have long environmental lifetimes (years to decades) and are strongly associated with sediment in water. None of the organochlorine insecticides have been used in this country for decades (except for lindane), but they are still being detected in bed sediment and fish tissue samples from agricultural streams across the Nation (Gilliom and others, 2006). DDT (and its transformation products DDE and DDD) and (or) other organochlorine insecticides are still present in fish tissues and bed sediments (detected in up to 90 and 50 percent of the samples analyzed, respectively). These chemicals have been replaced in recent decades by other insecticides that are less persistent and less accumulative, but the organochlorine insecticides will continue to be present in fish tissues and sediments, as well as air, water, and human tissues, for decades to come.

Nitrate and some pesticides and their transformation products are common legacy chemicals in groundwater (Gilliom and others, 2006; Dubrovsky and others, 2010; Puckett and others, 2011). Eighty-three percent of the studies of shallow groundwater in agricultural areas collected one or more samples (of 20–30 wells sampled) with a nitrate concentration greater than 10 mg/L as nitrogen (the Federal drinking water Maximum Contaminant Level [MCL] value). In subsurface environments with no or low dissolved oxygen (reduced conditions), nitrate is transformed relatively quickly (hours to weeks) and is seldom observed. In subsurface environments containing dissolved oxygen (oxic conditions), however, nitrate has a slow rate of transformation and, therefore, persists as a legacy chemical. Groundwater contributions of nitrate to streams are substantial. At least one-third of the total annual load of nitrate in two-thirds of 148 small streams studied across the Nation was derived from baseflow (Dubrovsky and others, 2010).

The potential for chemicals and their transformation products to remain in the environment and become legacy chemicals can be predicted based on chemical properties and an understanding of the hydrologic system. The environmental lifetime of the chemical and the percent of the chemical in the water for a number of agricultural chemicals are shown in figure 8.7.

Agricultural Chemicals in Shallow Groundwater

Throughout this report, streams are treated as the primary endpoint of water-quality concerns. Groundwater is only considered as a flowpath for water and chemicals as they travel from the land surface to the stream. In some areas, however, groundwater is intercepted by wells and pumped to the surface for human consumption, irrigating crops, or watering livestock. The drinking water for about 44 million people in the United States is from private wells (Belitz and others, 2016). It is, therefore, important to consider groundwater as more than just a pathway for water to travel from land surface to streams.

In agricultural areas, shallow groundwater is susceptible to contamination from agricultural chemicals and animal manure. Shallow wells in irrigated areas with well-drained soils are particularly vulnerable to contamination from the land surface (Nolan and Hitt, 2006). Wells with inadequate, leaking, or otherwise damaged casings are especially at risk (Eberts and others, 2013).

Nitrate is commonly detected in groundwater that underlies agricultural areas, frequently at concentrations exceeding the Federal drinking water Maximum Contaminant Levels (MCL) of 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 2009) (fig. 8.8). Commercial fertilizer and animal manure are agricultural sources of nitrate. Water-soluble pesticides, mostly herbicides, and the compounds into which they degrade also are found in shallow groundwater underlying agricultural areas. In addition to the currently used pesticides and pesticide transformation products (fig. 8.8*B*), groundwater also may be contaminated by chemicals that are no longer in use (Steele and others, 2008). Animal waste also may be a source of bacteria, salts, and pharmaceuticals such as antimicrobials and hormones in shallow groundwater. Concentrated animal feeding operations (CAFOs), in which large numbers of animals live in restricted spaces, can be substantial sources of these chemicals (Burkholder and others, 2007).

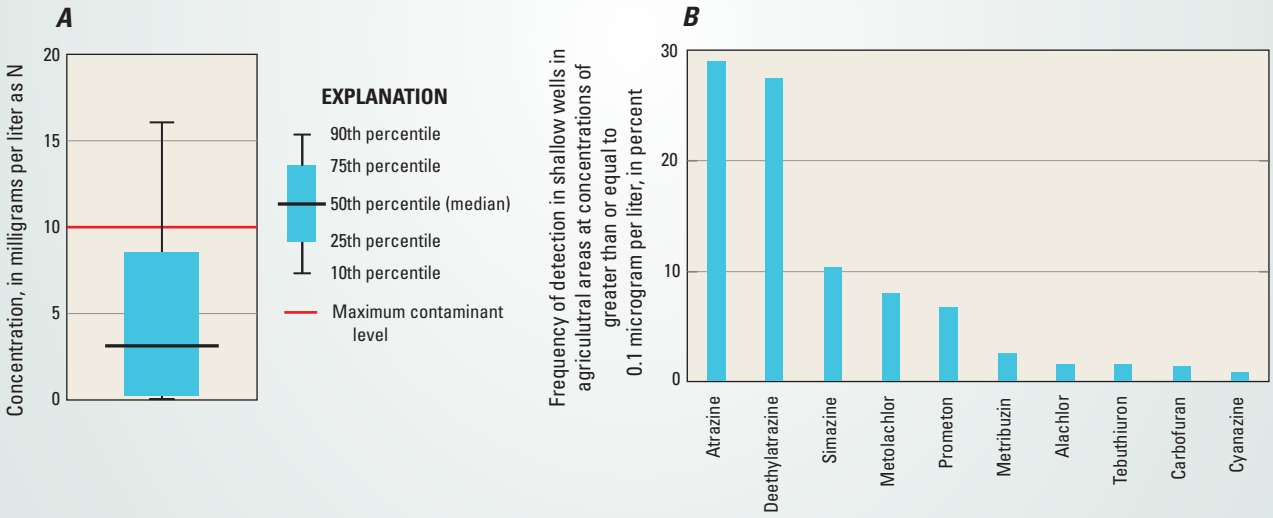


Figure 8.8. (*A*) Range of nitrate concentrations measured in shallow groundwater in agricultural areas throughout the United States (Dubrovsky and others, 2010). The red line indicates the Maximum Contaminant Level (MCL) of nitrate allowed by the U.S. Environmental Protection Agency for public drinking water. (*B*) Pesticides and pesticide transformation products detected in shallow groundwater in agricultural areas throughout the United States (Gilliom and others, 2006).

Summary

Thousands of chemicals are connected with crop and animal agriculture. Many chemicals are purposely used because they directly benefit agriculture—increase yield, protect crops or animals, increase soil quality, dispose of waste, facilitate the effectiveness of another chemical that has a purposeful use, or protect the environment—whereas others are produced by the crops and animals or by chemical or microbiological reactions as waste by-products. Some chemicals that are naturally stored in the soil and water are mobilized by agricultural activities. Finally, some chemicals are introduced into the agricultural landscape through "piggy-backing" on purposely applied chemicals. Nutrients (fertilizers and manure) and chemicals that protect the crops and (or) animals from pests (pesticides and antimicrobials) are purposely applied, but can cause water-quality impacts. The water-quality concerns from these chemicals result, in part, to their effects on the environment, and, in part, to their quantity of use and (or) release in agricultural activities.

Every chemical associated with agriculture has its own unique behavior in the environment; each agricultural chemical is subject to common chemical, biological, and hydrologic processes. These are processes that can be generalized to help interpret and predict the environmental behavior and fate of a specific chemical. Upon entering the environment, a chemical can undergo three different types of processes that affect and change its behavior and fate. The chemical can undergo a change as to its location (transport processes), its local (molecular-scale) environment (distribution processes), or its chemical form (transformation processes).

Many environmental concerns are the result of an excess of a chemical (or sediment or pathogens) compared to its natural background concentration. Agricultural activities can introduce an excess concentration of naturally occurring chemicals to the environment through tillage, manure, and fertilizer applications, or changes in the pre-agricultural flowpaths of water. Any presence of man-made chemicals in the environment, such as synthetic pesticides, antimicrobials, and surfactants, is in excess of the natural concentration (zero). The excess concentration of a chemical does not always affect the environment, but it is an indication that agricultural activities are affecting the environment.

Agriculture in Central Indiana

Central Indiana's Till Plain was formed 17,000 years ago when the Laurentide ice sheet that covered parts of the Midwest retreated, leaving behind thick rich soils and productive aquifers. Forests, prairies, and wetlands were all part of the central Indiana landscape (fig. 1.3). Swamps formed in areas of seasonally standing water. Beech-maple forests were common. Prairies dotted the northern and western fringes of the area, where bison herds roamed. Central Indiana forests also were inhabited with mountain lions, wolves, black bear, and elk. By the early 1800s appreciable populations of these species were gone from the area. The deep fertile soils that make up this region generally are poorly drained, nearly level, and loamy. The climate is characterized as humid, continental with hot summers and cold winters. The annual precipitation is about 90 cm and is fairly evenly distributed throughout the year.

Some of the earliest farmers in Indiana were Native Americans from the Mississippian culture who built large permanent communities supported by agriculture. The first Europeans in Indiana were French fur traders, who arrived in the late 1600s. The early pioneers were subsistence farmers who lived off their land and provided for themselves. With the construction of the National Road in the 1820s (U.S. Highway 40), more settlers arrived. Pressure for arable land increased; more forest was cleared, and lowland areas were drained either by ditches or subsurface drains to make land more suitable for crops. Within a generation the population soared from 5,600 people in 1800 to nearly 1 million by 1850. Without improved drainage, farming would not be possible in many areas. By 1910, more than 80 percent of the land had been cleared for agriculture. Woodlands remained mostly along the riparian corridors. Farmers planted the land in corn, wheat, oats, potatoes, flax, and apples and raised cattle, sheep, and hogs. Corn production steadily increased, and in the 1940s soybean was introduced as a rotation crop with corn. After World War II, a trend toward high yield, intensive agriculture increased the use of commercial fertilizers and pesticides. The average corn yield in the 1940s was about 2,500 kilograms per hectare (kg/ha); in 2010, the average hybrid corn yield was about 9,000 kg/ha. In 2010, about 65 percent of the land in Indiana was in farmland with the average size farm about 100 ha. Currently, corn and soybean are principal crops, and hogs, dairy, and chickens are the primary livestock raised in central Indiana. Recent trends show a small but increasing area used for specialty agriculture including tomatoes, apples, floriculture, and organic agriculture.

Recent studies by the USGS on the effects of agriculture on water quality in central Indiana have focused on the transport of nutrients and pesticides in watersheds where subsurface drains are present (Baker, Stone, and others, 2006; Baker and others, 2007; Stone and Wilson, 2006). There have been numerous USGS studies on the biological response to nutrients in Indiana streams (Caskey and others, 2007, 2010; Caskey and Frey, 2009; Frey and others, 2011). Other studies have focused on the effects of agricultural management practices on water quality in Indiana watersheds (Bracmort and others, 2004, 2006; Kladivko and others, 2004; Harper and Hartke, 2009), and the link between agricultural chemicals and birth defects (Winchester and others, 2009).

A ***B*** ***C***

The landscape of central Indiana. (*A*) The wetlands and beech forests typical of the time before agriculture, (*B*) typical cropped fields, and (*C*) the view from the air (23 square kilometers). Photograph *A* by Marion Jackson, Natural Heritage of Indiana (Hoot Woods, Owen County, Indiana), 1997; photograph *B* by Jeffrey Martin, U.S. Geological Survey, 2008; photograph *C* from U.S. Department of Agriculture, Farm Service Agency, National Agricultural Imagery Program, 2010.

Chapter 9—Connections Between Agriculture and Water Quality

How can we go from understanding these connections to informing agricultural management decisions and setting realistic expectations?

This chapter provides real-life examples of how understanding the connections between agricultural activities and the movement of water, chemicals, and sediment can be used to inform agricultural management decisions to improve and protect the quality of our Nation's streams and groundwater.

Agricultural activities impact water quality at many scales

The importance of considering the response of the ecosystem as a whole to modifications in agricultural activities—even those intended to improve water quality—is illustrated by the recent history of the Yakima River Basin. In the late 1990s, changes in irrigation practices, from furrow to sprinkler and drip methods, and the use of a soil stabilizer, polyacrylamide (PAM), were widely implemented in the Yakima River Basin in central Washington. These changes resulted in a substantial reduction of suspended sediment—loads were reduced by more than 90 percent in many areas such as in the Granger Drain, Washington (fig. 9.1*A*). This resulted in a dramatic improvement in stream-water clarity.

Prior to irrigation improvements, nuisance blooms of aquatic plants were limited by the turbidity caused by the sediment in agricultural runoff. Beginning in 2001, however, the increase in stream-water clarity enabled the growth of large, dense patches of aquatic plants in the nutrient-rich Yakima River during the spring and summer (fig. 9.1*B*). This growth is an aesthetic nuisance in the river; plant decay causes a decrease in dissolved-oxygen concentrations, which can harm fish.

Over the past few decades, the quality of groundwater has decreased in many of the Nation's agricultural areas, including the regional aquifer systems that underlie the Central Valley of California, Basin and Range, Rio Grande, Columbia Plateau, Snake River Plain, Florida, northern glacial areas, Mississippi Embayment, Northern Atlantic Coastal Plain, and the High Plains (DeSimone and others, 2009). Agricultural activities can introduce agricultural chemicals and mobilize naturally occurring trace elements and dissolved solids (table 8.1) that are transported to the groundwater. Elevated concentrations of nitrate, herbicides, insecticides, fungicides, and their transformation products; chloride and other dissolved solids; and trace elements, such as selenium, arsenic, and uranium, have been observed. In some areas of these regional aquifers, the water table has declined due to extensive withdrawals that exceed recharge. The combined effects of decreased water quality and declining water tables can have substantial—perhaps irreversible—impacts. The sustainable availability of water and limitations on the uses of water for drinking or irrigation due to poor water quality are important long-term concerns in many of these aquifer systems.

The High Plains aquifer is the principal aquifer that underlies parts of eight States on the Great Plains (fig. 9.2; Gurdak and others, 2009). Much of the landscape overlying the aquifer is used for crop and animal agriculture supported by extensive irrigation. The water table of the High Plains aquifer has declined in many areas over the past few decades because water withdrawal has been greater than recharge. Some of the excess irrigation water infiltrates into the soil and transports agricultural and natural chemicals to the groundwater. Elevated concentrations of dissolved solids, nitrate, and pesticides are observed at and below the water table in many areas. Nitrate concentrations greater than background levels are observed throughout the aquifer. Although the transit times of water from the land surface to the water table is generally slow (decades to centuries), there are local areas, such as beneath natural depressions in the land surface, that have transit times to the water table on the order of months to years.

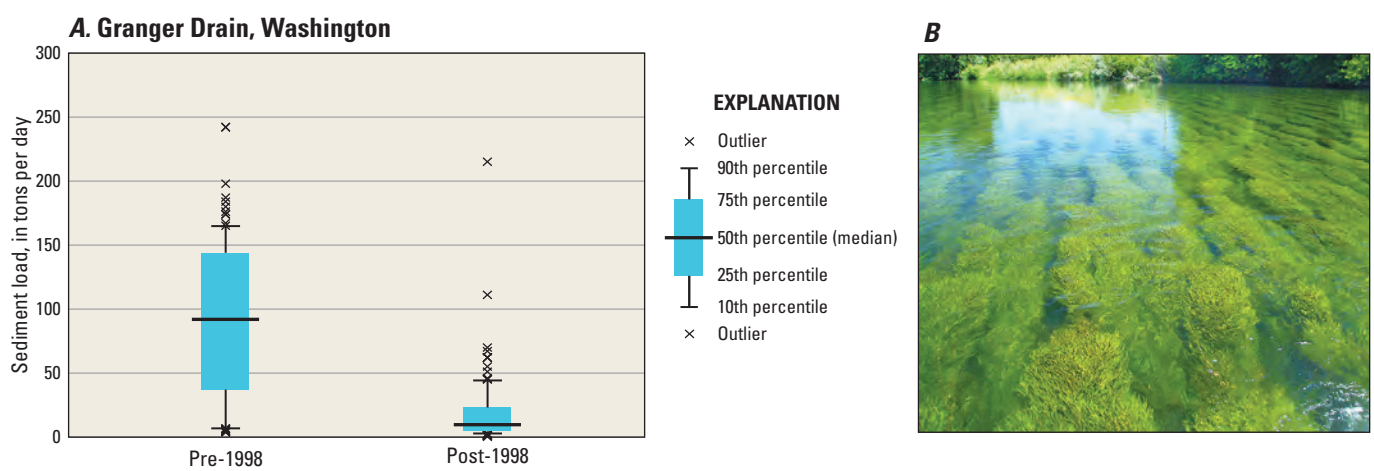
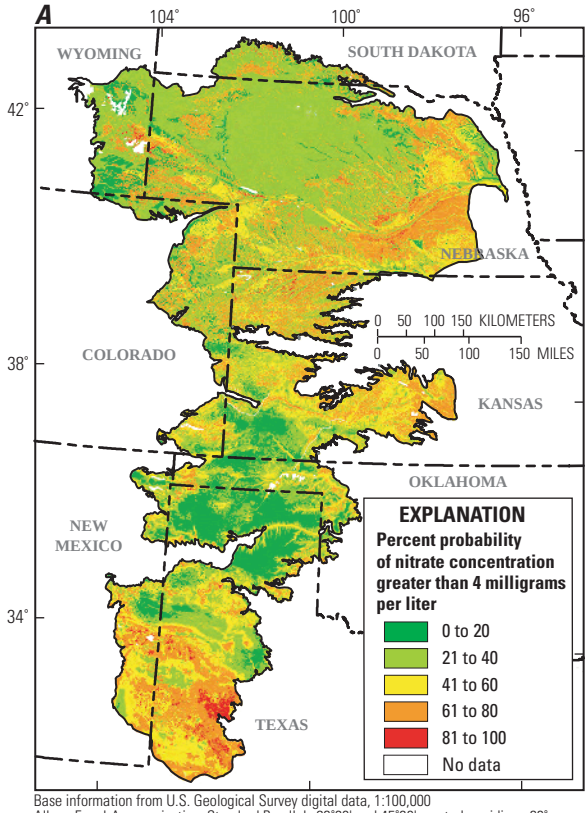


Figure 9.1. Changes in irrigation practices contributed to a significant reduction in the sediment load after 1998 and an increase in water clarity. The increased water clarity combined with nutrient-enriched waters contributed to the growth of large patches of dense aquatic vegetation in the spring and summer that resulted in decreased oxygen levels in the stream (Capel and Hopple, 2018). Photograph *B* by Kurt Carpenter, U.S. Geological Survey.



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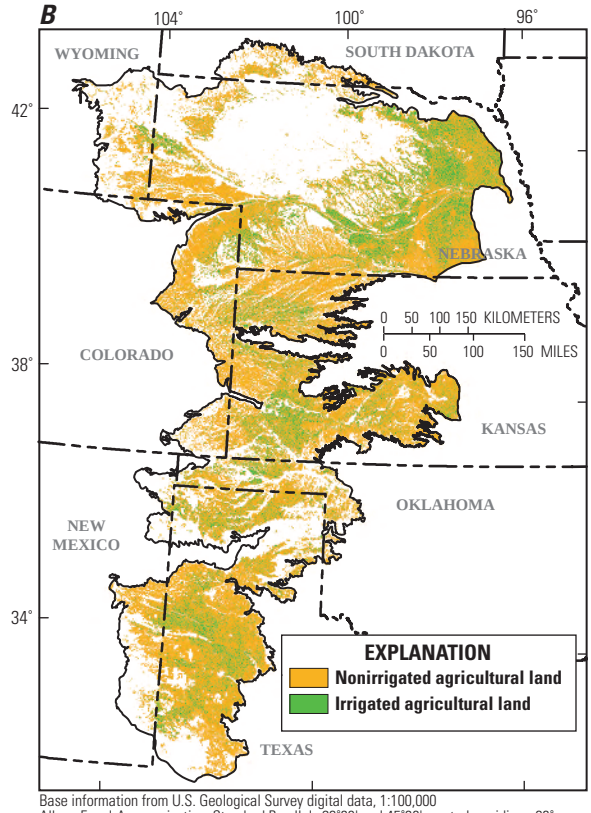

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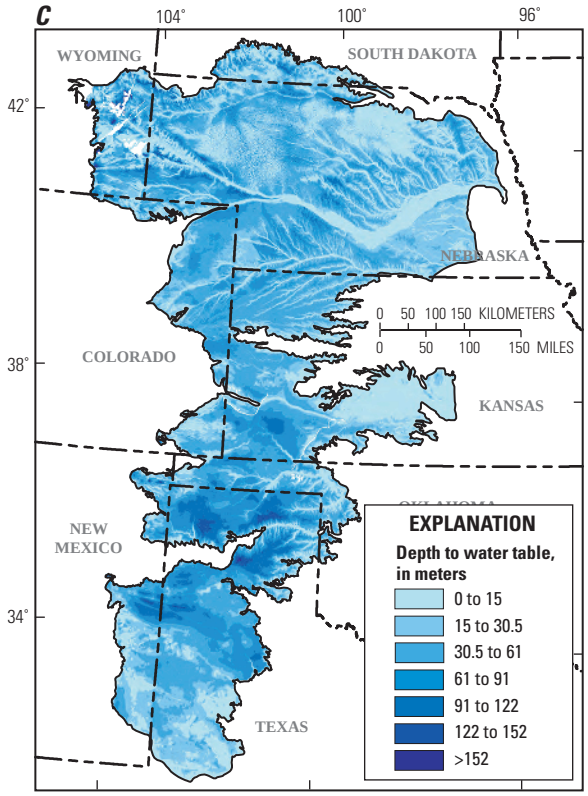


Base information from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area projection, Standard Parallels 29°30' and 45°30', central meridian –96°

Figure 9.2. Areas of the High Plains aquifer that are vulnerable to elevated nitrate concentrations have been identified through the use of field observations and statistical models (*A*) (Gurdak and Qi, 2006). Overall, about 21 percent of the High Plains aquifer has a probability of greater than 60 percent of elevated nitrate concentrations (>4 mg/L nitrate as nitrogen). Areas that have more agricultural land (irrigated and nonirrigated) (*B*), shallower depths to water table (*C*), and less clay in the unsaturated zone are areas with the greatest likelihood of elevated nitrate concentrations. In the northern region of the High Plains aquifer, the organic matter content of the soil is important. Areas with less organic matter in the soil have a greater likelihood of elevated nitrate concentrations.

Every summer a large **hypoxic** (low or no dissolved oxygen) zone forms in the Gulf of Mexico that extends along the Texas and Louisiana coastlines (fig. 9.3), threatening an ecosystem that supports valuable commercial and recreational fisheries—almost 80 percent of the U.S. landings of shrimp come from these prized waters. When dissolved-oxygen levels are less than 2 mg/L, less mobile or immobile animals such as mussels are often killed. Hypoxia also results in loss of habitat, displacement of fish, and decrease in reproductive ability in some fish species (Rakocinski and others, 1997; Craig and Crowder, 2005; Conley and others, 2009). This hypoxic zone is the second largest in the world. In 2015, the zone covered about 16,770 km^2, an area about the size of Connecticut and Rhode Island combined.

The annual size of the hypoxic zone is related to the annual amount of nitrogen and phosphorus delivered to the Gulf of Mexico by the Mississippi River. Each of the 31 States draining this vast watershed contributes different amounts of nitrogen and phosphorus. These nutrients stimulate algal growth in the Gulf of Mexico and consume the oxygen in the water when they die and decay (Rabalais and others, 2002). A USGS water-quality model, calibrated using more than 850 monitoring sites, helps identify which areas and sources are contributing the largest amounts of nutrients to the Gulf of Mexico (fig. 9.3; Robertson and Saad, 2013) Three States—Iowa, Illinois, and Indiana—represent 11 percent of the drainage area, but contribute about 40 percent of the total nitrogen to the Gulf of Mexico. The major sources of total nitrogen delivered to the Gulf of Mexico include farm fertilizer (41 percent), atmospheric deposition (26 percent), urban areas and wastewater treatment plants (14 percent), and confined animal manure (10 percent; fig. 9.3).

The Mississippi River/Gulf of Mexico Hypoxia Task Force has set a goal of reducing the size of the hypoxic zone to less than 5,000 km^2 by 2035 (U.S. Environmental Protection Agency, 2015). Twelve States along the main stem and major tributaries of the Mississippi River have developed nutrient reduction strategies to support this goal. Some of these States have used the results from the USGS water-quality model to prioritize which watersheds to target for nutrient reduction actions.

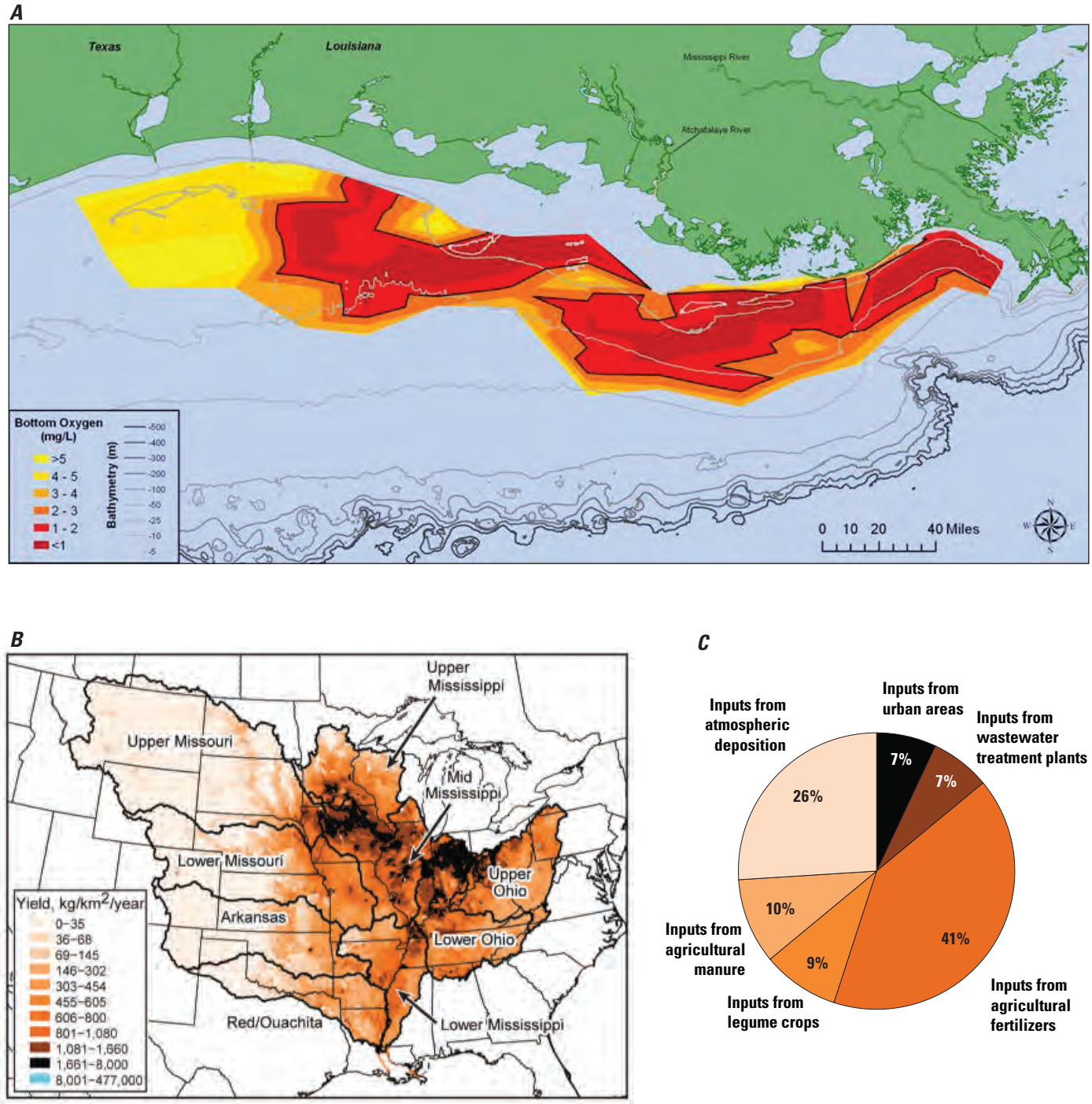


Figure 9.3. A large hypoxic area, also called a dead zone, develops in the Gulf of Mexico each summer. When oxygen levels are less than 2 milligrams per liter, less mobile or immobile animals such as mussels cannot move out of the hypoxic areas and often die during widespread hypoxic events. (*A*) The Gulf of Mexico hypoxic zone in 2015 covered about 16,770 square kilometers (6,474 square miles, an area about the size of Connecticut and Rhode Island combined, during the week of July 28–August 3, 2015). Nutrients from sources such as farm fertilizers, animal manure, and urban areas contribute nutrients that stimulate the growth of algae that die off and deplete oxygen levels in the Gulf of Mexico. (*B*) Areas contributing the largest amounts of nitrogen to the Gulf of Mexico are located in the corn and soybean growing region from Kansas to Ohio. (*C*) The relative importance of various watershed sources of nitrogen to the Gulf of Mexico. Agricultural activities contribute 60 percent of the total nitrogen. Source: (*A*) Nancy N. Rabalais, Louisiana Universities Marine Consortium and R. Eugene Turner, Louisiana State University, written commun., 2016; National Oceanic and Atmospheric Administration (2015); (*B* and *C*) Robertson and Saad (2013).

Nitrogen and phosphorus, used in fertilizers, are transformed into different chemical forms as they move through the environment, but they do not disappear

Fertilizers containing nitrogen and phosphorus are vital for agriculture. Once released into the environment, these elements are assimilated by crops, stored in the soil, or transported elsewhere. The nitrogen and phosphorus are transformed into many different chemical forms, but they do not disappear. They continue to be present somewhere, in some form. Generally, there is excess nitrogen and (or) phosphorus, an amount in excess of what the crop needs and what is available to the crops, some of which can move into the hydrologic environment. Many forms of nitrogen and phosphorus are found in all components of the hydrologic systems, including surface water, bed sediment in surface water, groundwater, air, rain, soil, soil water, and biota. By improving the estimates of the amounts of nitrogen and phosphorus actually needed by the crops and by optimizing application methods, the amounts of applied fertilizers could be decreased, and, therefore, decrease the excesses available for transport beyond the field (Sharply and others, 2005).

Accounting for the annual inputs and outputs of nitrogen in agricultural watersheds provides insights on the amount of nitrogen that moves into the groundwater and streams (fig. 9.4; Essaid and others, 2016). Nitrogen is applied to most cropped fields as either chemical fertilizer or manure. Some crops, such as soybean and alfalfa, also can transform atmospheric nitrogen gas to other forms of nitrogen that are usable by the plants. A small amount of nitrogen (nitrate) is deposited from the atmosphere through rain and snow. A large fraction of nitrogen is assimilated by the plants and removed from the field by way of harvest or transferred to the soil through the crop residue. A fraction is returned to the atmosphere, largely as nitrogen gas and nitrous oxide (fig. 8.5). Typically, a sizeable excess of nitrogen—ranging from about 18 to 40 percent of the output—remains, some of which is stored in the soil, transported with recharge to groundwater, or transported with runoff to streams. The fraction of the excess nitrogen that moves into groundwater and streams is the source of most of the water-quality concerns from nitrogen.

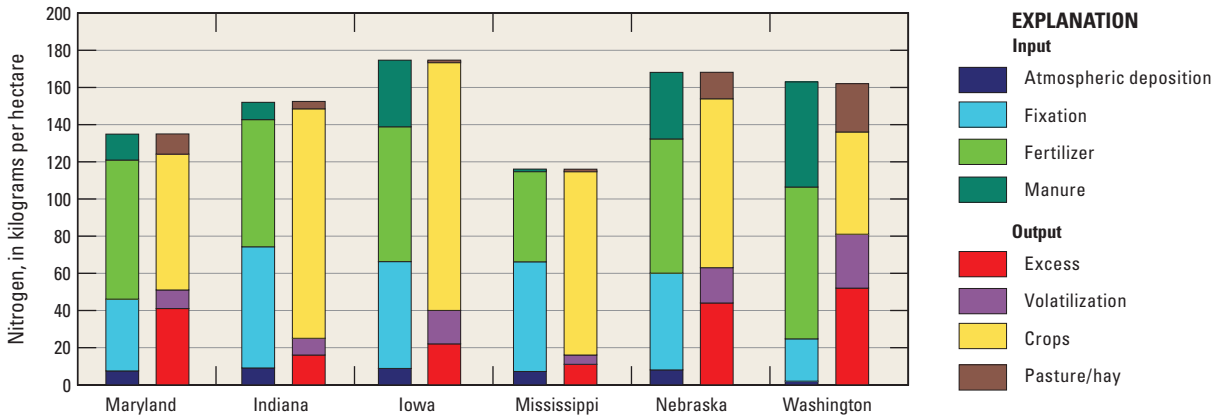


Figure 9.4. Accounting for the annual inputs and outputs of nitrogen in agricultural watersheds provides insights on the "excess" component, which is the amount of nitrogen that moves into the groundwater and streams and contributes to water-quality concerns. (Essaid and others, 2016.)

Nitrogen, as a fertilizer, is most often applied in the forms of urea, ammonia, and (or) organic nitrogen (manure), but it is readily transformed into nitrate—a highly mobile form. Nitrate was observed in every component of the hydrologic system in the Leary-Weber Ditch watershed, in central Indiana (fig. 9.5; Baker, Stone, and others, 2006). Nitrate was detected in relatively high concentrations in the subsurface drain water and the stream water. Nitrate also was present, although at much lower concentrations, in rain, groundwater, and surface runoff. These findings show that the movement of nitrate to this central Indiana stream is more likely through the subsurface drains than through groundwater or surface runoff. The nitrate observed in the various hydrological components in the watershed represents a fraction of the total excess nitrogen calculated in figure 9.5 for this same watershed.

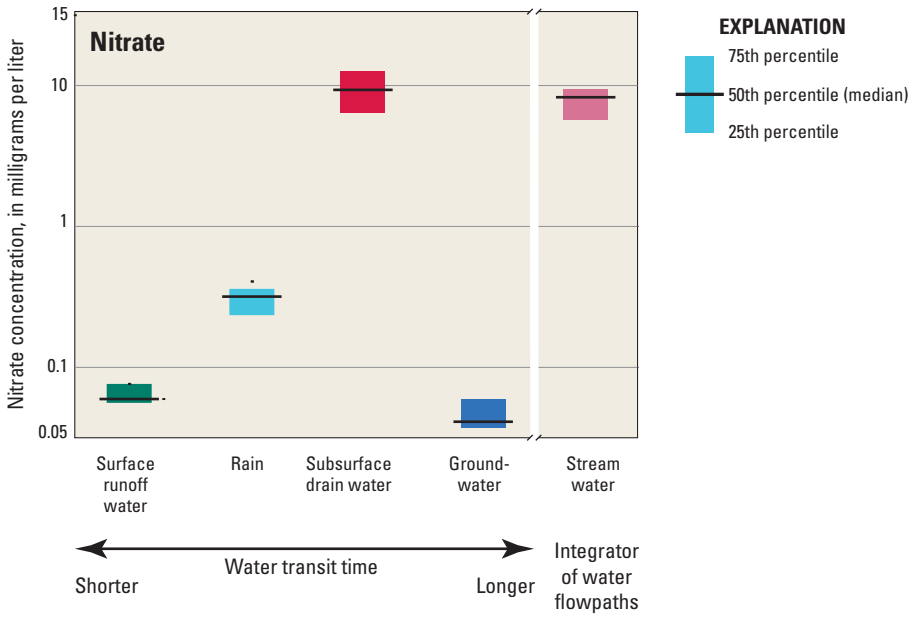


Figure 9.5. The "excess" nitrogen in this watershed is infiltrating through the soil, into the subsurface drains, and into the stream. Understanding how and when nitrate is moving into the groundwater and stream is critical to developing cost-effective nutrient-reduction actions. (From Baker, Stone, and others, 2006.)

Pesticides and their transformation products are detected throughout the environment

Many pesticides and (or) their transformation products can be found in all components of the hydrologic system, including surface water, bed sediment, suspended sediment, groundwater, air, rain, soil, and biota. The transformation products have different behaviors and health effects compared to the parent compound.

Metolachlor has been used as a corn and soybean herbicide for more than three decades. It is applied to the soil surface before the plants emerge from the soil. Metolachlor has two transformation products—metolachlor sulfonic acid and metolachlor oxanilic acid—that are widely detected throughout the environment. One or more of these chemicals were detected in all six hydrologic components in the Leary-Weber Ditch watershed, in central Indiana, where metolachlor is commonly applied to corn (fig. 9.6). The highest concentrations of metolachlor were in the stream and the surface runoff water just after application. In deep soils and groundwater, however, the concentrations of the two transformation products were higher than the concentrations of applied metolachlor because the two transformation products have greater mobility and longer persistence compared to the applied metolachlor.

Transit time is a key factor controlling which forms of metolachlor are detected in the various hydrologic components. The median values for metolachlor as a percentage of total metolachlor (sum of parent metolachlor, metolachlor sulfonic acid, and metolachlor oxanilic acid) tend to become smaller as the transit time of the water in the hydrologic component increases (Rose and others, 2018). The water transit times of each of the components are arranged in figure 9.6 from shortest to longest—surface runoff, rain, subsurface drain water, and groundwater. The stream integrates the water from all other components. Over the course of a year, surface runoff is the primary flowpath delivering applied metolachlor to the stream, whereas groundwater is the primary flowpath delivering the transformation products to the stream.

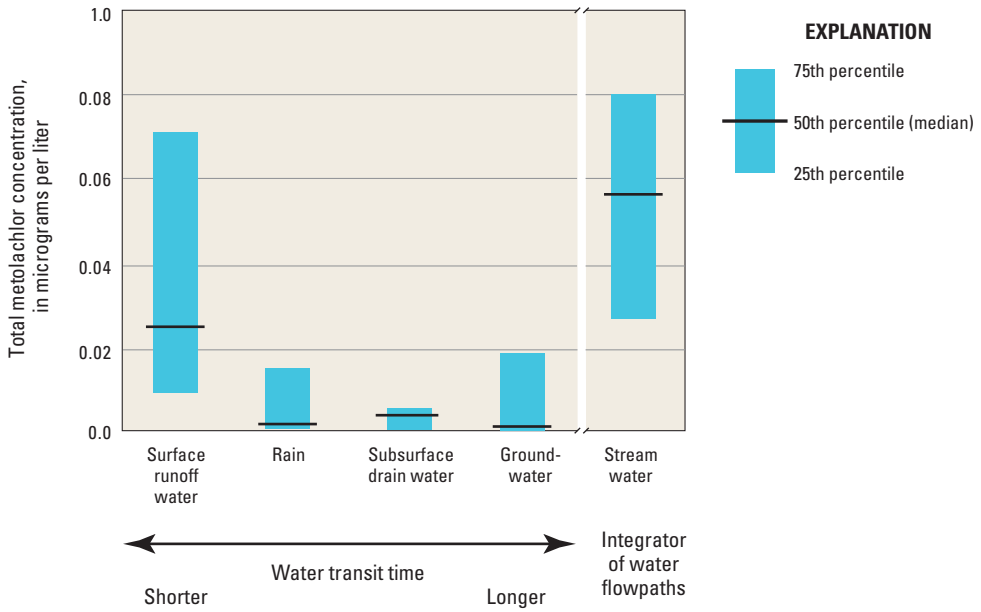


Figure 9.6. Metolachlor, an herbicide commonly applied to corn and soybean fields, and its transformation products were detected in all hydrologic components of the Leary Weber Ditch system, Indiana. The highest concentrations were detected in the stream and the surface runoff water. In deep soils and groundwater, however, the long-lived metolachlor transformation products were detected at higher concentrations than the more quickly transformed metolachlor. Over the course of a year, surface runoff is the primary flowpath delivering applied metolachlor to the stream, whereas groundwater is the primary flowpath delivering the transformation products to the stream. The measurement of metolachlor and the two long-lived transformation products provides a good understanding on the levels of this herbicide in this hydrologic system. (From Rose and others, 2018).

Metolachlor and its two transformation products are some of the most frequently detected pesticides in surface and groundwater (fig. 8.8; Gilliom and others, 2006), although metolachlor transformation products typically are detected more frequently in groundwater than the parent metolachlor. The generalized percentage of metolachlor, relative to its annual application present in each hydrologic component, is shown in figure 9.7. One hundred percent of the input of metolachlor is from application; the chemical does not occur naturally. About 10 percent of the metolachlor volatilizes into the atmosphere. Most of this amount is transformed by sunlight, but a small amount—about 0.3 percent of the total—returns to the land surface in precipitation. The largest fraction of the metolachlor (about 90 percent) moves into the shallow soil where it is either taken up by plants or transformed by microorganisms. About 0.4 percent is transported to streams during storm or irrigation events and another 0.4 percent is stored in the shallow soil. A small amount—typically less than about 0.02 percent—moves into groundwater and eventually may be discharged to streams.

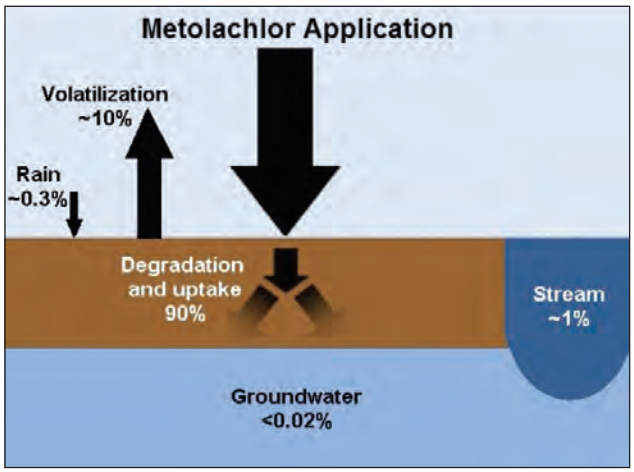


Figure 9.7. Although less than 1 percent of the pesticide applied moves off the field into streams and groundwater, metolachlor is found in all hydrologic components in many agricultural areas where it is applied. The detailed studies on the behavior of metolachlor provide insights into the environmental mobility of many other pesticides that have not been studied as extensively, some of which are far more toxic. The values are the typical percentage of the annual application. After years of study, a generalized mass budget of a yearly application of metolachlor can be calculated. However, not enough is known about the transformation products to do similar mass budget calculations. Understanding the behavior and transport of pesticide transformation products continues to be an important topic of investigation. (From Rose and others, 2018.)

Agricultural chemicals can be transported in the atmosphere

Natural processes and agricultural activities continually introduce water, dust, chemicals, and microorganisms into the atmosphere. Interactions between the agricultural activities on the landscape and the atmosphere can cause various environmental impacts. These impacts vary by chemical, by scale—from local (odors from concentrated animal feeding operations) to global (climate change and global dispersion of pesticides), and by environmental impacts (such as human health effects from inhalation, accumulation of greenhouse gases, loss of soil, and disruption of ecosystems and of neighboring agricultural fields). Animal agriculture, particularly concentrated feeding operations, release many odor- and irritation-causing chemicals (for example, hydrogen sulfide, ammonia), methane (a greenhouse gas), and dust into the air. Activities associated with crop agriculture introduce dust, nitrogen, pesticides, and volatile-organic compounds (from pesticide formulations) into the atmosphere through spray drift, wind erosion, and volatilization. Once in the atmosphere, these compounds can be transported locally to globally with the winds, deposited back onto the landscape, and (or) undergo transformation reactions induced by sunlight. Pesticides and dust particles have been observed to move globally through the atmosphere from their points of origin to their points of deposition (Welch and others, 1991). Organochlorine insecticides (for example, DDT, lindane, and toxaphene) have been transported to the Arctic Ocean where they have accumulated in the ocean biota (Bidleman and others, 1989). Pesticides transported through the atmosphere sometimes have had a negative effect on neighboring crops and vegetation (Seiber and others, 1993).

A mixture of herbicides, insecticides, and fungicides are commonly present in the air during the growing season. During the 2007 growing season in an agricultural area in Mississippi, from 3 to 11 of 16 monitored herbicides (median 7 herbicides) were detected in the air (fig. 9.8; Majewski and others, 2014). Glyphosate was detected in every weekly air sample, although at low concentrations (Chang and others, 2011). Widely used pre- and post-emergent corn, cotton, and soybean herbicides (pendimethalin, metolachlor, and atrazine) were detected early in the growing season. Propanil, used only on rice, appeared in the air later in the growing season (Majewski and others, 2014).

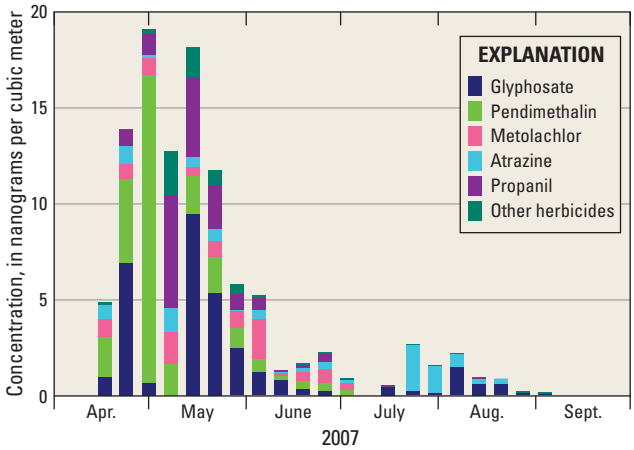


Figure 9.8. A mixture of herbicides were commonly detected in the air during the growing season in an agricultural area in Mississippi. The atmosphere is a largely unrecognized source of current-use pesticides to aquatic ecosystems and humans in agricultural and non-agricultural areas. Atmospheric transport of pesticides is one way that aquatic biota, wildlife, and humans are exposed to pesticides. The health effects from this exposure route are poorly understood (Capel and Hopple, 2018).

Five common forms of nitrogen can be present as gases (molecular nitrogen [N_2], nitrogen oxides [NO, NO_2, N_2O] and ammonia [NH_3]; fig. 8.5). Agriculture-related activities, including release of nitrogen fertilizers from soil, manure management, and burning of agricultural residues, consistently contribute about 70 percent of the Nation's nitrous oxide (N_2O) emissions into the atmosphere (U.S. Environmental Protection Agency, 2012a). Nitrous oxide is an extremely potent greenhouse gas that accounts for about 5 percent of the Nation's total greenhouse gas emissions from human activities. Nitric oxide (NO) and nitrogen dioxide (NO_2) are reactive gases that contribute to acidic precipitation and ozone layer destruction (fig. 2.4). Ammonia is released into the atmosphere during fertilizer application, from fields throughout the growing season, and through the off-gassing of livestock waste. Ammonia is a weak greenhouse gas and, at higher concentrations, is toxic and an irritant (U.S. Environmental Protection Agency, 2012a).

Water flowpaths determine how quickly chemicals are transported from fields to streams

Water and its movement over and through agricultural landscapes is the primary mechanism by which agricultural chemicals move throughout the various components of the hydrologic system. The timing and intensity of precipitation and (or) irrigation and the nature of the primary water flowpaths have a large effect on the timing and magnitude of the delivery of an agricultural chemical to a stream, to groundwater, or to the atmosphere. Agricultural modifications, such as drainage and irrigation, substantially change the water flowpaths compared to the natural hydrologic system, and can quickly move agricultural chemicals to the stream.

Flowpaths from fields have characteristic transit times. Transit times when water moves to streams by way of fastflow (surface runoff) are characteristically short (minutes to hours). Transit times to streams by way of slowflow (subsurface flowpaths) can be much longer (months to decades). These slower subsurface connections create a "**lag time**" between the time when agricultural activities occur on the landscape and when their effect is observed in other parts of the hydrologic system. Transit times to streams through drainflow have both slowflow and fastflow components. Subsurface drains are designed to move water quickly out of the soil root zone. Initially after a period of rain, subsurface drainage creates relatively fast flowpaths to the stream (through infiltration and lateral movement) for areas near the drains. However, areas of the field that are far from the subsurface drains have slower flowpaths because the distances for lateral movement are greater. Water can move vertically to drains from hours to days, and laterally from hours to months.

In some watersheds, especially those with steep slopes and (or) clayey soils, surface runoff (fastflow) is the most important flowpath. The streamflow in these watersheds responds quickly to rain events, usually within minutes to hours. Chemicals (total phosphorous, some trace elements, and some pesticides) and sediment are primarily transported to the stream with the surface runoff. Connections often are minimal between the stream and the groundwater. In Bogue Phalia, Mississippi, streamflow and nitrate increased and decreased quickly following a rainfall period that occurred 3 days before the streamflow peak (fig. 9.9). The nitrate concentration increased abruptly with the increase in streamflow and actually reached a maximum concentration before peak streamflow. The nitrate was moved quickly off the landscape in this watershed where surface runoff is an important flowpath. Nitrate concentration was lower during the periods between storms.

In watersheds with gentle slopes and permeable soils, groundwater generally is an important contributor to streamflow (slowflow). Rain water can infiltrate through the soil and recharge the groundwater. This water eventually is discharged to the stream. The total time between when rain falls and when the water appears in the stream can be months to decades. These streams also receive some fastflow from periods of heavy or intense rain. Chemicals that readily dissolve in water are moved with recharge to groundwater. The groundwater and dissolved chemicals move slowly through the subsurface to the stream. There can be a long lag time (months to decades) between when the chemical is applied at the land surface and when it appears in the stream.

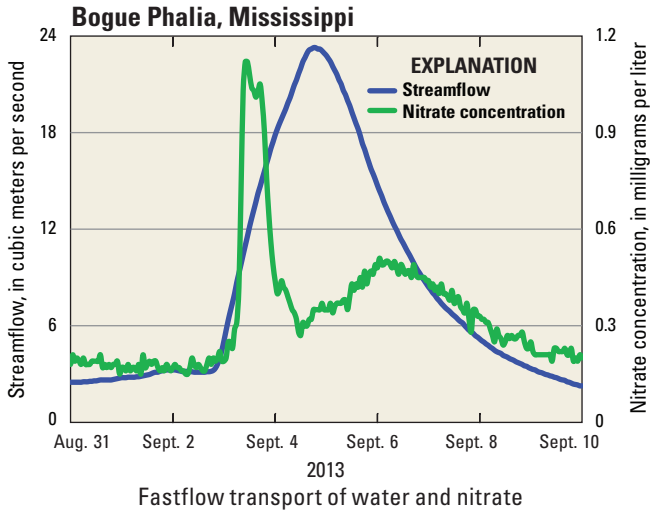


Figure 9.9. Fastflow is an important pathway for the delivery of nitrate to Bogue Phalia, Mississippi. Many conservation management practices, such as buffer strips and conservation tillage, are effective in preventing sediment and sediment-associated chemicals from reaching the stream. However, these practices are less effective at controlling dissolved chemicals such as nitrate (Capel and Hopple, 2018).

Groundwater with high concentrations of nitrate discharges into Chesterville Branch on Maryland's Eastern Shore (fig. 9.10). During the growing season, the highest concentrations of nitrate occur during the periods of low flow between storms; stream nitrate concentrations decrease when streamflow increases and low-nitrate runoff dilutes the nitrate in the stream. For the single storm shown in figure 9.10, the increase in streamflow is from rain that occurred the day of the streamflow peak. Low streamflow prior to and after the peak is from groundwater. The nitrate concentration decreased with increased streamflow and actually reached a minimum concentration just after peak streamflow, then increased again as the streamflow decreased. The high nitrate concentrations come from the groundwater. The increased flow in the stream is water moving by fast flowpaths after the rain. The storm water, which moved quickly off of the landscape, contained less nitrate, thus diluting the nitrate concentration in the stream. The high concentrations of nitrate in the stream during periods of low flow were from nitrogen that was applied to agricultural fields years to decades before.

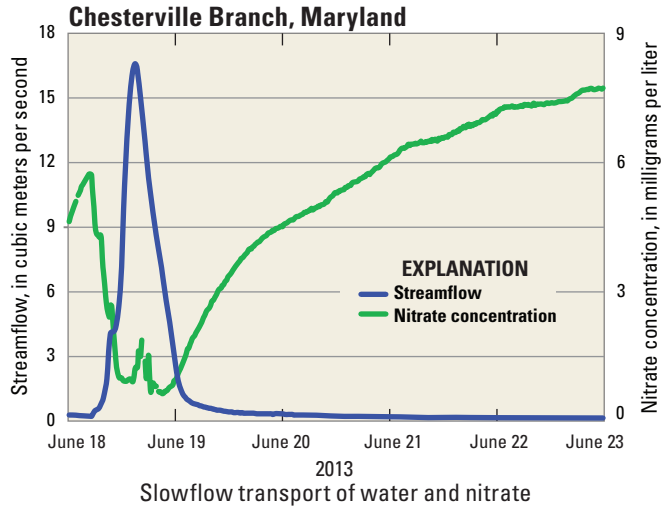


Figure 9.10. The increase in nitrate concentration following the peak streamflow comes from slowflow groundwater—the legacy from nitrogen that was applied to agricultural fields years to decades previously. Thus, benefits of current conservation actions may not be realized in a stream for several decades (Capel and Hopple, 2018).

Subsurface drains, which create an artificial water flowpath, are engineered to quickly move water out of the soil and into the stream. The drains, located below the root zone, control the level of the groundwater. The water flowing in the drains is a combination of recent excess rainfall/irrigation (fastflow) and (or) groundwater (slowflow). The flow in the drains can respond to rainfall or irrigation within hours. Chemicals that readily dissolve in water (nitrate, salts, herbicides, and herbicide transformation products) can move quickly through the soil root zone into the drains and directly to the stream. The chemicals moving through subsurface drains bypass many of the soil's natural removal processes. For the 2-day storm in the South Fork of the Iowa River in north-central Iowa, the increase in streamflow was from rain that started 2 days prior to the peak of streamflow (fig. 9.11*A*). Much of the water moved off of the landscape within a few days, but some water took almost a week to get to the stream through the network of surface and subsurface drains. Nitrate decreased with the initial increase in streamflow, but then increased and peaked a day after the streamflow peak. This was followed by a decrease in concentration, which was at a slower rate compared to the decrease in streamflow. In the context of the entire growing season (fig. 9.11*B*), the nitrate concentrations in the drainflow-source stream in north-central

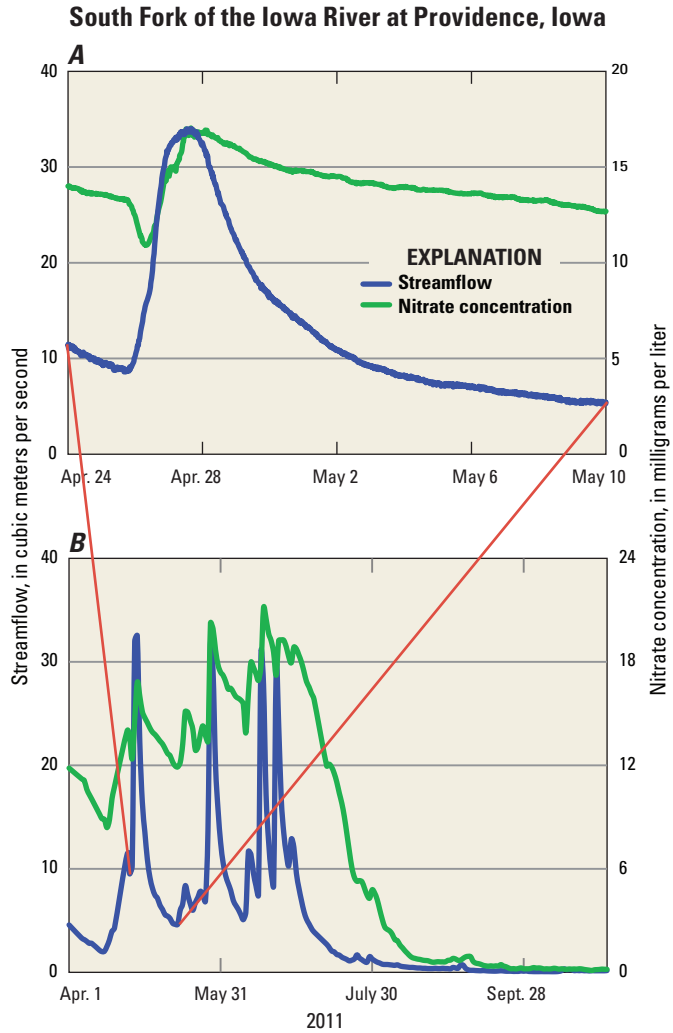


Figure 9.11. (*A*) Subsurface drainage quickly drains wet soils, but this engineered flowpath bypasses much of the capacity of the soil to remove nitrate. In this watershed, the nitrate that moves through the top layers of the soil quickly reaches the subsurface drain and is routed to the stream. (*B*) The nitrate concentration remained elevated throughout the entire growing season due to the frequent rains and the delivery of water from the drained landscape (Capel and Hopple, 2018).

Iowa remained high due to the frequent rains and the steady delivery of water from the drained landscape. The nitrate concentrations in this stream were substantially greater than the other two example hydrologic settings and in agreement with previously studies (Dubrovsky and others, 2010).

Agricultural activities to improve water quality may not be observed for years or decades

Expected improvements in water quality from new management practices in a field with subsurface flowpaths (long transit times) may not be realized for years to decades because the concentration of nitrate in the older groundwater discharging to the stream is reflective of historical inputs and agricultural activities. The agricultural chemicals stored in the shallow groundwater constitute a legacy (fig. 8.7), and can be released to the stream for years to decades after they were used on the fields. This result has been observed for nitrate and (or) herbicides in streams and wells used for drinking water (McMahon, Böhlke, Kauffman, and others, 2008; McMahon, Burow, Kauffman, and others, 2008; Puckett and others, 2011; Ator and Denver, 2012; Kalkhoff and others, 2012; Tesoriero and others, 2013). In contrast, improvements in water quality from new management practices in a field with rapid flowpaths, such as runoff and subsurface drainage (short transit times), are likely to be observed within months or a few years.

Long groundwater flowpaths, which have long lag times between when nitrate is used at the land surface and its delivery to the stream, occur in the Tomorrow River watershed in central Wisconsin (Tesoriero and others, 2013). This stream receives approximately 80 percent of annual streamflow from groundwater. The average age of groundwater discharging to the Tomorrow River is 27 years. More than an estimated 95 percent of nitrate in this stream is derived from groundwater (fig. 9.12; Tesoriero and others, 2013). Figure 9.12*A* represents hydrologic conditions in 2009. The applications of nitrogen fertilizer yielded a concentration of 12 mg/L as nitrogen in the shallow groundwater. The water in the stream had a nitrate concentration of 3 mg/L, indicating that stream water was a mixture of groundwater with elevated nitrate concentrations and water from shorter flowpaths with lower concentrations of nitrate near the stream. Figure 9.12*B* represents expected hydrologic conditions in 2019, if the land had been entered into the Conservation Reserved Program (CRP) in 2009. Nitrate concentrations in this stream would likely increase, not because of recent fertilizer applications, but because groundwater discharging to the stream in 2019 would have recharged the aquifer during a period of more intensive fertilizer application two to three decades earlier. Starting in about 2020, the nitrate concentration in the shallow groundwater under the field would begin to decrease due to the CRP. It would be approximately three decades, however, before the land-use change and lower applications of nitrogen would result in lower nitrate concentrations in the stream.

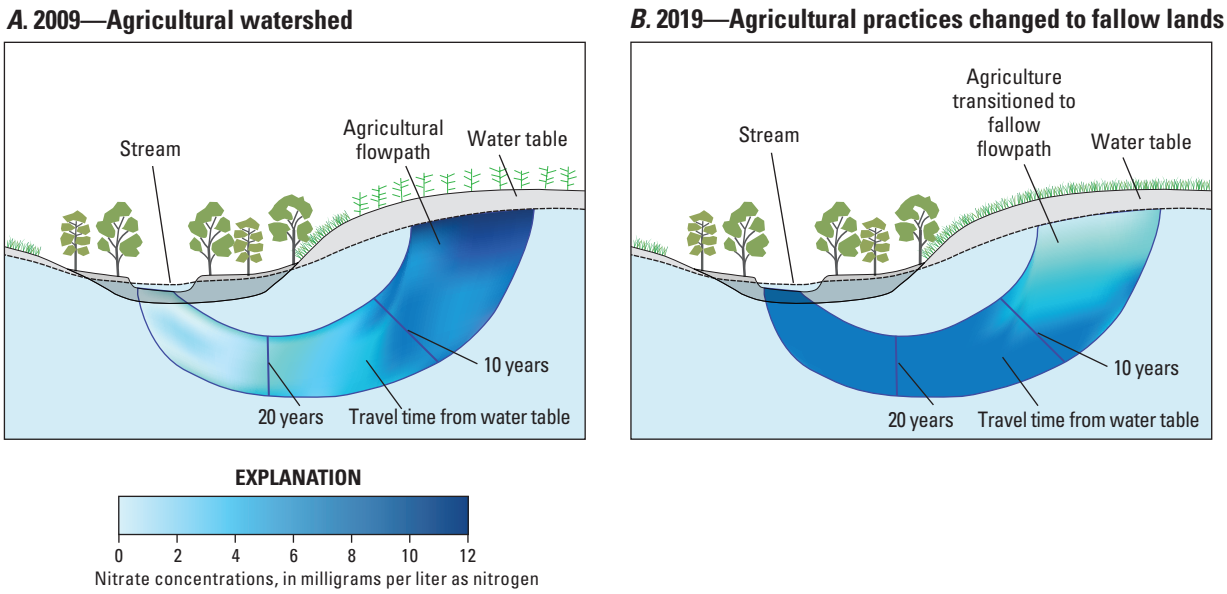


Figure 9.12. Nitrate concentrations in the stream during 2009 (*A*) were a mixture of older water with elevated concentrations of nitrate that entered the groundwater system in the 1980s under agricultural fields and recent water with lower concentrations entering from areas bordering the stream. If the land were entered into the Conservation Reserve Program starting in 2009, the input of nitrogen to the fields would have decreased (see "U.S. Department of Agriculture Conservation Programs" in Chapter 3). Nevertheless in 2019 (*B*), the nitrate concentrations in the stream would be expected to be greater because the nitrogen applied at the land surface during the 1980s to 2000s continued to move through groundwater and discharge into the stream. This figure is based on the conditions at Tomorrow River, Wisconsin.

Some parts of the landscape disproportionately affect water quality

Each location on the landscape has a unique set of hydrologic flowpaths and a unique effect on the environment; not all locations contribute water, sediment, and chemicals in an equal manner. Some locations on the landscape are more susceptible to the movement of sediment and chemicals ("critical contributing areas") and, thus, disproportionately affect the water quality. The identification of the critical contributing areas can assist water managers in targeting limited management resources at both field and watershed scales.

In many areas of the glaciated Midwest, the relatively flat landscape contains shallow topographic depressions that are underlain by fine-grained soils. After snow melt or heavy rainfall, temporary ponds can form in the depressions; therefore, surface inlets (fig. 6.5*C*) connected to the horizontal subsurface drainage network have been installed to quickly remove water from the temporary ponds. The water that enters the surface inlet moves through the horizontal subsurface drains into a surface ditch or stream. The area of the field containing the topographical depression is connected directly to the stream at the drain outlet. The ponded water that drains directly to the stream makes the depressions critical contributing areas (fig. 9.13; Roth and Capel, 2012b). This surface inlet-to-stream connection creates a direct flowpath that bypasses all natural removal process and all conservation practices designed for trapping sediment (Roth, 2010; Feyereisen and others, 2015).

At a regional scale, there are also parts of the landscape that disproportionately affect the water quality. In the Chesapeake Bay watershed (fig. 9.14), excess nitrogen from fertilizer and manure moves through the soil to groundwater and eventually discharges to the tributaries of the Bay. The relative importance of this pathway is unevenly distributed across the watershed, partly because of the type of underlying aquifer and the amount of land in agriculture. The highest concentrations of nitrate in shallow groundwater are in agricultural areas with carbonate and sandy aquifers.

Strategic, long-term water-quality monitoring and modeling provide a basis for sound management decisions.

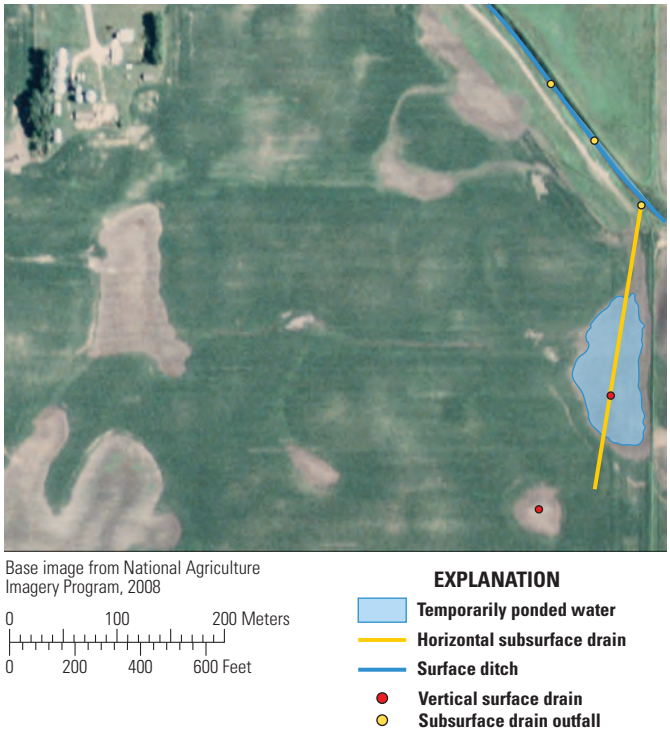
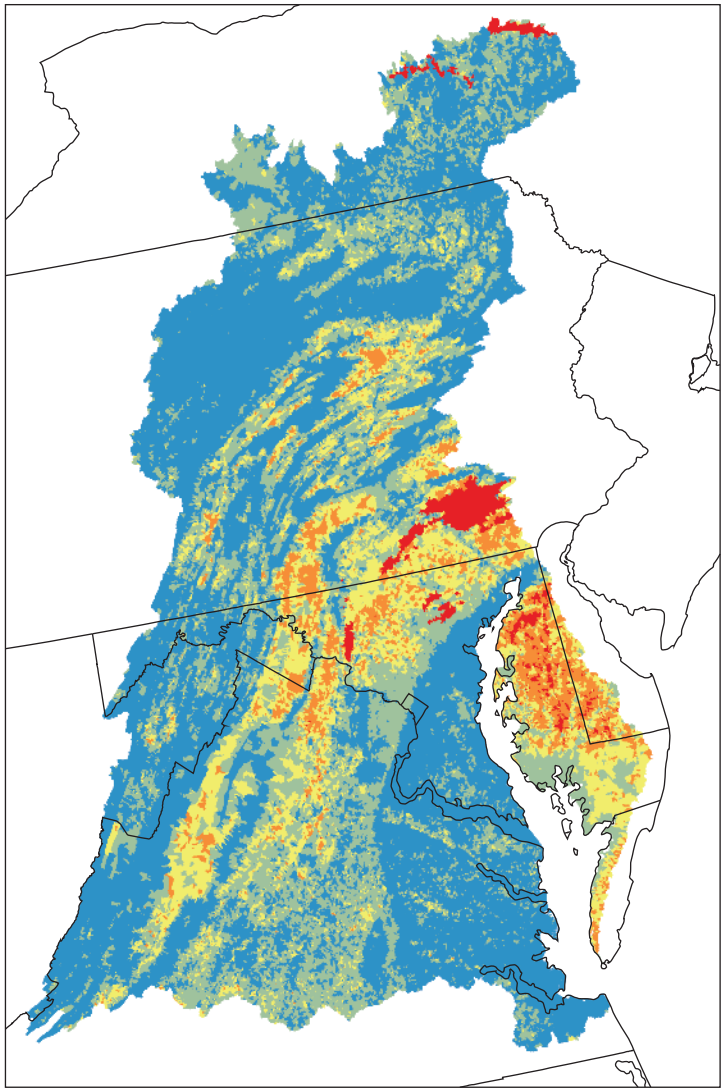


Figure 9.13. The temporarily ponded depression on the right edge of the photograph has a surface inlet connected to a horizontal subsurface drain that empties into the surface ditch. Agricultural chemicals and sediment are delivered directly to the stream through the surface inlet. The gray/brown areas show additional depressions where saturated soils prevented crop growth.



EXPLANATION

Concentration of nitrate in groundwater, in milligrams per liter nitrate as nitrogen

- < 1.0
- 1.1–2.0
- 2.1–3.0
- 3.1–4.0
- > 4.0

Figure 9.14. The concentration of nitrate in groundwater is not evenly distributed across the Chesapeake Bay watershed due to differences in land uses, nitrogen use as fertilizer, and type of underlying aquifer. The spatial distribution of the nitrate concentration in groundwater has been estimated with a statistical model based on chemical monitoring data, land use, and type of underlying aquifer (Terziotti and others, 2017). Annual loads of nitrogen delivered from groundwater to streams were calculated based on the nitrate concentrations in streams during baseflow conditions.

Strategic, long-term water-quality monitoring and modeling provide a basis for sound management decisions

Long-term monitoring data provide critical quantitative information on past, present, and future water-quality conditions. These data can be used to track changes in water quality in response to past and present agricultural activities, quantify the effectiveness of implemented changes, and inform the development of new agricultural strategies and policies. Sustained monitoring provides insights into long-term trends and can provide understanding that may be obscured in short-term monitoring efforts because of changing climate, hydrology, and inputs of chemicals and sediment. Early recognition of trends is critical for implementing changes to prevent deterioration of water resources, and ongoing monitoring provides the best assurance for early recognition.

Monitoring is the foundation for the development of hydrologic mathematical models that simulate and help understand the complex interactions within a hydrologic system. Water-quality models are used to simulate the flow of water, chemicals, and sediment through a hydrologic system for distances ranging from meters to thousands of kilometers. Models can use available streamflow and water-quality monitoring data to extrapolate observed water-quality conditions to unmonitored areas and to quantify the magnitude of different sources. Models also can be used as decision-support tools to evaluate the effects of alternative management practices on water quality. Additionally, models can be used to identify which types of data are most important to collect and where monitoring gaps exist.

Long-term monitoring provides a rare glimpse into changes in stream nitrate levels over the last 60 years

Only a few of the Nation's rivers have been monitored for nitrate for long periods of time, more than a few decades (Stets and others, 2015). These rare, long monitoring records provide insights into long-term trends in nitrate concentration, and into the human and natural drivers that control these trends. Monitoring data collected for almost six decades in the Maumee River in northwestern Ohio show a strong relationship between human activity (nitrogen fertilizer and manure application in the watershed) and increases in the average nitrate concentration (fig. 9.15). The Maumee is one of 22 rivers that have observations ranging back to the 1950s. Most of the watersheds had their greatest increases in nitrate concentration over the period of 1945–1980, whereas during the more recent period of 1981–2008 the concentrations have increased at a slower rate or have somewhat stabilized (fig. 9.15). In most cases, these increases in nitrate concentration were related to the increase in fertilizer use, agricultural expansion, and urban development.

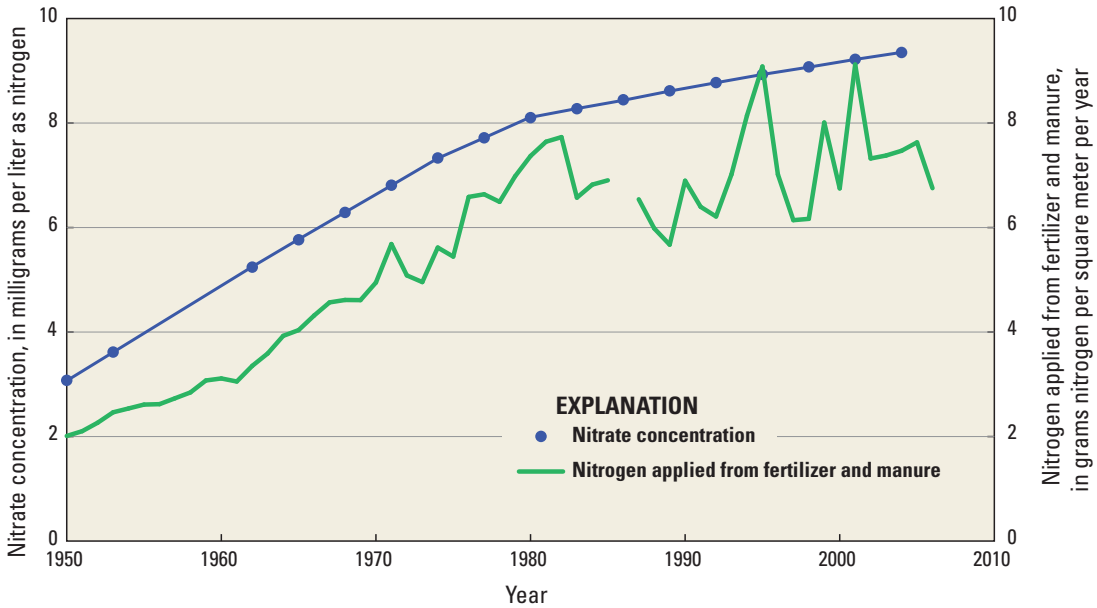


Figure 9.15. The Maumee River flows through the intensely row-cropped area of northwestern Ohio into Lake Erie. The trend in nitrate concentration in the Maumee River showed a rapid increase between 1950 and 1980 as nitrogen inputs from fertilizer and livestock increased. Since 1980, the upward trend in nitrate concentration has been much smaller because the upward trend in nitrogen inputs was much smaller. This record of nitrate river concentrations and fertilizer use for almost six decades provides a perspective that short-term monitoring efforts may miss. For example, if monitoring occurred only over a short period, such as 1990 to 2005, then different conclusions would have been reached concerning the relation between nitrate concentration and fertilizer. (Modified from Stets and others, 2015.)

Long-term monitoring reveals an early warning of future changes in sediment and phosphorus loading to the Chesapeake Bay

The Susquehanna River, the largest tributary to the Chesapeake Bay, is estimated to have contributed 46 percent of the total phosphorus load to the Chesapeake Bay from 1979 to 2012 (Zhang and others, 2016). The outlet of the Conowingo Reservoir, the most downstream and largest reservoir on the Susquehanna River, has been monitored for suspended sediment, total phosphorus, and other chemicals since the 1970s and the primary inflow has been monitored since the mid-1980s. These long-term monitoring data allow a quantification of how effective the reservoir is at trapping and removing sediment and total phosphorus.

One way of quantifying the removal efficiency of the reservoir system is to divide the daily output load by the daily input load, adjusted for the water transit time through the reservoir. When outputs are less than inputs (that is, when the value on the y-axis in figure 9.16 is less than 1), the reservoir traps a fraction of the incoming sediment and total phosphorus. The Conowingo Reservoir decreased the mass of total phosphorus transported to the Chesapeake Bay by about 45 percent annually from 1990 to 2000 (Zhang and others, 2016).

The storage of phosphorus and sediment by the reservoir has improved the water quality of the Susquehanna River downstream of the reservoir and in Chesapeake Bay. However, the sediment that has collected in the reservoir over the last nine decades has also slowly filled up the reservoir. Bathymetric studies have shown that the Conowingo Reservoir is approaching its maximum storage level. As the reservoir fills in, its ability to trap and remove sediment and total phosphorus will be limited. In this era when management practices are being implemented in agricultural and urban areas to improve the water quality of the Chesapeake Bay, this long-existing trap for sediment and phosphorus will no longer act as a phosphorus and sediment trap. Planning and management of water quality of the Chesapeake Bay and other areas depend largely on accurate estimates of the loads of sediment and chemicals being transported through the system. This long record of inputs and outputs to Conowingo Reservoir demonstrates how monitoring can provide insights into environmental processes and provide an early warning of future changes.

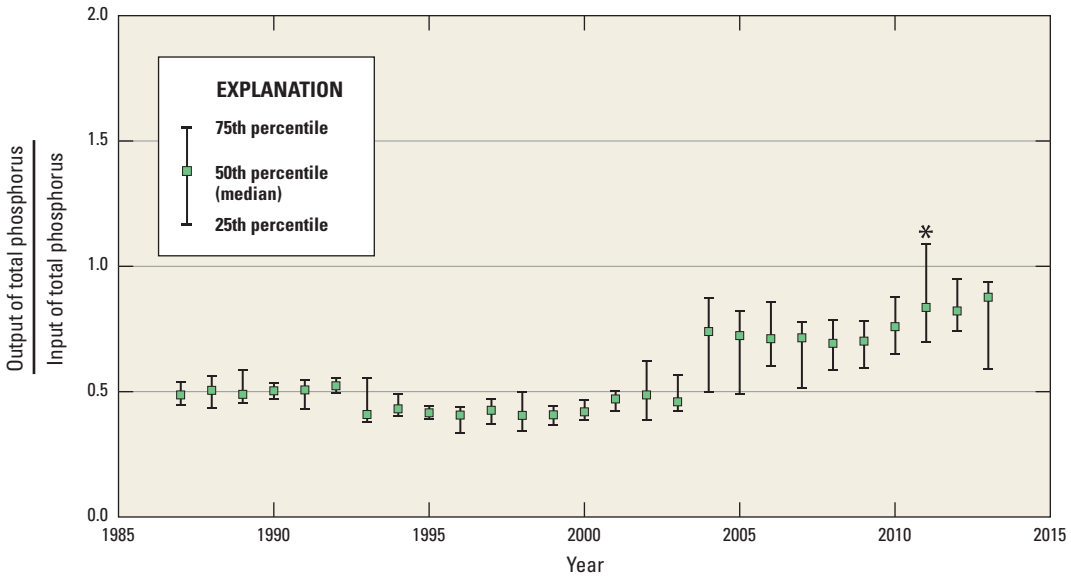


Figure 9.16. From 1990 to the early 2000s, the Conowingo Reservoir on the Susquehanna River in Pennsylvania and Maryland trapped or removed about 45 percent of the annual total phosphorus inputs. As sediment has filled up the reservoir, the amount of phosphorus trapped in the reservoir has started to decrease. Since about 2005, there has been an upward trend in the ratio of the daily output of total phosphorus to the daily input of total phosphorus. The Conowingo Reservoir has, or is near, the end of its lifetime for efficiently removing sediment and total phosphorus. For much of the year there will be minimal removal. During extreme flows, such as following hurricanes, the reservoir will release stored sediment and total phosphorus to the downstream river and to the Chesapeake Bay, due to scour of the bed sediments. The asterisk shows the ratio affected by an extreme event. (Modified from Zhang and others, 2016.)

Long-term, strategic monitoring of atrazine provide insights into annual concentration pattern, year-to-year variability, and long-term trends

Long-term, strategic monitoring of streamflow and pesticide concentrations can aid in our understanding of time trends in concentration and environmental processes governing their behavior. Documenting the seasonal changes in agricultural chemicals in streams over many years has improved the understanding of how chemistry, biology, hydrology, pesticide use, and agricultural practices govern the transport, behavior, and fate of agricultural chemicals in the environment.

The herbicide atrazine has been monitored in the White River at Hazleton, Indiana, for more than 20 years (fig. 9.17*A*). These data provide insights into the annual pattern of atrazine concentrations in the river, the year-to-year variability, and the long-term trends. Atrazine concentrations are highest during the "first flush" spring rains after application of the herbicide to agricultural fields (generally April–June) (Gilliom and others, 2006). The data also indicate that atrazine is present in the river at all times, generally in concentrations from 0.1 to 10 micrograms per liter (µg/L).

Long-term data can be used to assess trends. Atrazine concentrations in the White River decreased by about 9 percent from 1992 to 2001. No significant trend in atrazine concentrations was observed from 2001 to 2010 (Ryberg and others, 2014). During this period, many factors influenced atrazine use, including a change in the EPA labeled application rate, the introduction of new herbicides and genetically modified corn, an increase in the area planted in corn due to biofuels, and changes in tillage practices. The long-term monitoring data aid the understanding of the multiple influences on pesticide concentrations in streams.

The monitoring data from the White River, and from many other sites across the Nation, form the basis of models (decision-support systems) used to estimate pesticide concentrations and probabilities of exceeding human and aquatic life benchmarks (Stone and others, 2013). These models can be used to estimate pesticide concentrations in unmonitored areas (fig. 9.17*B*).

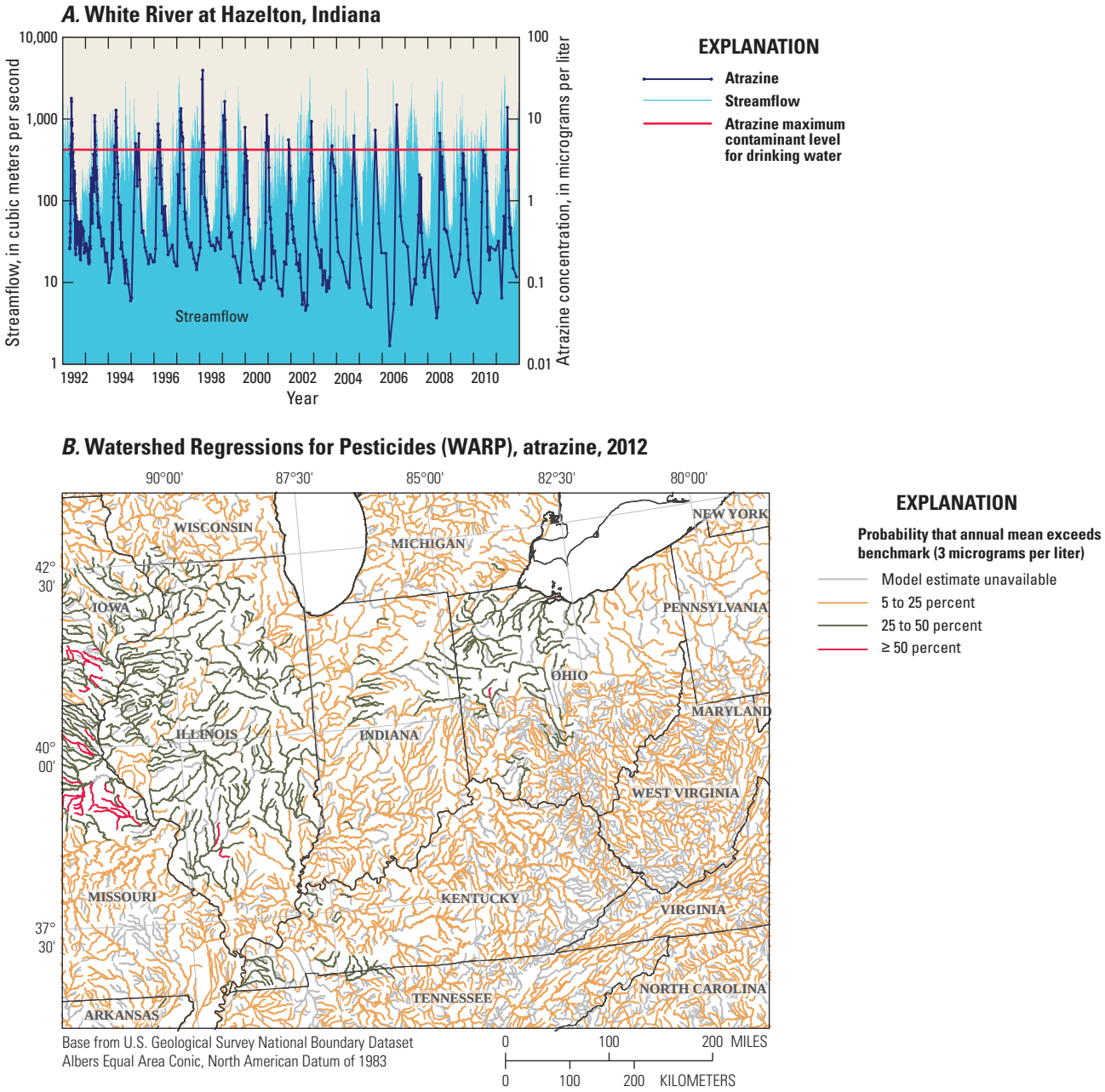


Figure 9.17. (*A*) A 20-year monitoring record of the herbicide atrazine in the White River, Indiana, shows that the atrazine concentrations are highest during the "first flush" spring rains after application of the herbicide to agricultural fields (generally April–June) (Gilliom and others, 2006). Atrazine concentrations infrequently exceed the Maximum Contaminant Level (MCL) for drinking water (indicated by the red horizontal line). Even though the river water at this location is not used as a source of drinking water, it provides a useful concentration benchmark. (*B*) A model simulation based on monitoring data at multiple sites throughout the Midwest and geographical information of atrazine use and watershed characteristics provides an estimate of the probability that the annual mean atrazine concentration will exceeded its MCL for drinking water for the rivers and streams in Illinois, Indiana, and Ohio in 2012 (Stone and Bucknell, 2014).

Water-quality model helps target new water-quality monitoring activities and inform nutrient reduction strategies

The Elk River watershed drains south-central Tennessee and northern Alabama and flows into an embayment of Wheeler Reservoir in Alabama (fig. 9.18). Water-resource managers are concerned about eutrophication in the embayment. In the past, agricultural activities were thought to be the major source of phosphorus to the embayment and the cause of the eutrophication. However, simulations from the USGS SPARROW (SPAtially Referenced Regressions On Watershed Attributes) model of the area indicated that the largest source of phosphorus to the embayment was from natural phosphate-bearing rocks (83 percent; Garcia and others (2011), whereas, agricultural activities (crops and animals) contributed about 13 percent, and mined lands and wastewater contributed only about 1 percent each. Because of the understanding provided from the model, new water-quality stream-monitoring sites have been installed to provide quantitative information to confirm the estimated model simulation results. The implementation of agricultural conservation practices would have had limited effect on reducing annual inputs of phosphorus to the embayment. One of the benefits of a water-quality model is to provide information that will help improve the design of monitoring programs in the future.

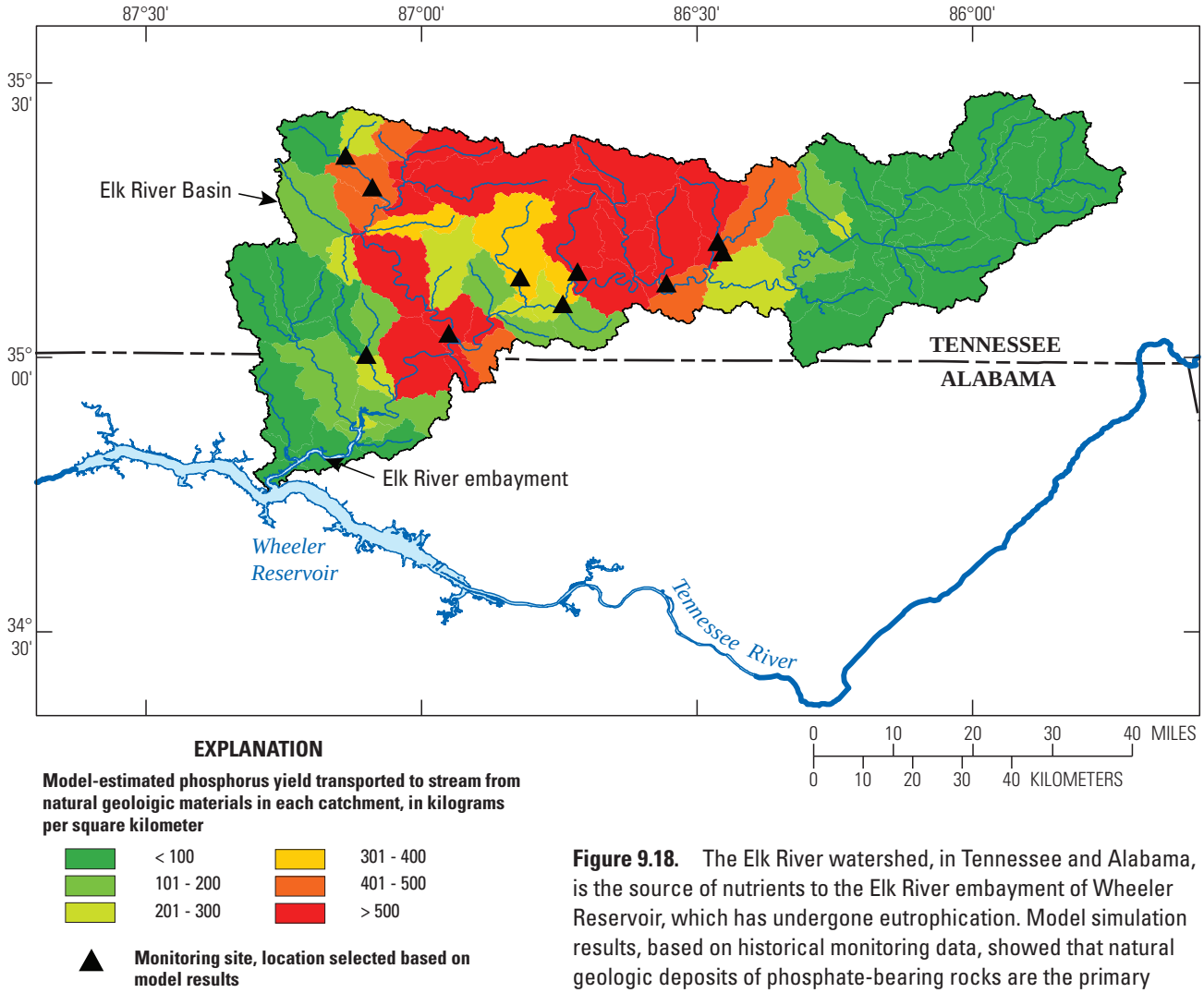


Figure 9.18. The Elk River watershed, in Tennessee and Alabama, is the source of nutrients to the Elk River embayment of Wheeler Reservoir, which has undergone eutrophication. Model simulation results, based on historical monitoring data, showed that natural geologic deposits of phosphate-bearing rocks are the primary source of phosphorus. This information has led to a more informed monitoring design to enhance water-quality management decisions.

Water-quality model provides regional insights on nutrient sources to streams

The Chesapeake Bay is a vital ecological and economic resource. The National Oceanic and Atmospheric Administration reported in 2009 that the commercial seafood industry in Maryland and Virginia contributed $3.39 billion in sales, $890 million in income, and almost 34,000 jobs to the local economy (Chesapeake Bay Foundation, 2016). Excess inputs of nitrogen and phosphorus to Chesapeake Bay have negatively affected the water quality and the overall health of the ecosystem. To improve the aquatic health of Chesapeake Bay, a better understanding of nutrient sources and transport was needed.

The USGS SPARROW model provides regional insights about which nutrient sources and watershed areas are contributing the highest and lowest amounts of nutrients to the Chesapeake Bay (fig. 9.19). Model estimates throughout 80,000 stream reaches in the Chesapeake Bay watershed improve the understanding of the areas contributing the most nutrients and help water resource managers target the most effective nutrient reduction actions.

A SPARROW model was developed to estimate the sources, fate, and transport of nutrients in the Chesapeake Bay watershed (fig. 9.19; Ator and others, 2011). The estimated source contributions of nitrogen to the Chesapeake Bay are 54 percent from the combination of manure and fertilizer applications and fixation by crops, 17 percent from atmospheric deposition, 16 percent from point sources, and 12 percent from urban areas. The estimated source contributions of phosphorus to the Chesapeake Bay are 43 percent from fertilizer and manure applications, 32 percent from point sources, 14 percent from natural sources, and 11 percent from urban sources.

Crop and animal agricultural in Maryland. Photograph by Bob Nichols, U.S. Department of Agriculture, Natural Resources Conservation Service photo gallery, NRCSMD08058, 2008.

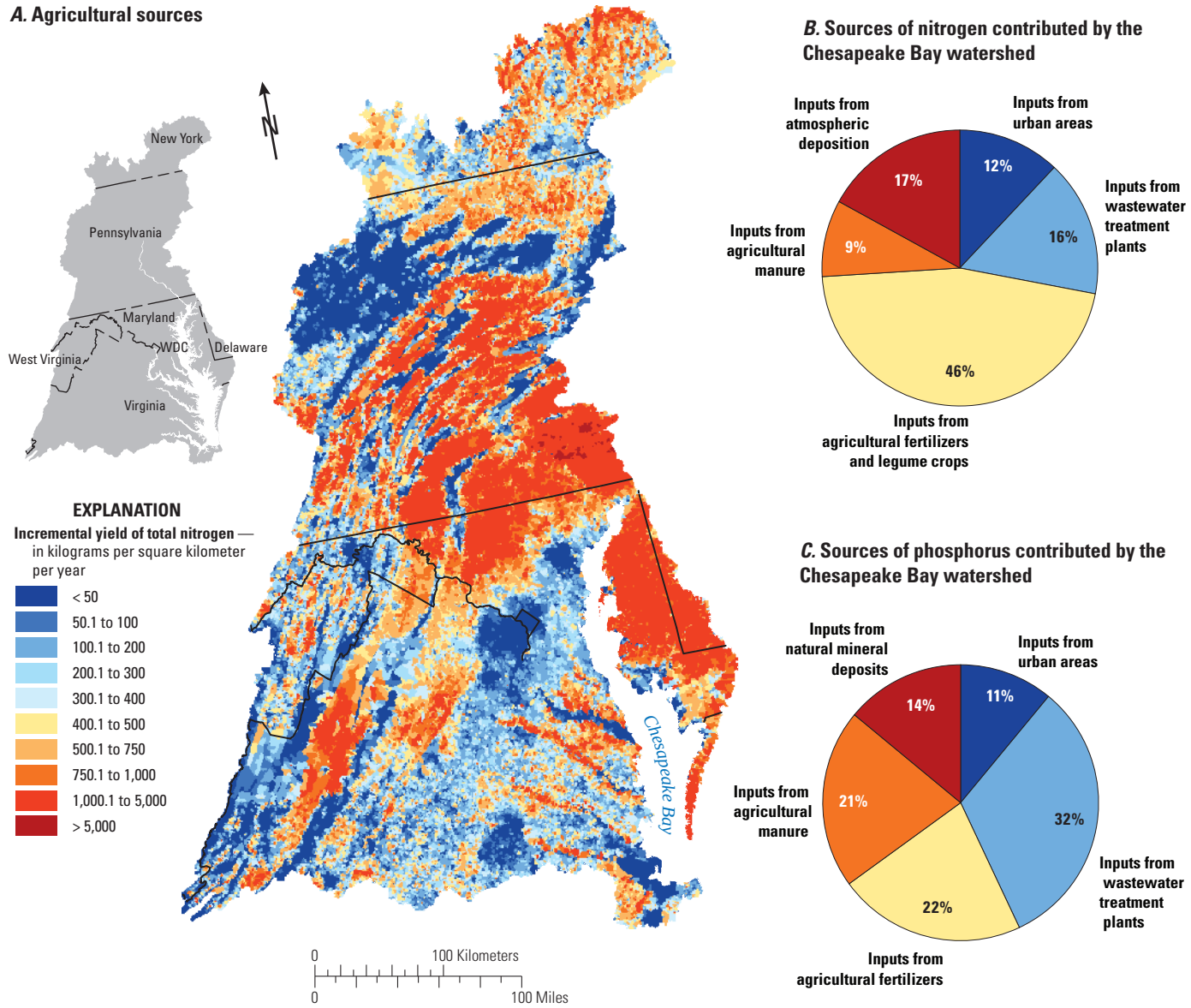


Figure 9.19. Excess inputs of nitrogen and phosphorus to Chesapeake Bay have negatively affected the water quality and the overall health of the ecosystem. To improve the aquatic health of Chesapeake Bay, a better understanding of the nutrient sources was needed. A complex hydrological model (SPARROW [SPAtially Referenced Regressions On Watershed Attributes]) was developed to estimate the spatially variable sources of the nutrients from small catchments across the Chesapeake Bay watershed. (*A*) Spatial distribution of total nitrogen yields across the watershed. The model is based on monitoring observations of the chemicals and streamflows, as well as the spatial characteristics of land use, topography, and soils. Model use has greatly increased the understanding of nutrient sources to Chesapeake Bay and helped in the development of programs to manage the nutrient inputs. The model also estimates the relative magnitude of various sources of (*B*) nitrogen and (C) phosphorus to Chesapeake Bay. Agricultural activities contribute 54 percent of the total nitrogen and 43 percent of the total phosphorus to the Bay (Ator and others, 2011).

Understanding the connections among hydrologic settings and chemical behaviors can help set realistic expectations for water-quality improvements

Understanding the connections between agricultural activities, water flowpaths and associated lag times, and behavior of specific chemicals and (or) sediment can be combined into a framework to guide policy and management decisions to reduce current and prevent future impacts on water quality (Capel and others, 2018). This framework is built on a generalization of stream hydrology—water, whether from natural rainfall or irrigation, moves to a stream by a combination of slowflow, fastflow, and (or) drainflow, and these flowpaths are associated with a range of timescales. The framework generalizes the behavior of chemicals and sediment—all chemicals are distributed on a continuum between those completely associated with water and those completely associated with sediment (fig. 8.4). Finally, each agricultural activity is assumed to have its expected effect on the movement of water and chemicals across the landscape. This framework, shown as a decision tree (fig. 9.20), is a gross simplification, but it is supported by observations in the environment and quantified in mathematical models. The decision tree is not intended to be used on a site-specific basis. More detailed knowledge of the local environment, climate, and agricultural production is needed to make design decisions for the implementation of an agricultural activity at a particular location.

The expectations of the effectiveness of an agricultural activity must consider the local hydrologic flowpaths within a specific field and an understanding of the environmental behavior of the specific chemical or sediment to be controlled. Few agricultural activities will be effective for all chemicals. Although valuable knowledge can be gained from a generalized understanding, as presented in this conceptual framework, specific knowledge of the hydrology and the chemical is required for a specific field or watershed. With this specific knowledge, agricultural activities can be designed to optimize efficiency on a field-by-field basis.

The first question in the decision tree concerns the environmental behavior of the chemical of concern: Is the chemical of concern primarily sediment associated? The second question addresses the presence of permanent or semi-permanent agricultural modifications to the landscape that are already in place: Is the water moving through subsurface drainage? The final question regards the nature of the hydrologic setting: Is groundwater an important source of flow in the stream? The answers to these three questions can guide the selection and expectation of the effectiveness of implementing an agricultural activity (table 9.1).

The decision tree is simplified to the non-reactive chemical and sediment. The horizontal lines between "yes" and "no" on the tree represent three continuums, starting at the top, degree of association with sediment (from 100 percent water-associated to 100 percent sediment-associated), the density of subsurface drains (from zero to a closely spaced, patterned drain network), and the importance of groundwater to total streamflow (from 0 to 100 percent). The decision tree defines and traces the two extremes for the degree of sediment association by chemicals. Chemicals that are intermediate between these two extremes, that is they have a substantial fraction associated with both water and sediment phases, will follow multiple routes through the decision tree and, thus, it may be more difficult to identify realistic expectations of the effectiveness of agricultural activities. The rate of transformation of chemicals does not affect the use of the decision tree, except that chemicals with short lifetimes may disappear from the environment as they are transported via moving water if the hydrologic transit time is greater than the environmental lifetime of the chemical.

Few agricultural activities will be effective for protecting water quality for all chemicals in all hydrological settings. Some changes will be effective; some changes will be counterproductive (Capel and others, 2018). In some situations water quality can be improved and protected by adding new, well-selected agricultural activities and (or) landscape modifications. In other situations, the removal of the existing landscape modifications, such as drainage, may be more effective.

Table 9.1. Examples of agricultural management practices and other agricultural activities which are used to help minimize soil and (or) chemical loss to protect and improve water quality.

Trapping practices
Terraces, grassed waterways
Buffer/filter strips
Brims at edge of stream
Cover crops
Srip cropping
Tillage practices
Conservation tillage
No-till tillage
Contoured plowing
Drainage practices
Controlled subsurface drainage
Biofilters on subsurface drains
Removal of subsurface drains
Removal of surface inlets to subsurface drains
Irrigation practices
General decrease in volume and energy of irrigation water
Chemical use practices
Decrease in chemical use
Use of chemicals with short environmental half-lives
Set-aside land for conservation
Conservation reserve programs (Federal and state, for example USDA CRP)
Constructed wetlands

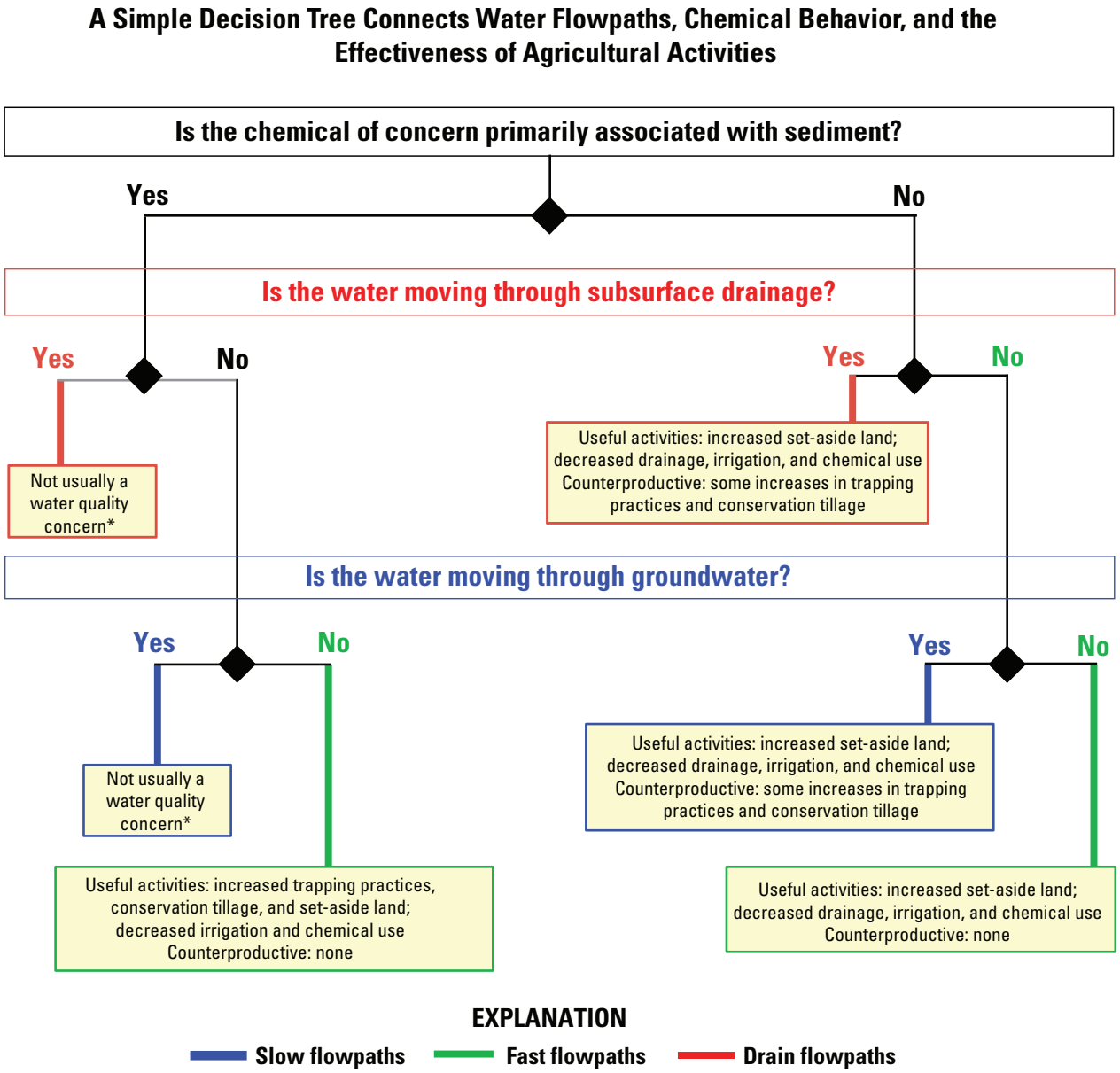
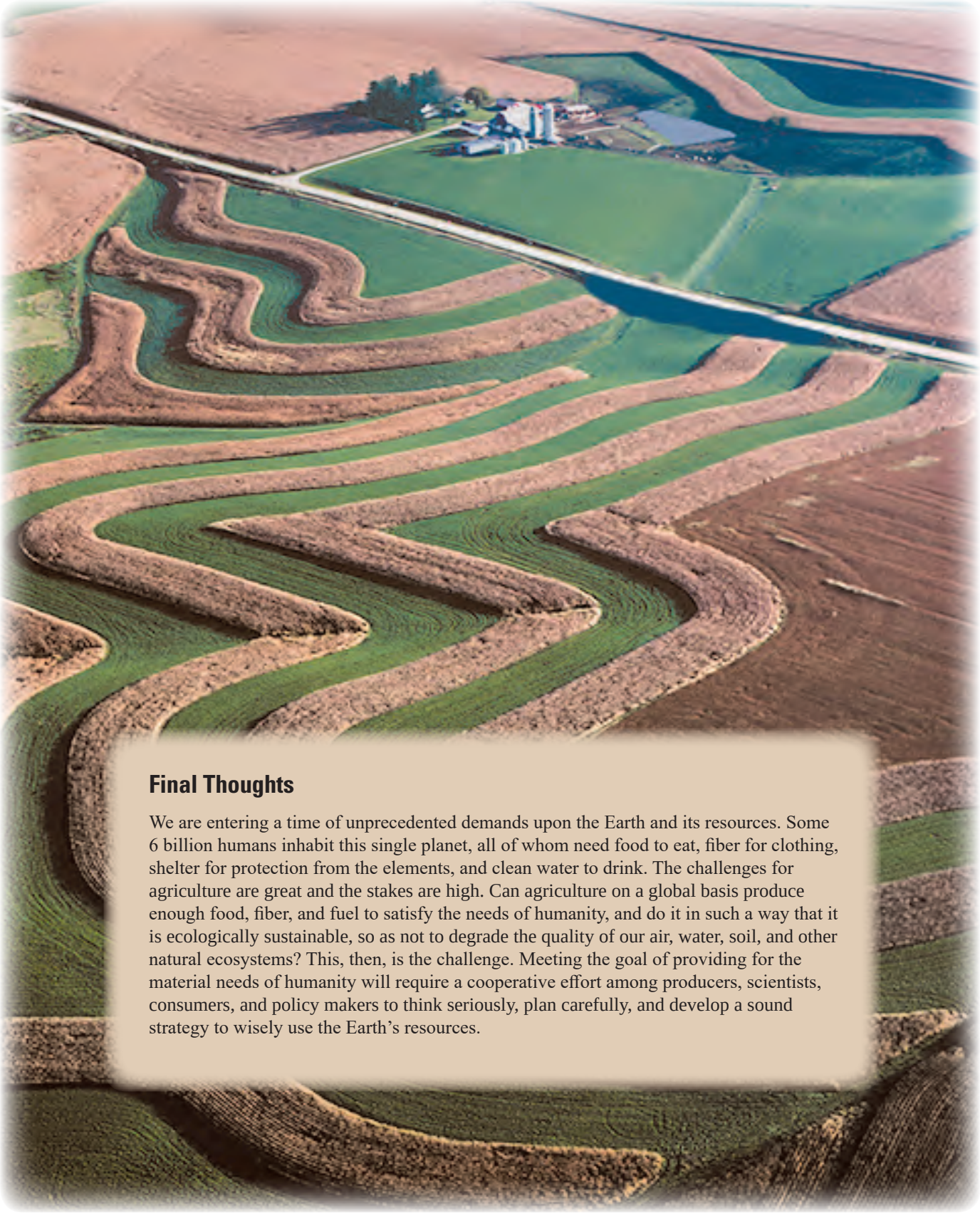


Figure 9.20. The decision tree can assist with identification of which agricultural activity(s) could be effective in protecting or improving stream-water quality and which agricultural activity(s) could be counterproductive (table 9.1). * denotes that these chemicals do not usually cause a water-quality concern from the part of the water moving through subsurface flowpaths (for example, moving through soil to groundwater or to subsurface drains), but these chemicals can cause a concern in the part of water moving through flowpaths across the land surface.

Numerous agricultural activities have been implemented over the past few decades to improve and protect water quality. Although the effectiveness of many of these activities has been quantified at the field scale (Reeder and Westermann, 2006), the cumulative effects of these activities at a watershed scale have been difficult to quantify because of simultaneous, multiple sources (including non-agricultural sources) and variability in hydrology and landscapes (National Research Council, 1999; Tomer and Locke, 2011). An innovative approach combining information from process-based models from the USDA Agricultural Research Service and the Natural Resources Conservation Service (Tomer and Locke, 2011; Osmond and others, 2012) with a USGS statistical model was used to overcome these limitations (Garcia and others, 2016). SPARROW model results indicate that soil conservation practices in the Upper Mississippi River watershed can reduce nitrogen inputs to some streams and rivers by as much as 33 percent (median: 15; range: 7 to 33 percent), providing new insights on the benefits of conservation practices (Garcia and others, 2016). Estimated reductions in nitrogen loads are consistent with known hydrological and biogeochemical processes.

Reducing and slowing down runoff and increasing infiltration will significantly reduce the amount of nitrogen that is eventually transported to streams. Structural and erosion control practices, such as conservation tillage, in the Upper Mississippi River Basin (fig. 9.21) have been shown to decrease runoff and peak flows, thereby increasing water infiltration into the soils and the subsurface geology. The routing of large quantities of water to the subsurface by conservation practices contributes to increased hydraulic storage that can lead to an increase in denitrification rates and, thus, reductions in nitrogen delivery to streams. The effectiveness of conservation practices in reducing nitrogen delivery to streams is highly dependent on subsurface hydrological and biogeochemical conditions that favor the permanent removal of nitrogen through denitrification and (or) delay of the delivery of nitrogen to streams in discharging groundwater.

Figure 9.21. Innovative modeling approaches provide new insights on the benefits of conservation practices in reducing nitrogen inputs in the Upper Mississippi River (Garcia and others, 2016). Model estimates indicate that agricultural conservation practices in the upper Mississippi River watershed can reduce nitrogen inputs to area streams and rivers by as much as 33 percent, as compared to the same landscape without soil conservation practices. In some areas, slowing the water and routing it into the ground can significantly reduce the amount of nitrogen that is eventually transported to streams.



Final Thoughts

We are entering a time of unprecedented demands upon the Earth and its resources. Some 6 billion humans inhabit this single planet, all of whom need food to eat, fiber for clothing, shelter for protection from the elements, and clean water to drink. The challenges for agriculture are great and the stakes are high. Can agriculture on a global basis produce enough food, fiber, and fuel to satisfy the needs of humanity, and do it in such a way that it is ecologically sustainable, so as not to degrade the quality of our air, water, soil, and other natural ecosystems? This, then, is the challenge. Meeting the goal of providing for the material needs of humanity will require a cooperative effort among producers, scientists, consumers, and policy makers to think seriously, plan carefully, and develop a sound strategy to wisely use the Earth's resources.

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Glossary of Terms

aerobic Conditions or processes requiring the presence of air or free oxygen.

anaerobic Conditions or processes occurring in the absence of air or free oxygen.

antimicrobial Substance produced by or a semisynthetic substance derived from a microorganism and in dilute solution, able to inhibit or kill another microorganism.

artificial drainage Engineered removal of surface and subsurface water from an area.

baseflow Sustained flow of a stream in the absence of direct runoff. Baseflow includes natural and human-induced streamflows. Natural baseflow is sustained largely by groundwater discharge.

basin geographic area drained by a single major stream; consists of a drainage system comprised of streams and often natural or man-made lakes.

best management practices (BMPs) Practical, structural, or nonstructural methods that prevent or reduce the movement of sediment, nutrients, pesticides, and other pollutants from the land to surface or groundwater, or that otherwise protect water quality from potential adverse effects of agricultural activities. These practices are developed to achieve a balance between water-quality protection and the production of crops within natural and economic limitations.

buffer strip Strips of grass or other erosion-resisting vegetation between or below cultivated strips or fields.

channel Natural or artificial watercourse with a definite bed and banks to confine and conduct flowing water; a ditch or channel excavated for the flow of water. River, creek, run, branch, and tributary are some of the terms used to describe natural channels, which may be single or braided. Canal, aqueduct, and floodway are some of the terms used to describe artificial (man-made) channels.

constructed wetlands Wetlands constructed either as part of a wetland banking, wetland clumping (aggregation), or wetland mitigation program, or to achieve the goals of some other environmental preservation or restoration program.

cultivar Variety of a plant developed for desirable characteristics and maintained under cultivation.

ecosystem Complex of interacting plants and animals with their physical surroundings. Ecosystems are isolated from each other by boundaries that confine and restrict the movement of energy and matter; for example, an ecosystem could be recognized at a watershed scale by designating an area of common drainage.

evapotranspiration Loss of water to the atmosphere from the soil and surface-water bodies by evaporation and by transpiration through plants.

floodplain Strip of relatively flat and normally dry land alongside a stream, river, or lake that is covered by water during a flood.

flowpath (pathway) Course a water molecule or chemical follows in a given location.

hypoxic Condition in which natural waters have a low concentration of dissolved oxygen.

intrabasin transfers Water movement within the same water basin.

lag time Time during which some action is awaited.

micropores Fine soil pores, typically a fraction of a millimeter in diameter. They are responsible for the water holding capacity of soil.

moldboard plow Curved iron plate attached above a plowshare used to lift and turn the soil in conventional tillage.

overland flow Flow of rainwater or snowmelt over the land surface toward stream channels.

pathogen Microorganism (for example, virus, bacterium, prion, fungus) that causes disease in animals and (or) plants.

pH Measure of acidity and alkalinity of a solution.

photosynthesis Process in green plants and certain other organisms by which carbohydrates are synthesized from carbon dioxide and water using light as an energy source. Most forms of photosynthesis release oxygen as a byproduct. Chlorophyll typically acts as the catalyst in this process.

recharge Water added to an aquifer. For instance, rainfall that seeps into the ground.

reservoir Artificially created lake.

riparian Transition area between a stream and the nearby, upland terrestrial ecosystem. Zones are identified by soil characteristics and (or) plant communities and include the wet areas in and near streams, ponds, lakes, springs, and other surface waters.

root zone Upper layer of the soil to the depth interwoven by plant roots.

runoff Precipitation discharged into stream channels from an area. The water that flows off the surface of the land without infiltrating into the soil is called surface runoff.

saturated soil Soil that has absorbed, to the maximum extent possible, water from rainfall or snowmelt. Any further precipitation on saturated soils will result in surface runoff with down-gradient effects on flooding and erosion.

stream corridor (stream valley) Complex and valuable ecosystem that includes the land, plants, animals, and network of streams within it.

streamflow Volume of water passing through a channel during a specified time.

subsurface drainage Process of directing excess water away from the root zones of plants by natural or artificial means, such as by using a system of pipes and drains placed below ground surface level.

surface inlet Vertical pipe with one opening at or above land surface and the other connected to a horizontal drain used to remove ponded water from the land surface.

tailwater Water from irrigation that reaches the lower end of a field. Tailwater is not necessarily lost; it can be collected and reused on the same or adjacent fields.

tillage Plowing of the soil, seedbed preparation, and cultivation practices.

tolerant A plant capable of resisting the adverse effects of a particular substance (for example, an herbicide or an antibiotic) or an environmental factor (for example, drought, freezing, high temperature, or high salinity).

transformation product Chemical compound formed from the reaction of a chemical or a chemical compound (or another transformation product) after its release into the environment.

transpiration Process by which water vapor escapes from a living plant, principally through the leaves, and enters the atmosphere. Transpiration, combined with evaporation from the soil, is referred to as evapotranspiration. Transpiration, combined with evaporation from the soil, is referred to as evapotranspiration.

uplands Ground above a floodplain; that zone sufficiently above and (or) away from transported waters as to be dependent upon local precipitation for its water supplies; land which is neither a wetland nor covered with water.

water budget Accounting of the inflows to, the outflows from, and the storage changes of water in a hydrologic unit or system.

water table Upper surface of the saturated zone in soil (or rock) that is equivalent to the water level in a well in an unconfined aquifer.

wetland Area that is periodically inundated or saturated by surface or groundwater on an annual or seasonal basis, that displays hydric soils (formed under saturation conditions), and that typically supports or is capable of supporting hydrophytic vegetation.

yield (crop) Measure of cereal yield per unit area.

Glossary of Farm Implements

This glossary includes definitions of some common types of tillage, cultivation, and chemical application implements used in modern, mechanized agriculture. The variety of specific agricultural implements currently available is large and, to some extent, manufacturer specific and, new types of implements are continually introduced.

The implements mentioned are basic implements traditionally used in the production of the Nation's major crops (corn, soybean, and wheat); however, these implements often are used in other cropping systems as well. Besides the obvious exclusion of implements used in specialty crops, such as fruit and vegetable production, this glossary does not attempt to include the implements used in relatively new methods of production of the aforementioned major crops, such as ridge-till agriculture.

Tillage, as it relates to soil preparation, can be classified in three ways: primary, secondary, and cultivating. These classifications are related to production goals, and are based on the intensity and timing of tillage. Another way to classify tillage practices is by the amount of "residue" left on the soil surface, using categories such as "conventional" and "conservation" tillage. In many cases, detailed implement settings can determine whether a tillage implement will perform satisfactorily to meet a production goal (for example, helping dry out the soil sufficiently for planting activities) while also conforming to conservation goals (for example, maintaining a status of conservation tillage). Tillage implements also can be used in combination, resulting in another category of tillage called "combination tillage." Combination tillage typically involves the use of two or more dissimilar tillage technologies (for example, chisels with discs in combination primary tillage, or packer rollers with spring teeth in combination secondary tillage) to achieve either primary or secondary tillage goals.

Primary Tillage Implements Primary tillage involves displacing and shattering soil, reducing soil strength, and mixing plant materials, air, and soil amendments in the zone of tillage depth. Primary tillage generally leaves a rough soil surface, which is smoothed using secondary tillage techniques that break up the large soil clods left behind by primary tillage. As compared with secondary tillage implements, primary tillage implements operate at deeper depths and act more aggressively on the soil.

Secondary and Cultivating Tillage Implements Secondary tillage involves the further mixing and pulverization of soil in the zone of tillage depth. Specifically, secondary tillage is used to: smooth rough surfaces and break up large soil clods left behind by primary tillage; mix in soil amendments such as nutrients and pesticides; close soil air pockets; level and firm soil for seedbed preparation; and eradicate weeds. Secondary tillage implements have shallower operating depths than primary tillage implements and leave the soil in a finer, more uniform state. Cultivating tillage is, essentially, focused secondary tillage that occurs post-planting. The goals are to aid the crop by loosening the soil and by mechanically eradicating weeds. Cultivating tillage implements are designed for in-row cultivation (for example, for row-crops such as corn) as well as for other production methods (for example, for broadcast-seeding systems such as wheat); implements also are designed for either pre-emergent or post-emergent cultivation.

Chemical Application Implements Depending on the types of chemicals being applied (for example, herbicides, insecticides, fungicides, or nutrients), there are various ways of classifying different chemical-application techniques. Chemicals can be applied directly to the foliage of a crop, applied to the soil surface, or applied deeper in the soil (incorporation). Chemicals are applied as granules, solids, dissolved in water, or as emulsifications in water. Manure can be applied in liquid or solid form. Another option for application of soluble chemicals is chemigation, which involves the addition of chemicals to irrigation water.

Table G.1. Implements for primary tillage.

Implement name	Description	Implement depiction	Used in: Conventional tillage	Used in: Conservation tillage
Chisel	The chisel plow is one of the most commonly used implements today, and has been in widespread use since the 1950s. Chisels consist of individual curved shanks with interchangeable sweep, chisel, spike, winged, or shovel tips that penetrate and shatter the soil without inverting it or burying surface residue. Twisted shanks may be used to provide some degree of soil inversion and mixing. The chisel was originally developed to help control wind erosion after the Dust Bowl, so it is often used in conservation-tillage systems. Chiseling is generally done in the fall, and is often accompanied by one or more secondary tillage operations in the spring. Operating depth is between 15 and 30 centimeters.		Yes	Yes
Heavy disk	Heavy disks (or ***Heavy offset disks***) consist of circular, concave cutting blades (disks) that are drawn through the soil at an angle. The goal is to pulverize and partially or completely invert the soil, burying surface residue. Disking leaves large soil clods and appreciable surface roughness, but soil generally is left bare and susceptible to erosion. Disking typically is done on relatively well drained soils, either fall or spring, and is often accompanied by one or more secondary tillage operations in the spring. Gangs of disks are "offset" for primary tillage, making a "V" shape; serrated disks are also used. Operating depth can be up to 23 centimeters.		Yes	No
Moldboard plow	The moldboard plow is designed to partially or completely invert the soil, burying surface residue. It is used often in poorly drained soils. The plow leaves large soil clods and significant surface roughness, but the soil is left susceptible to erosion. Plowing is done in either fall or spring, and is often accompanied by one or more secondary tillage operations in the spring. Operating depth can be up to 35 centimeters. This once ubiquitous implement in historical agriculture is still in use today, but its use has waned with the advent of conservation-till and no-till practices.		Yes	No
Subsoiler	Subsoilers (***rippers***) consist of heavy duty shanks designed to break up and loosen soil deep into the profile, particularly in soils where compacted layers (or "pans") are formed by machinery traffic. In conservation tillage, subsoiling practices are often used in lieu of conventional tillage practices that would otherwise break compaction. Subsoilers also are used to increase infiltration into the soil. Subsoiling is done in either fall or spring, and requires relatively dry soil conditions. Operating depth is between 30 and 56 centimeters.		Yes	Yes

Table G.2. Implements for secondary and cultivating tillage.

Implement name	Description	Implement depiction	Used in: Conventional tillage	Used in: Conservation tillage
Disk harrow	Disk harrows utilize circular, concave cutting blades (disks), smaller than those of the ***disk plow***, and are used in fall or spring. Like other harrows, disk harrows break up larger soil clods. The intensity of disk harrowing depends greatly on the size, shape, and orientation of its disks, and the speed of travel. Disk harrows are commonly used on light- to medium-textured, well-drained soils. Gangs of disks generally are "tandem" for secondary tillage, making an "X" shape.		Yes	No
Harrow	Harrows (***drag harrows***) are designed to break up soil clods and smooth the soil surface for planting by dragging the implement across the field surface. There are three harrow technologies distinct from the disk harrow: ***chain harrows***, ***spring tine harrows***, and ***roller harrows***. Chain harrows consist of a connected network of heavy wire (much like a heavy chain-link fence, but with pointed teeth). Tine harrows consist of various rows of tines, of which there are many varieties (for example, spring tooth, wire-tooth, spike-tooth). Roller harrows use cultivating teeth between two in-line gangs of ridged rollers.		Yes	No
Field cultivator	Field cultivators (or simply ***cultivators***) generally utilize shanks with attachments (like the chisel plow), but are operated at a shallow depth (2–5 centimeters) to uproot or bury weeds, and for seedbed preparation. Depending on the implement design, settings and operation, cultivation may or may not leave sufficient residue on the soil surface for conservation tillage practices. Field cultivators differ from row-crop cultivators in that they affect the entire field surface and perform some secondary tillage functions in addition to cultivation.		Yes	Yes
Roller	There are various types of rollers, but there generally are two technologies: ***packer rollers*** (or simply ***packers***) and ***basket rollers*** (or ***crumblers***). Packer rollers consist of one or two in-line gangs of rollers, which are made of lugged or ridged wheels of varying design, and are designed to crush soil clods and compact the soil. Basket rollers consist of cylindrical, reel-type assemblies (baskets) made of wire rods, bars or blades, and are used to break soil clods and to mix and level the soil surface.		Yes	No

Table G.3. Implements for chemical application.

Implement name	Description	Implement depiction
Anhydrous ammonia applicator	Anhydrous ammonia is an efficient and widely used method of nitrogen application. This method is used particularly often in row-crop agriculture. Because anhydrous ammonia becomes a gas when exposed to air, it must be injected into the soil, and is stored in tanks that are pulled behind the injecting implement. Application generally is of low disturbance to the soil surface.	
Fertilizer spreader	This type of implement generally is used to spread soil amendments over the field surface, including fertilizers (for example, granular urea) and other amendments such as lime, gypsum, and compost. Special spreaders are used for manure. For some amendments, such as urea, application is followed with incorporation by either tillage or irrigation.	
Manure injector	As the name suggests, these implements apply manure in an "injected" fashion. Manure injectors can be of the umbilical cord type, where the manure supply is stationary, or of the tank type, where the manure supply is pulled behind in a tank. They also can be of high or low disturbance to the soil, dependent on implement design and settings, which affect the resulting residue levels.	
Manure spreader	There are a variety of manure spreader designs, because these implements can spread liquid, slurry, or solid manure. Like manure injectors, spreaders can be of the umbilical cord or tank type. Manure is applied in a "broadcast" fashion, and is sometimes incorporated by tillage after application.	
Boom sprayer	Boom sprayers (***field sprayers***) are used to apply chemicals, commonly pesticides, to the field surface or to plant foliage. They can be calibrated for broadcast or banding depending on crop and chemical. Sprayers can be self-propelled or towed behind tractors, and can be used with a row-crop sprayer (which has tall, narrow tires to spray in standing crops) or a floater sprayer (which has 3-wide, floater tires to minimize crop damage by distributing machine weight).	
Aerial applicator	Also known as a ***Crop Duster*** or ***Spray Plane***. Aerial application involves the use of an airplane or helicopter to apply chemicals to a field. Aerial applicators are often used to apply pesticides, but can also be used to apply fertilizers—known as aerial topdressing. Aerial application is fast and does not compact the land, but generally is more expensive than other methods.	
Chemigation	Chemigation (***fertigation*** when referring to nutrients) involves the use of irrigation water as a solvent for soluble fertilizers and pesticides. The chemicals are then transported to the foliage or soil directly through irrigation, both by above-ground irrigation and by subirrigation	

Acknowledgments

We wish to say thank you to the many individuals and organizations who contributed to this report. These include USGS personnel across the Nation who collected, analyzed, and interpreted data. In addition, numerous USGS partners in the governmental and non-governmental sectors helped guide the scientific efforts and ensure that USGS information meets the needs of local, State, tribal, regional, and National stakeholders. Finally, we would like to thank those who contributed sections of the text and reviewed parts of the report.

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Jeannie R. Barlow, "Strategic, long-term monitoring, in concert with hydrologic modeling, provides a basis for sound management decisions"

Jack E. Barbash, "Organic Agriculture"

Scott C. Kronholm, "Manure", figure 2.4, figure 8.5, figure 8.9

Michael S. Majewski, "Important Agricultural Chemicals"

Gustavo H. Merten, "Effects of Tillage on Runoff and Recharge"

Jason L. Roth, "Quantifying Water and Sediment Budgets", figure 6.3, figure 9.15

Michael T. Talbot, "A Year with Corn in Central Indiana," "Nutrient Management Plans," "Glossary of Farm Implements"

Jason R. Vogel, parts of Chapters 6 and 7

Heather L. Welch, "Nitrogen and phosphorus, used in fertilizers, are transformed into different chemical forms, but they do not disappear. These elements move throughout the environment"

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Publishing support provided by the
U.S. Geological Survey
Scientific Publishing Network,
Tacoma Publishing Service Center

ISSN 2330-5703 (online)
https://doi.org/10.3133/cir1433