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Unintended Consequences of Biofuels Production: The Effects of Large-Scale Crop Conversion on Water Quality and Quantity

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In the search for renewable fuel alternatives, biofuels have gained strong political momentum. In the last decade, extensive mandates, policies, and subsidies have been adopted to foster the development of a biofuels industry in the United States. The Biofuels Initiative in the Mississippi Delta resulted in a 47-percent decrease in cotton acreage with a concurrent 288-percent increase in corn acreage in 2007. Because corn uses 80 percent more water for irrigation than cotton, and more nitrogen fertilizer is recommended for corn cultivation than for cotton, this widespread shift in crop type has implications for water quantity and water quality in the Delta. Increased water use for corn is accelerating water-level declines in the Mississippi River Valley alluvial aquifer at a time when conservation is being encouraged because of concerns about sustainability of the groundwater resource. Results from a mathematical model calibrated to existing conditions in the Delta indicate that increased fertilizer application on corn also likely will increase the extent of nitrate-nitrogen movement into the alluvial aquifer. Preliminary estimates based on surface-water modeling results indicate that higher application rates of nitrogen increase the nitrogen exported from the Yazoo River Basin to the Mississippi River by about 7 percent. Thus, the shift from cotton to corn may further contribute to hypoxic (low dissolved oxygen) conditions in the Gulf of Mexico.

Top photograph: Furrow irrigation of corn acreage in the Mississippi Delta. Photograph courtesy of the Mississippi State University Extension Service.

Bottom photograph: Water-level monitoring of an alluvial aquifer well in Bolivar County, Mississippi. Photograph by Michael A. Manning, U.S. Geological Survey.

Why has the Production of Biofuels Become Important?

Biofuels are fuels produced directly or indirectly from organic materials such as plants and animal waste. Corn-based ethanol is the most common type of biofuel produced in the United States—approximately 34 billion liters (L) were produced in 2008 (data accessed on June 7, 2010, at *http://www.afdc.energy.gov/afdc/ethanol/production.html*). Biofuels have received considerable support because they use renewable resources and have the potential to reduce greenhouse gas emissions. However, there are some environmental concerns attributed to the increase in corn acreage for biofuels production, such as the need for irrigation in some areas, the application of increased amounts of nitrogen fertilizers and water-soluble pesticides, and soil erosion from the tillage of crops (National Research Council of the National Academies, 2008).

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The Biofuels Initiative (BFI), which was implemented by the U.S. Department of Energy (DOE) Biomass Program in late 2006, was developed by the DOE Office of Energy Efficiency and Renewable Energy to help meet the goals of the Energy Independence and Security Act (EISA; Public Law Number 110-140). The goal of the EISA is to increase the production of renewable and alternative fuels and reduce dependence on foreign oil within the United States. Two primary goals for the BFI and Biomass Program are to (1) produce 230 billion L of ethanol to replace 30 percent of current gasoline levels by 2030 and (2) reduce ethanol costs to prices that are competitive with gasoline by 2012.

The Mississippi Delta—Consequences of Biofuels Production from a Local Perspective

The Yazoo River Basin is the largest river basin in Mississippi, with a drainage area of 34,590 square kilometers (km^2), and is divided equally between lowlands and highlands. An area referred to locally as the "Delta" covers about 18,130 km^2 of the lowlands part of the Yazoo River Basin in northwestern Mississippi. The U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program has spent much of the last two decades studying the relation between agriculture and water quality and quantity in the Mississippi Delta (fig. 1). Because of fertile soils and a long growing season, about 90 percent of the land is used for agriculture, including the cultivation of cotton, corn, rice, and soybeans. Although the climate is humid and subtropical, and the average rainfall ranges from 114 centimeters per year (cm/yr) in the north to 152 cm/yr in the south, about 28 percent of the rainfall occurs during the growing season (Snipes and others, 2005). Thus, irrigation is needed to maximize crop production.

The primary source of water for irrigation in the region is the Mississippi River Valley alluvial (MRVA) aquifer—a relatively thin hydrogeologic unit with an average thickness of 41 meters (m) and an areal extent of approximately 85,470 km^2. The aquifer is composed of highly permeable layers of sand, gravel, and silt (with minor amounts of clay) that underlie parts of Arkansas, Louisiana, Mississippi, Missouri, and to a lesser extent Illinois, Kentucky, and Tennessee (fig. 1). In Mississippi, the aquifer is overlain by a relatively impervious clay layer, and therefore, only a small percentage of precipitation infiltrates the soils to directly recharge the aquifer. Estimates of recharge to the aquifer from precipitation range from 5.8 to 10.9 cm/yr (Arthur, 2001; Green and others, 2009; Welch and others, 2009). Because the Delta is a low, flat area with low permeability, the remaining precipitation is lost through evapotranspiration and to streamflow, which is supplemented by irrigation return flow during the summer months. During the winter, most of the runoff from rainfall drains into streams.

Approximately 15 million cubic meters per day (m^3/d) of water are withdrawn from the MRVA aquifer during the May to August growing season in Mississippi, which makes it the most heavily used aquifer in the State (Maupin and Barber, 2005). Owing to the large amount of withdrawal, water levels in the aquifer have been declining since at least 1980. The average groundwater level has declined 0.1 meter per year (m/yr) or less in most areas, but has declined as much as 0.5 m/yr in some areas. Overall, the total volume of water stored in the aquifer has declined since 1980 (Arthur, 2001), and current withdrawals from the alluvial aquifer exceed recharge. From October 1987 to October 2009, there was an average annual loss in storage of approximately 355 million cubic meters (m^3) from the MRVA aquifer in the Mississippi Delta (Mark Stiles, Yazoo Mississippi Delta Joint Water Management District, written commun., 2010; fig. 2).

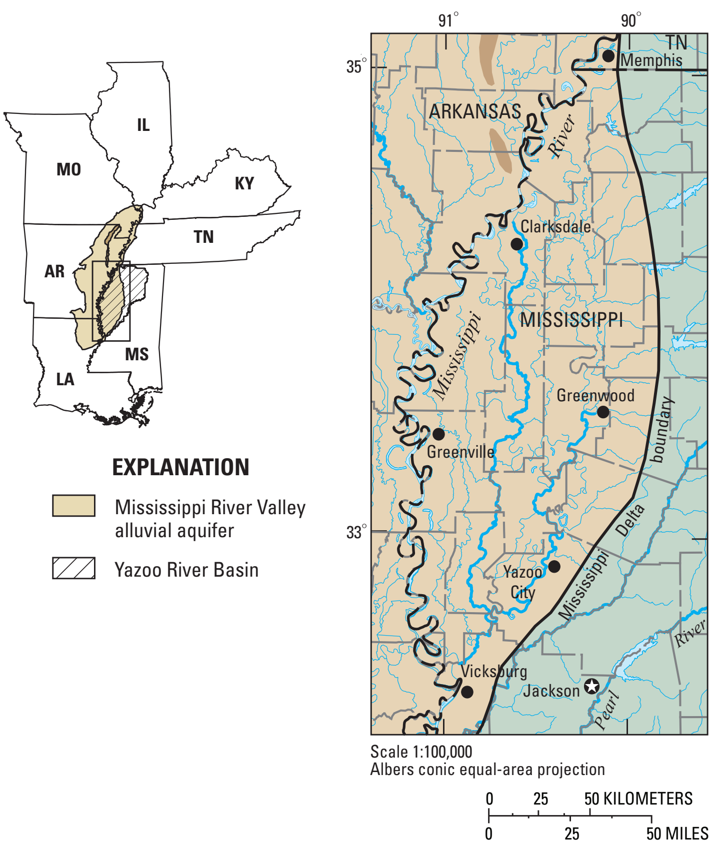

Figure 1. Areal extent of the Mississippi River Valley alluvial aquifer and the location of the Mississippi Delta in northwestern Mississippi.

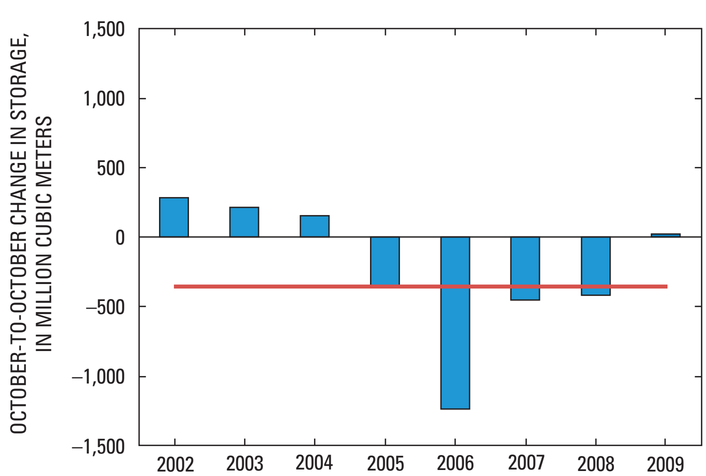

Figure 2. Annual (October-to-October) change in storage of the Mississippi River Valley alluvial aquifer in the Mississippi Delta, 2002–2009. Red line denotes the 22-year average change in storage for the aquifer (Mark Stiles, Yazoo Mississippi Delta Joint Water Management District, written commun., 2010).

Increased Withdrawals for Corn and Soybeans Are Accelerating Groundwater Declines in the MRVA Aquifer

Withdrawals from the MRVA aquifer have increased due to market-driven land conversion from cotton to corn and soybeans. The increase in corn prices driven by demand for ethanol-based biofuels resulted in a 47-percent reduction in cotton acreage concurrent with a 288-percent increase in corn acreage in 2007 relative to 2006 (fig. 3). From 2007 to 2009, corn acreage decreased by 21 percent and soybean acreage increased by 46 percent in response to rising demand for soybeans to replace corn as feed for livestock (fig. 3). Groundwater withdrawal rates (and application rates) for a particular crop vary from year to year, depending on weather conditions, irrigation methods, and other factors. For example, withdrawals for corn increased from 219 million m^3 in 2006 to 566 million m^3 in 2007, whereas withdrawals for cotton decreased from 855 to 282 million m^3 during this same period. Although corn acreage increased in 2007, groundwater application rates (withdrawal volume per unit land area in production) were about 30 percent lower in 2007 than in 2006 because of timely precipitation (fig. 3; table 1). Because soybean production uses nearly as much water as corn production, the 2008 to 2009 shift in crop further increased the demand for groundwater from the MRVA aquifer.

Withdrawal rates for cotton production ranged from 0.09 million cubic meters per square kilometer per year ($m^3/km^2/yr$) in 2004 to 0.25 million $m^3/km^2/yr$ in 2006 (table 1). The average annual withdrawal rate from 2002 to 2009 was 0.15 million $m^3/km^2/yr$ for cotton, 0.22 million $m^3/km^2/yr$ for soybeans, and 0.27 million $m^3/km^2/yr$ for corn (table 1; Yazoo Mississippi Delta Joint Water Management District, 2009). Based on these averages, which normalize withdrawals for inter-annual differences in weather, converting 1 km^2 of cotton to 1 km^2 of corn results in a 0.12 million $m^3/km^2/yr$ increase in withdrawals from the MRVA aquifer. Corn production in the Delta increased from 598 km^2 in 2006 to 2,321 km^2 in 2007, while cotton production fell from 3,505 km^2 in 2006 to 1,853 km^2 during the same period (fig. 3; *http://www.nass.usda.gov/Statistics_by_State/Mississippi/index.asp*; accessed April 10, 2010). Assuming that about 1,652 km^2 of cotton were converted to corn between 2006 and 2007, the additional increase in groundwater withdrawn, based on the measured 2007 application rates, was 165 million m^3. A similar analysis for the entire 2008 through 2009 period, including changes in soybean production, indicates that an additional 270 million m^3 of water were withdrawn from the MRVA aquifer from 2008 through 2009 as a result of crop conversions—a total of 435 million m^3 more groundwater withdrawn for the entire 2007 to 2009 period.

Two scenarios for the volume of change in storage of the MRVA aquifer from 2007 to 2009 indicate that the conversion from cotton to corn and soybean acreage increased storage loss in the MRVA aquifer. A change in water withdrawals for cotton, corn, and soybeans was calculated for 2007 to 2009, using average withdrawal rates (table 1), in reference to 2006, the year prior to the large-scale crop conversion. In 2007, storage loss in the aquifer would have been approximately 250 million m^3 if the conversion from cotton to corn acreage had not occurred (fig. 4). In 2008, storage loss in the aquifer would have been approximately 210 million m^3 if the conversion from cotton to corn and soybean acreage had not occurred (fig. 4). A slight increase in storage of 18 million m^3 occurred in 2009 because of decreased groundwater withdrawals during the growing season as a result of timely rainfall. However, potential storage would have been 189 million m^3 if further increases in total acreage for soybean and corn, relative to 2006 levels, had not occurred (fig. 4).

Table 1. Groundwater withdrawal rates for cotton, corn, and soybean acreage in the Mississippi Delta, 2002–2009.

[Source: Yazoo Mississippi Delta Joint Water Management District (2009). All values are in million cubic meters per square kilometer per year]

Year	Cotton	Corn	Soybeans
2002	0.15	0.28	0.22
2003	0.15	0.19	0.19
2004	0.09	0.12	0.12
2005	0.15	0.31	0.19
2006	0.25	0.37	0.31
2007	0.15	0.25	0.25
2008	0.19	0.37	0.31
2009	0.09	0.25	0.19
8-year average	0.15	0.27	0.22

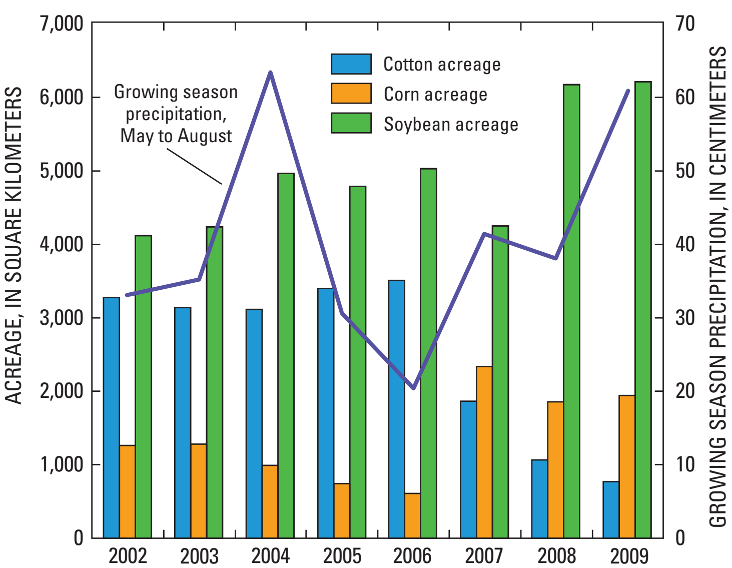

Figure 3. Crop acreage and total growing season precipitation in the Mississippi Delta, 2002–2009.

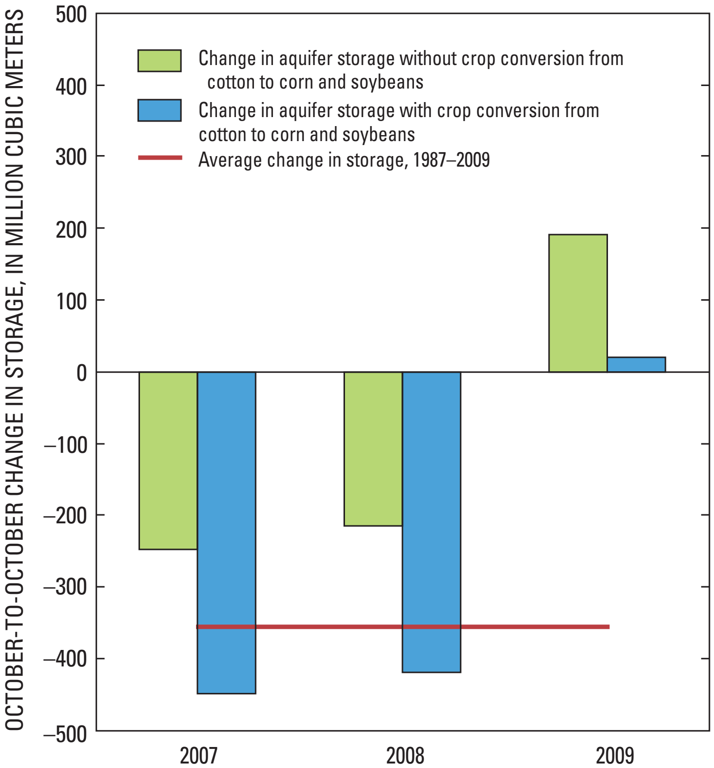

Figure 4. October-to-October change in Mississippi River Valley alluvial aquifer storage that can be attributed to the crop conversion from cotton to corn and soybeans, 2007–2009. For 2007, only the crop conversion from cotton to corn is considered.

Increased Agrichemical Application Rates Have Affected Groundwater Quality

The USGS developed a mathematical advection-reaction water-quality model for a study site in the Delta to investigate changes in fertilizer application rates resulting from an increase in corn production and corresponding decrease in cotton production. The model was calibrated to existing conditions to assess fluxes of water and chemicals from agricultural fields to groundwater (Green and others, 2009; Welch and others, 2009). As with many other agricultural sites across the country, nitrate-nitrogen (N) contamination was found in shallow groundwater as a result of the leaching of chemical nitrogen (fig. 5). At this site, nitrate-N was absent in samples at depths of 4.4 m below the water table and deeper due to a biodegradation reaction known as denitrification. The depth of leached nitrate-N was controlled largely by the slow downward movement of water, which is a function of soil properties, and the annual nitrogen fertilizer application rate to the overlying farm fields. Because of the link between fertilizer application rates and the degree of nitrogen contamination in groundwater, potential changes in nitrogen application rates in response to crop conversion for biofuels production have important implications for groundwater quality in the Mississippi Delta.

The results of a mathematical model indicate that increased nitrogen fertilization due to additional corn production will expand the area of nitrate-N contamination of groundwater in Mississippi Delta groundwater. Figure 5 shows two hypothetical scenarios for future agriculture and water quality. In scenario 1, the crop types and fertilizer application in the Delta remain at 2006 levels (fig. 5*B*). Nitrogen fertilizer application rates for this scenario are based on county agricultural chemical use from 1960 to 2008 (U.S. Department of Agriculture, 2010). Under scenario 1, steady-state conditions are reached after 35 years, at which point predicted nitrate-N concentrations exceed the U.S. Environmental Protection Agency Maximum Contaminant Level (MCL) of 10 milligrams nitrate-N per liter (U.S. Environmental Protection Agency, 2006) in the upper 2 m of groundwater, and nitrate-N is transported to a maximum depth of 7 m below the water table (fig. 5*A*). Once steady-state conditions are reached, the maximum depth of contamination remains at 7 m because the rate of downward transport reaches equilibrium with the rate of denitrification. In scenario 2, an increase in corn production results in a rapid increase in nitrogen application rates to 269 kilograms nitrate-N per hectare per year based on recommended fertilizer application rates from the Delta Planning Budget for corn acreage in Mississippi (fig. 5*B*; Mississippi State University Department of Agricultural Economics, 2009). Under this scenario, steady-state conditions are reached after 95 years, at which point nitrate-N concentrations in ground-water are much higher than in scenario 1 and exceed the MCL up to 14 m below the water table. Nitrate-N migrates downward to a maximum depth of 18 m below the water table. Other hydrologic factors not considered in the model could result in an increase in the depth of migration of nitrate-N in the aquifer. For example, downward groundwater velocities could increase as a result of increased withdrawals.

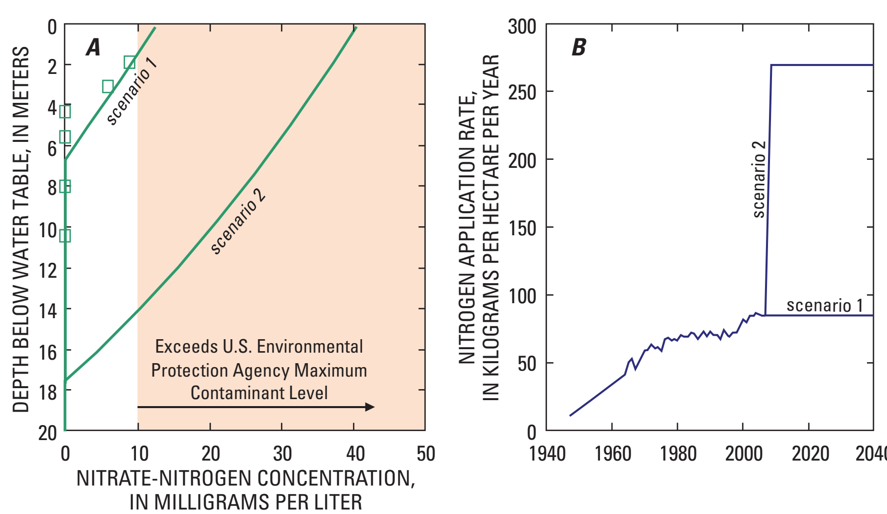

Figure 5. Two model scenarios for future agricultural practices and resulting water quality at the study site in the Mississippi Delta: (*A*) measured (indicated by green squares) and simulated nitrate-nitrogen concentrations in groundwater at various depths below the water table, and (*B*) fertilizer application for both scenarios over time. Scenario 1 assumes crop acreage and fertilizer application remain at 2006 levels, whereas scenario 2 is an immediate conversion to 100 percent of the recommended nitrogen application rate for corn.

Nitrogen Export to the Gulf of Mexico Has Increased

Since at least 1980, a hypoxic zone has formed during the summer in the Gulf of Mexico off the coast of Louisiana. The zone has increased in size since measurements began in the early 1980s, and its extent is positively related to the annual amount of nitrogen entering the Gulf from the Mississippi River (Rabalais and others, 2002).

The USGS developed the SPAtially Referenced Regressions on Watershed attributes (SPARROW) model to relate water-quality measurements to contaminant sources and environmental factors that affect both the rates of delivery of compounds to streams and their rates of in-stream processing. SPARROW has been used to identify the watersheds that are the largest contributors of nitrogen to the Gulf of Mexico, which includes the Yazoo River Basin (fig. 6; Robertson and others, 2009). Using regional SPARROW model estimates of both the nitrogen application rates and the loss rates for nitrogen for the Yazoo River Basin, the conversion of cotton to corn acreage (comparing 2002 with 2007) is estimated to have caused a 7 percent increase in the nitrogen load for the Yazoo River (Richard A. Rebich, U.S. Geological Survey, written commun., 2010). Significant increases in nutrient inputs tied to changes in cropping patterns could mask any progress toward meeting the 45-percent nutrient reduction target by 2015 as specified by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2008).

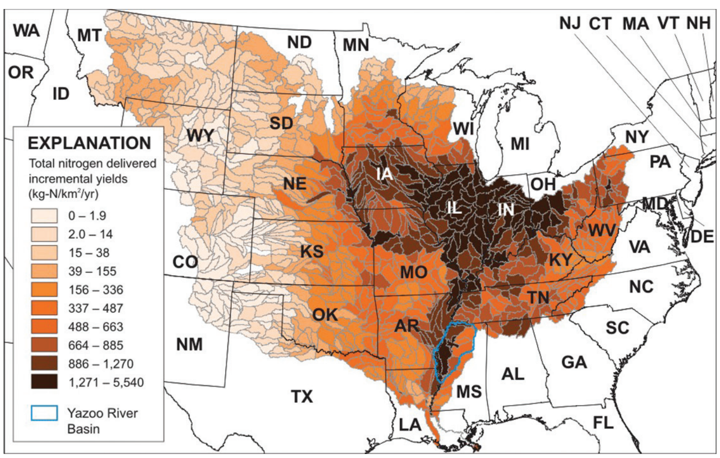

Figure 6. The extent of the Mississippi/Atchafalaya River Basin watersheds and total nitrogen delivered to the Gulf of Mexico from the basin. The Yazoo River Basin lies within the bold blue line (Robertson and others, 2009; kg-N/km²/yr, kilograms nitrate-nitrogen per square kilometer per year).

Stream Ecosystem Health Is Affected by Declining Water Quality and Quantity in Delta Streams

Groundwater input to a stream during periods of low rainfall is essential to stream ecosystem health because it maintains baseflow, regulates stream temperature, and generally is of higher quality than surface-water runoff. Prior to the rapid expansion of corn acreage in response to the BFI, baseflow in some Delta streams had been declining in recent years because of declining water levels in the MRVA aquifer (fig. 7), and some stream reaches have remained dry (or nearly so) for months in the summer and fall during periods of low rainfall (fig. 8).

Most streams in the Delta have been hydrologically altered, and about 75 percent of the original forested wetlands have been cleared or drained, thus changing ecosystem structure and function (Creasman and others, 1992). A presumed decline in ecosystem health in Delta streams prior to 2007 is evidenced by a loss of habitat complexity and structure and a change in metabolic dynamics resulting from increased water temperatures and decreased dissolved oxygen levels (Kleiss and others, 2000). Continued declines in ecosystem health have led to further biodiversity losses through substantial changes in biological community assemblages and the increasing prevalence of more tolerant, but less desirable, species. The continued expansion of corn and soybean acreage in the Delta is expected to exacerbate the stresses on stream ecosystems primarily by (1) reducing groundwater inflow to streams—a change with particularly acute consequences during periods of low flow during the summer, and (2) increasing nutrient input to streams through increased fertilizer use.

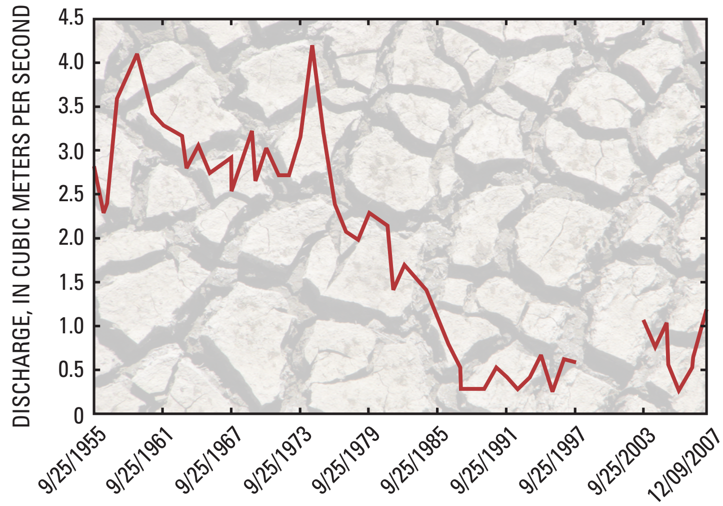

Figure 7. Annual minimum mean daily flow at the Big Sunflower River at Sunflower, Mississippi, showing decline in baseflow most evident since groundwater withdrawals from the Mississippi River Valley alluvial aquifer increased in the late 1980s. Data are missing for 1998 to 2002.

Figure 8. A Delta stream that is nearly dry during the summer because of loss of baseflow. Photograph by Matt Hicks, U.S. Geological Survey, September 25, 2007.

Summary—How Has the Biofuels Initiative Affected Conditions in the Mississippi Delta?

- Higher groundwater withdrawals associated with the conversion of cotton to corn and soybean crops have exacerbated already declining water levels in the Mississippi River Valley alluvial (MRVA) aquifer leading to further loss of baseflow in most Delta streams.
- Results from a mathematical water-quality model indicate that an increase of nitrogen fertilizer application to rates recommended for corn could increase nitrate-N contamination in much of the MRVA aquifer to levels that exceed the U.S. Environmental Protection Agency Maximum Contaminant Level. Maintaining fertilization rates at 2006 levels will result in only a minor increase in nitrate-N contamination.
- Increased fertilizer application rates on corn have increased slightly (about 7 percent) the export of nitrogen from the Mississippi Delta to the Mississippi River and, ultimately, to the Gulf of Mexico where it may further exacerbate the hypoxic zone.

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Additional Information

For additional information about the Biofuels Initiative and (or) the Mississippi Delta contact:

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