

Reducing hypoxia in the Gulf of Mexico: Reimagining a more resilient agricultural landscape in the Mississippi River Watershed

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In 1972 President Nixon signed the Clean Water Act (CWA) into law, making clean water a public right and establishing a goal that the nation's waters should be both "fishable and swimmable." It is considered by many to be the most important and effective environmental law ever passed. Before the CWA, two-thirds of US waterways were considered unsafe for fishing and swimming, and waste from households, municipalities, factories and power plants, including sewage, livestock processing, waste oil, and chemicals, flowed untreated into rivers, streams, and lakes. The law reduced the discharge of sewage and other industrial point source pollution into waterways, but most agricultural nonpoint source pollution, the greatest source of water pollution today, was exempted. The agriculture exemption, called "one of the last, great intractable problems of environmental law," results in an inconsistent system for addressing water pollution, with regulation for the majority of urban sources and a voluntary, incentive-based system for much of agriculture (Laitos and Ruckriegle 2013).

Despite more than 40 years of largely voluntary efforts by federal, state, and local government, and tens of billions of US dollars of investment in conservation, nationwide progress on nutrient control has not yet been achieved. Concentrations of nitrogen (N) and phosphorus (P) in streams and groundwater are 2 to 10 times higher than recommended to protect aquatic life, and contamination of drinking water is still widespread, especially in rural areas (Dubrovsky et al. 2010).

Complicating the matter, federal policies to protect water quality are at times at odds with policies designed to maximize commodity production and global exports (USEPA 2007).

The consequences of agricultural nonpoint source pollution are particularly evident where the Mississippi River enters the Gulf of Mexico. The Gulf's hypoxic, or "dead zone" is the largest hypoxic region in the United States and the second largest in the world (Rabalais et al. 1991). In 2014 the Gulf's hypoxic zone, measured annually by scientists at Louisiana Universities Marine Consortium, was 13,080 km² (5,052 mi²) (figure 1). No environmental phenomenon of such ecological importance to coastal marine systems has changed so drastically in such a short time, threatening to "inexorably change the biology of the region," including its US\$2.8 billion commercial and recreational fishing industry (Diaz and Rosenberg 1995; USEPA 2008).

LEAKY CORN PRODUCTION SYSTEMS

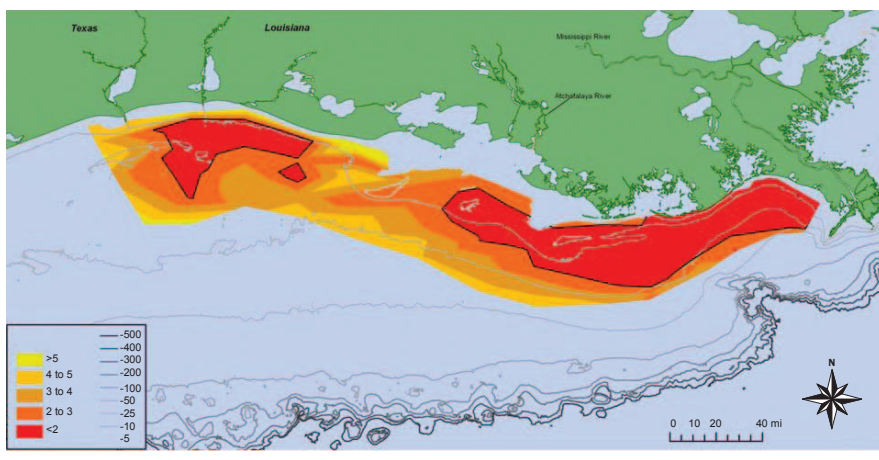
The historic land use change from perennials to row crops is a major factor in increased rates of nonpoint source pollution. For thousands of years after glaciations, deep-rooted prairie grasses

covered 69 million ha (170 million ac) of the central United States, seminal to the region's organically rich and fertile soils. Waters were, for the most part, clean and clear. In the early 1900's the Midwest underwent the first dramatic shift in agricultural land use. World War I increased demand for food production, and the advent of mechanized farming led to "the great plow-up." There was a dramatic shift from deep-rooted, drought resistant, native prairies and forests to a landscape dominated by annual cultivated crops.

The increase in row crop production at the expense of grasslands has been shown to increase groundwater recharge, stream flows, water export from agricultural watersheds and nutrient loading (Schilling et al. 2008). Although corn (*Zea mays* L.) is a remarkable, high-yielding crop—an agricultural "phenom" with many commercial advantages—environmental sustainability is a major concern. The required annual planting, wide crop rows, the amount and type of fertilizer inputs and tillage, and that much of the soil in a cornfield has limited cover for more than half the year leaves fields susceptible to water runoff, especially in areas with tile drainage. As much as 60% of the N fertilizer applied to a corn crop isn't utilized and "leaks" from cornfields

Figure 1

Levels of dissolved oxygen in the Gulf of Mexico measured between July 27 and August 1, 2014. Image courtesy of N.N. Rabalais (Louisiana Universities Marine Consortium) and R.E. Turner (Louisiana State University).



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into surface waters as nitrate (NO_3) and into the air as nitrous oxide (N_2O), a potent greenhouse gas (Simpson et al. 2008; Smith et al. 2013). The upper Mississippi and Ohio River basins, dominated by corn and soybean (*Glycine max* L.) fields with extensive tile drainage systems, contribute about 82% of the NO_3 and 58% of the total P to the Gulf (USEPA 2007). An average of 1.57 million t (1.73 million tn) of N are transported annually by the Mississippi River to the Gulf of Mexico, more than 70% of which comes from agricultural nonpoint sources (Goolsby et al. 1999; Alexander et al. 2008).

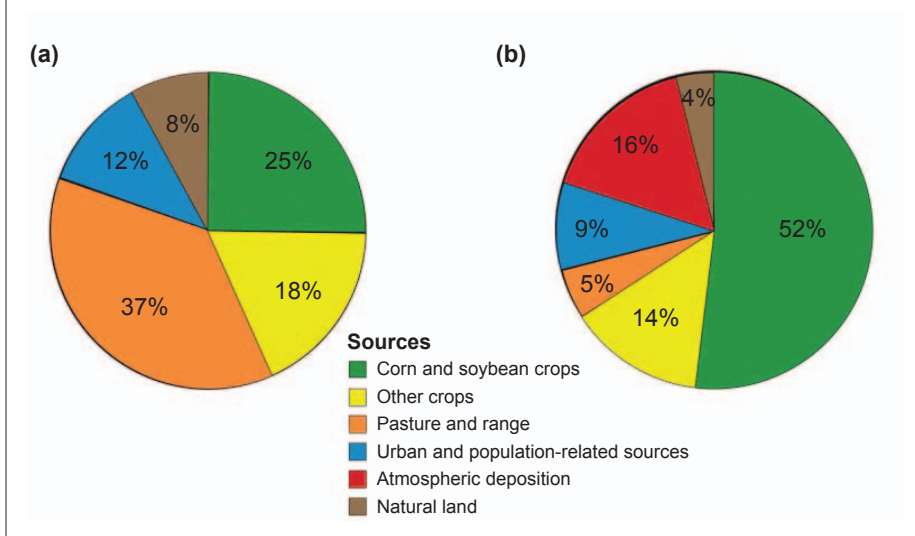
More recently, skyrocketing corn and soybean prices, changes in crop insurance, and the passage of the Energy Independence and Security Act, increased demand for corn and corn-based biofuels, and the Midwest experienced another great plow-up, with grassland conversion rates not seen since the Dust Bowl. Between 2006 and 2011, 0.5 million ha (1.3 million ac) of grasslands were converted to corn and soybeans in five midwestern states “comparable to deforestation rates in Brazil, Malaysia, and Indonesia” (Wright and Wimberly 2013). Between 2007 and 2013, corn hectares planted nationally increased by 25% (USDA NASS 2014). Today seven midwestern states produce 42% of the US corn (Wu et al. 2012).

GRASSLANDS: NATIVE CONSERVATIONISTS

The loss of the nation’s grasslands shouldn’t be shrugged off as merely the price of progress. Perennial grasses have unique physiology and morphology that contributes to their conservation role in the agricultural landscape. They are deep-rooted with belowground biomass equal to or greater than their aboveground biomass. They only need minimal tillage at planting, being no-till seeded into crop residue. Their extensive and deep root systems promote soil organic matter and improved soil water holding capacity, reducing runoff, trapping nutrients, and capturing and storing (sequestering) atmospheric carbon dioxide (CO_2). Perennials show greater N use efficiency than annuals, and in the autumn as grasses senesce, transfer N from the aboveground biomass into their roots

Figure 2

Primary sources of (a) phosphorus and (b) nitrogen delivered to the Gulf of Mexico. Image courtesy of Alexander et al. (2008), US Department of Interior and US Geological Survey.



where it is stored. In addition, while fossil fuels are a carbon (C) source, contributing atmospheric CO_2 , perennial grasses are a C sink capturing and storing (sequestering) atmospheric CO_2 .

The perennial life cycle of grasses is a critical factor leading to improved water quality. Perennial grasses stabilize watershed hydrology by reducing peak flows, increasing soil water holding capacity, and promoting uptake and filtering of nutrients. A four-year Minnesota study found that NO_3 losses from corn and soybeans were 30 to 50 times greater than from alfalfa (*Medicago sativa* L.) and perennial grasses (Randall et al. 1997). Many others have reported nutrient losses from row crops several orders of magnitude higher than those from perennials (Carpenter et al. 1998; Brye et al. 2001; Schilling et al. 2008; Smith et al. 2013).

The strategic integration of perennials into the agricultural landscape could restore a healthy, well functioning agricultural system (Schulte et al. 2006). A five-year study of 12 agricultural watersheds in central Iowa found that strategically planting 10% of row crop fields to perennial prairie grass strips reduced runoff water N by 84% and P by 89%, respectively (Helmers et al. 2012; Zhou et al. 2014). Compared to cool-season grasses, prairie grasses have stiffer stems and stand erect, reducing runoff

volume, trapping and filtering nutrients, and dramatically lowering nutrient loads and sediments (Liebman et al. 2013). Prairie strips also increased bird species and insect pollinators.

MIDWEST AGRICULTURE AND GULF HYPOXIA

Extensive research during the last 30 years has led to a clearer understanding of the causes and impacts of hypoxia in the Gulf of Mexico (Rabalais et al. 2002). Nutrients linked to row crop production are chiefly responsible (Goolsby et al. 1999; Donner and Kucharik 2003; USEPA 2007). Agriculture contributes the largest source of N and P delivered to the Gulf, 71% and 80%, respectively (figure 2). Among crops, corn and soybean contribute the most N (52%) and the second most P (25%). Animal manure from pasture and rangeland is the largest source of P. Approximately 24% of N and 12% of P come from urban and atmospheric sources (wastewater treatment effluent, septic systems, lawn fertilizers, car exhaust, and emissions from power plants).

Of the 31 states that drain into the Mississippi River basin, nine midwest states contribute approximately 75% of the nutrients entering the Gulf (Alexander et al. 2008). On average 1.57 million t (1.73 million tn) of N are transported annually by the Mississippi River to the Gulf of Mexico, more than 70% of which comes from agri-

cultural nonpoint sources (Goolsby et al. 1999; Alexander et al. 2008). The total annual N delivery from the Mississippi to the Gulf has increased nearly 300% since the 1950s (Goolsby et al. 1999).

POLICY-BASED EFFORTS TO REDUCE GULF HYPOXIA

Since Gulf hypoxia was first reported in 1972, scientists have gained critical understanding of the sources and impacts of nutrient pollution, but control efforts have been limited. In the mid-1990s, absent progress to address Gulf hypoxia, several citizen groups filed lawsuits against the US Environmental Protection Agency (USEPA) to reduce pollution to the Mississippi River and, in turn, the Gulf's hypoxia.

In 1997, the USEPA announced the formation of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Hypoxia Task Force) to study the causes of hypoxia and develop a plan to reduce the size and severity of its impacts. In 2001, the Hypoxia Task Force reported that the hypoxic zone, which varies in size annually, had increased from 10,000 km² (3,861 mi²) in 1993 to 20,000 km² (7,722 mi²) in 1999 (USEPA 2001). A basin-wide, dual nutrient (N and P) reduction approach was agreed upon along with a goal to reduce the hypoxia zone to 5,000 km² (1,930 mi²) by 2015.

By 2007, the USEPA's Scientific Advisory Board noted a "regime shift" in the Gulf's ecosystem, leaving it more vulnerable than ever to nutrient influx and urged rapid action. If the size of the hypoxic zone was to be reduced, a dual nutrient approach and at least a 45% reduction for both N and P was required (USEPA 2007). Nitrogen reduction was key for limiting algae growth in the ocean, while P reduction was key for reducing algae in freshwater. The Scientific Advisory Board underscored that nutrient reduction cobenefits, including ground and surface water, wildlife, C sequestration, and greenhouse gas (GHG) reduction, may "exceed the benefits of hypoxia reduction itself." In 2008, the Hypoxia Task Force updated its plan, including a "dual nutrient strategy targeting at least a 45% reduction" in both P and N loading to the Mississippi River (USEPA 2008).

In 2011, the USEPA initiated an approach warning N and P runoff had "escalated dramatically" and was among the country's "most challenging environmental problems." It directed regional offices to make "greater progress in accelerating reduction of N and P loadings to the nation's waters." It suggested a voluntary state-based nutrient reduction framework including development of work plans and timelines, ongoing watershed sampling, and public reporting on progress toward goals (Stoner 2011).

The National Research Council, advising USEPA on implementation of the CWA in the Mississippi River Basin, noted that to date voluntary actions were insufficient for achieving water quality goals:

A weakness of the 2008 action plan is that it contains nothing to suggest that actions discussed in the plan will in fact achieve the goals...The current framework of mainly voluntary coordination of actions and programs, although useful for promoting dialogue and raising awareness of water quality issues, has not realized substantive accomplishments in terms of on-the-ground project implementation or documented improvements in water quality. (NRC 2012)

HYPOXIC ZONE PROGRESS REPORT: WATER QUALITY GOALS PROVE ELUSIVE

Reducing nutrient loading to the Mississippi and the Gulf has proven elusive. Between 1997 and 2007, the five-year average for total N delivered to the Gulf declined, but since 2007 it has increased steadily (figure 3a). The five-year average for P delivered to the Gulf has also generally increased since 1997 (figure 3b). The five-year average size of the Gulf hypoxic zone is 14,352 km² (5,541 mi²), three times larger than the Hypoxia Task Force's action plan goal of 5,000 km² (1,930 mi²) (figure 4).

ADVANCED GENERATION BIOFUELS: AN OPPORTUNITY FOR WATER QUALITY IMPROVEMENTS?

A national priority has been development of a clean energy economy including a sustainable, domestic biofuels industry.

However, the Renewable Fuel Standard (RFS), established by USEPA in 2005 under the Energy Policy Act, led to a rapid investment and increase in primarily corn ethanol facilities. The RFS was widely criticized for driving the conversion of millions of acres of grasslands to croplands, increasing corn prices, harming water quality and wildlife, and disrupting global food production. Between 2000 and 2010, US ethanol production increased from 6.13 to 50.3 billion L (1.62 to 13.3 billion gal), and the share of corn utilized for ethanol increased from about 5% to 40% of annual US corn production (USDA ERS 2014).

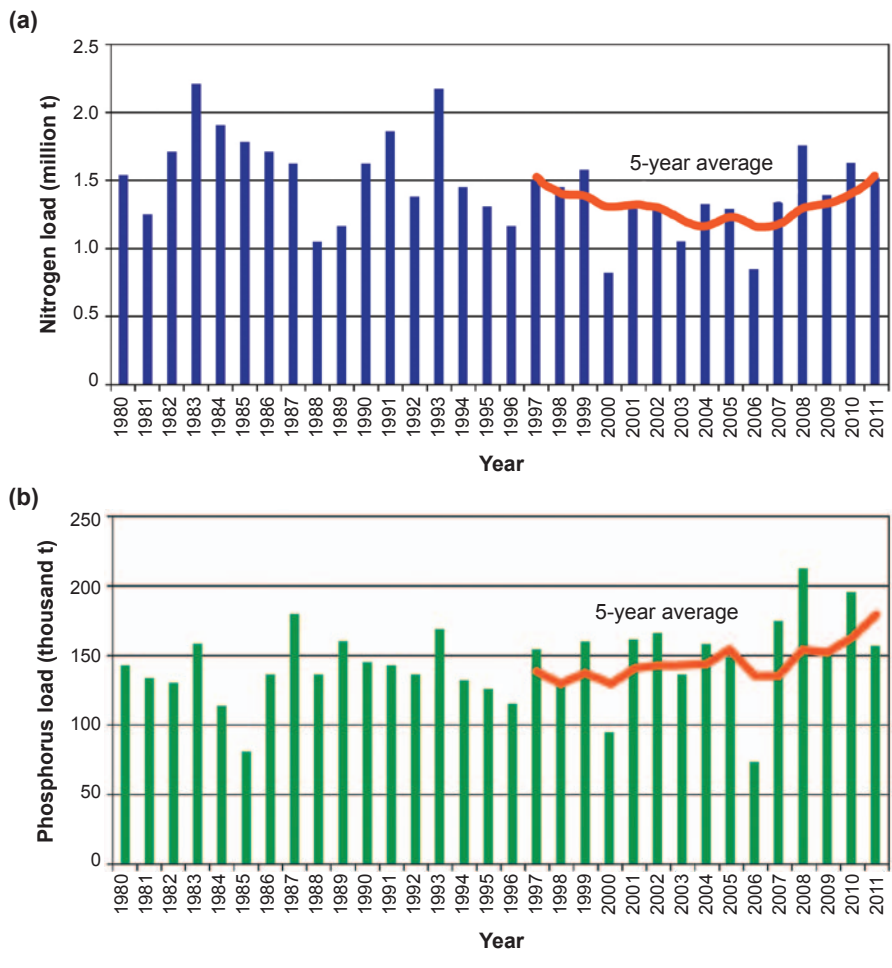
To moderate these impacts, the RFS was amended under the Energy Independence and Security Act of 2007 to incent cellulose-based biofuels (i.e., perennial grasses, wood chips, or agricultural residues). The law allowed for GHG emissions from traditional starch-based (i.e., corn) and advanced cellulose-based fuels to be compared. Typically cellulosic biofuels require less fertilizer and pesticides, less tillage, and have lower net GHG emissions compared to corn-based biofuels (Fargione et al. 2008).

It is anticipated, or at least hoped by many, that as new, advanced biofuels and bioproducts are commercialized, the United States will see an increase in perennial bioenergy crops on the landscape (Mitchell et al. 2010). A watershed-scale working-lands strategy, based on perennial cropping systems may be among the most practical ways to achieve the large agricultural nutrient reductions necessary for addressing hypoxia. It has been suggested that such a strategy, implemented in the Mississippi River Watershed, would reduce nutrient loading, improve the resiliency of midwestern cropping systems, and help mitigate Gulf hypoxia (Simpson et al. 2008; Davis et al. 2012; Smith et al. 2013; Zhou et al. 2014).

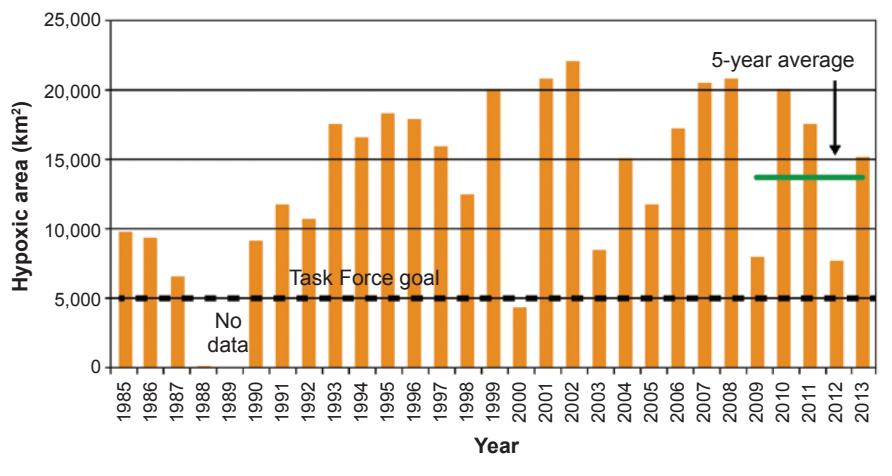
Addressing the diversity of agricultural fields in terms of the amounts of nutrient runoff, perennial grasses could be targeted to "hot spots," portions of farms that have greater slope, more moisture, or more erodible soils and contribute more nutrient runoff than other areas. They could be planted strategically to "sculpt the landscape," adding diversity

Figure 3

Annual total (a) nitrogen and (b) phosphorus loading into the Gulf of Mexico (USEPA 2013).

**Figure 4**

The size of the Gulf of Mexico Hypoxia Zone, 1985 to 2013. Defined by dissolved oxygen (<math> < 2 \text{ mg L}^{-1}</math>) in bottom water (USEPA 2013). Image courtesy of N.N. Rabalais (Louisiana Universities Marine Consortium) and R.E. Turner (Louisiana State University).



to the problems caused by large, single crops planted fence-row to fence-row. Perennial energy grass mixtures, or strips of perennial grasses, could be established in large zones throughout the Mississippi River Watershed, targeting acres that are more prone to flooding or that may leak nutrients, such as along waterways or in contour strips on steep slopes, providing a new source of income while improving the environmental performance of mid-western farms.

SUSTAINABLE BIOENERGY RESEARCH

The United States has made major investments into research on perennial-based bioenergy. The US Department of Energy has established three national bioenergy research centers to foster breakthroughs in advanced biofuels. USDA's National Institute of Food and Agriculture awarded US\$157 million in grants to support seven regional, sustainable bioenergy coordinated agricultural projects (CAPs). Their goal is building regional, sustainable bioenergy systems that "integrate research, education, and extension/tech transfer to lead to real-world outcomes." Three of the seven CAPs, in the central, southeast, and northeast United States, focus on perennial grass-based biofuels and bioproducts.

One of the CAPs, "Central USA Agro-Ecosystem approach to Sustainable Biofuels Production Via the Pyrolysis-Biochar Platform" (CenUSA), is investigating a biofuels system that converts perennial grasses into bio-oil via fast pyrolysis technology. The five-year research project, involving eight institutions led by Iowa State University, is evaluating perennial prairie grasses native to the central United States, including switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogon gerardii* Vitman), and indiangrass (*Sorghastrum nutans* [L.] Nash).

A research goal of CenUSA is to develop a detailed set of models for the upper Mississippi River Watershed that will link land use decisions to nutrient loading into the Gulf. Greater detail is being added to the Soil and Water Assessment Tool models for the Upper Mississippi, Upper Ohio, and Tennessee River basins using US Geological Survey subwatershed information. The models will evaluate

the placement of switchgrass and other perennial bioenergy grasses to optimize economics, water quality, C, and ecosystem services at the landscape scale. They will allow the analysis of impacts from perennial grasses restricted to marginal lands or certain fields and the effects of different soil types. The research will help policymakers, farmers, and the bioenergy industry make more informed decisions about which perennial bioenergy feedstocks to grow, where to plant them, what environmental impacts they will have, and how biomass production systems are likely to respond to and contribute to climate change or other environmental shifts. These models can also assess the potential for cellulosic feedstocks to reduce the frequency and magnitude of flooding.

SUMMARY

Forty years after the passage of the CWA, industrial pollution has been significantly reduced, but billions of pounds of agricultural nutrients still flow into the Mississippi River Watershed each year and are deposited into the Gulf of Mexico. Despite valiant efforts, voluntary conservation practices haven't worked well enough, fast enough, or at the scale needed to improve the Mississippi River waters and reduce Gulf hypoxia. Will we continue to subsidize farming practices that maximize commodity production at the expense of water quality and then pay for conservation measures to mitigate the environmental effects of those practices? Could the environmental benefits attributed to perennial grasses improve the efficiency and resiliency of midwestern agricultural cropping systems and enable rapid and measurable nutrient reductions to the Mississippi River Watershed and the Gulf of Mexico?

Perennial grass-based biofuels and bio-products provide opportunity to integrate perennial grasses back into agricultural systems, at a landscape scale and achieve significant water and ecosystem service benefits. They could be targeted strategically, offering a tool for landowners to stabilize areas of their farm that are environmentally sensitive, fields that are adjacent to waterways, or that are steeper, wetter, more erosive, or that may be mar-

ginally profitable for row crops. Planting perennial prairie grasses or prairie grass strips could be an effective strategy for nutrient removal and enhanced environmental performance while still farming a majority of the field. In addition, perennial grasses could serve a dual purpose for grazing cattle.

In a time of constrained federal and state budgets, a key attraction of perennial grass-based biofuels and bioproducts may be its "working lands" approach to conservation. Building new market demand could allow perennial grasses, once native to the central United States to be reestablished on lands that are better suited to perennial production. In short, perennial grasses for bioenergy is a market-driven agricultural system that provides conservation benefits as an outcome, rather than direct payment to landowners for conservation as an add-on.

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