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Review

Convergence of agricultural intensification and climate change in the Midwestern United States: implications for soil and water conservation

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Abstract. Society faces substantial challenges to expand food production while adapting to climatic changes and ensuring ecosystem services are maintained. A convergence of these issues is occurring in the Midwestern United States, i.e. the 'cornbelt' region that provides substantial grain supplies to world markets but is also well known for its contribution to hypoxic conditions in the Gulf of Mexico due to agricultural nutrient losses. This review examines anticipated trends in climate and possible consequences for grain production and soil resource management in this region. The historic climate of this region has been ideal for large-scale agriculture, and its soils are among the world's most productive. Yet under current trends, degradation of the soil resource threatens our capacity to ensure a stable food supply and a clean environment in the face of a changing climate. A set of strategies and practices can be implemented to meet these challenges by maintaining and improving hydrologic and plant-growth functions of soil, which will improve outcomes for aquatic ecosystems and for the agricultural sector. Soil management ensures our long-term capacity to provide a reliable food supply, and mitigates pressures to expand agricultural practices into marginal croplands that would lead to further environmental degradation.

Additional keywords: agroecosystems, food security, hypoxia, soil management.

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Introduction

As the human population expands in the coming decades, the need to provide a stable global food supply and access to safe water supplies will continue to garner increasing attention. As one of the world's largest commodity producers, the United States' agricultural industry will have a critical role in determining society's capacity to provide for a burgeoning population. However, the need to expand agricultural production must be met in a way that fully balances the importance of water resources and aquatic ecosystems, both freshwater and marine, as they also provide critical ecosystem services for society. In addition, climate change effects will need to be considered and accounted for, both in terms of maintaining the stability of agricultural production and the resilience of aquatic systems that agriculture can impact. This review is aimed to reinforce the argument that greater soil conservation and soil improvement efforts are needed as the cornerstone of any strategy to meet the critical, interdependent needs for the future of agriculture and the sustainability of ecosystem services provided by agricultural and aquatic systems.

Soil inherently filters and slows rainfall as it moves through the landscape towards aquatic systems. Soil also has the inherent capacity to store water and nutrients for crop production. Therefore, the pivotal role of soils in simultaneously determining the resilience of agricultural and aquatic ecosystems is clear. In the USA, land, and hence soil, is a privately held resource that has a dominant impact on water, which is a public resource. However, both private and public interests are served by encouraging management practices that prevent soil degradation in the long term. Moreover, ensuring optimal soil function will provide the best possible buffer against the extreme weather events that our changing climate may bring, and help mitigate effects of climate change on both agriculture and aquatic systems. This review provides an overview of present-day agricultural systems in the USA, the role of soil in ensuring the productivity of those systems, and impacts on water quality and aquatic ecosystems that may in fact result from changes in our soil resource.

Agricultural production in the United States

Role of USA and Midwest agriculture in global food production

Agriculture in the United States is complex, producing over 200 different commodities with a value of over US$300 billion each year. The market value of USA agriculture is distributed across

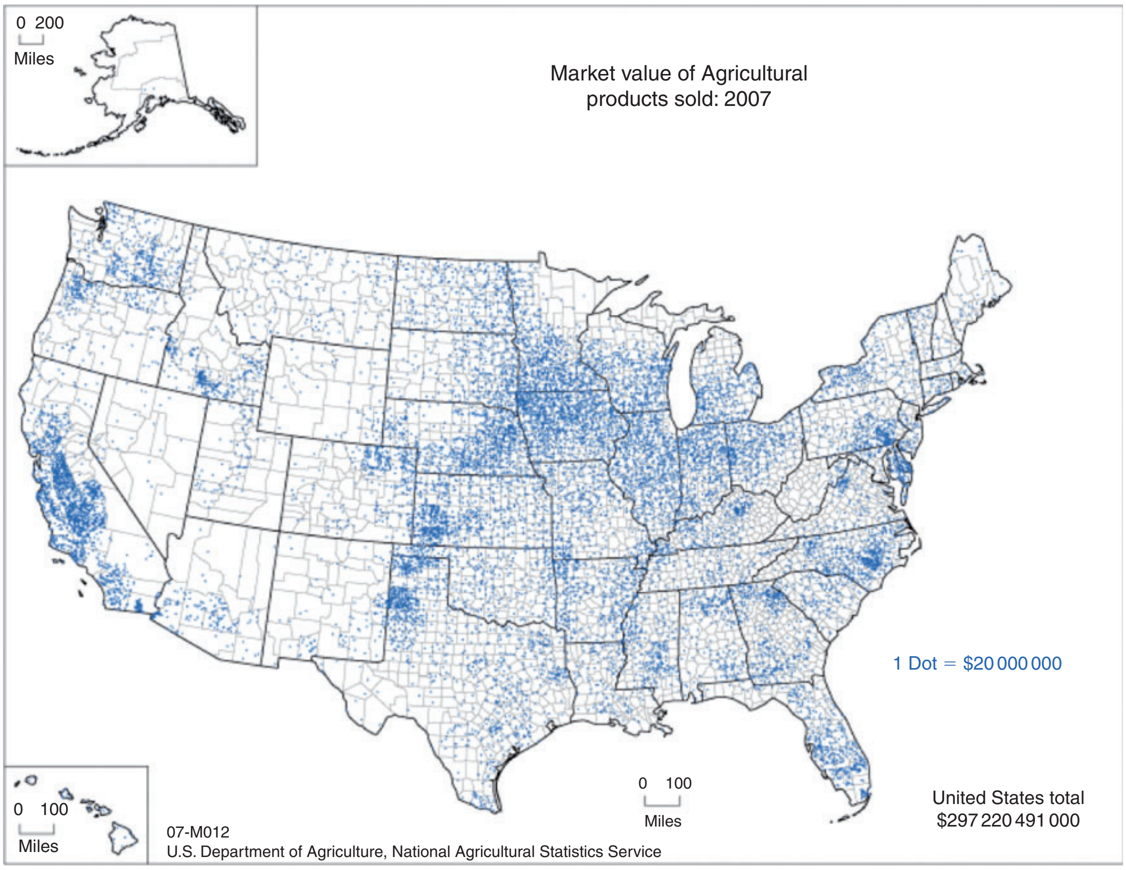

Fig. 1. Market value of agricultural products sold across the United States in 2007 (US Department of Agriculture – National Agricultural Statistics Service, 2009).

the USA as shown in Fig. 1 with the central Valley of California and the upper Midwest (north-central states) being two of the more concentrated areas in terms of market value. The Midwest represents a large portion of the USA agricultural production system as evidenced by state production rankings (Table 1). Across these states, corn (*Zea mays*) and soybean (*Glycine max* (L.) Merr.) are the primary crops and are the top two exports from the USA. During the past 40 years, these agricultural exports have contributed to a positive balance of agricultural trade (Fig. 2), with exports from the USA providing large grain supplies into world markets. However, annual row-cropping systems in the Midwest, implemented across large areas with artificial drainage systems ($>20 \times 10^6$ ha by 1930, according to McCorvie and Lant 1993), have resulted in large amounts of nutrients being transported via the Mississippi River to contribute to hypoxic conditions in the northern Gulf of Mexico (Burkart and James 1999).

Trends in commodity production

Agricultural production has steadily increased since 1940 for grain crops across the USA. Part of this increase in production is due to the use of technological advances, including enhanced genetics, use of commercial fertilisers, and crop protection chemicals. Although production has increased, instability in yield exists among years because of weather variability and its impact on crop growth. Hatfield (2011) evaluated these trends in crop yields to determine the effect of climate variation on crop yields. Corn production varies largely with summer precipitation; below-normal rainfall in the Midwest causes most of the deviations from the trend of increasing yields (Fig. 3). Soybean production is dominantly grown in rotation with corn in the Midwest, and yield variation follows a similar pattern to corn (Fig. 3). Wheat (*Triticum aestivum* L.) production has varied, with several years showing reduced production compared to prior yields, due to limited precipitation across the plains states, and late frost in the north-central plains (Fig. 3) (Hatfield 2011). Rice, also an exported grain, has shown less variation as it is flood-(irrigated) and water availability is not a limiting factor (Fig. 3). These trends are found in other crops (www.agcensus.usda.gov), although spring crops generally show less variation among years because drought stress impacts are rarer in spring than summer.

Role of biofuels in cropping trends

With the drive to provide domestic energy sources in the USA, recent years have seen substantial increases in corn acreages to provide feedstock for ethanol production. During 2000–10, ethanol production in the USA increased from 6.0 to 40.8 billion litres (US Department of Energy, Energy Information Administration 2010). To support this increase, corn acreage expanded by

Table 1. Commodities produced and state rank for the Midwest region of the United States
Source: USDA, National Agricultural Statistics Service

Commodity	Illinois		Indiana		Iowa		Michigan		Minnesota		Ohio		Wisconsin	
	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank
Livestock (millions of animals)														
Layers	5.3	18	24.2	3	53.8	1	9.0	14	10.6	11	20.1	2	4.9	19
Hogs and pigs	4.3	4	3.7	5	19.3	1	1.0	14	7.6	3	1.8	10		
Pullets	0.9	28	6.9	5	11.4	1	2.0	16	3.2	12	6.8	6	1.2	22
Turkeys	0.8	19	6.0	7	4.0	9	2.0	16	18.3	1	2.0	14	3.7	10
Cattle and calves	1.2	26			3.9	7	1.0	30					3.4	9
Broilers			5.5	23					8.6	21	10.0	20	7.1	22
Milk and other dairy products from cows ($100,000)														
	340.3	20	583.2	14	689.7	12	1285.6	7	1475.9	6	861.3	11	4573.3	2
Crop production (1000 ha)														
Corn for grain	5300.0	2	2574.9	5	5614.1	1	951.3	11	3157.1	4	1459.4	8	1315.6	10
Soybean	3356.5	2	1936.0	4	3485.6	1	694.3	12	2539.0	3	1714.4	6	551.6	15
Forage	240.1	32	221.3	33	455.5	23	469.6	21	964.7	15	468.0	22	1132.1	7
Corn for silage			42.9	17	89.3	8	120.3	7			74.0	11	296.5	1
Oats for grain					27.0	7								
Wheat for grain	360.8	12	146.7	19			211.7	17	691.4	10	296.3	15		
Sorghum for grain	31.0	11												
Sugar beets for sugar									196.5	1				
Vegetables													120.3	4

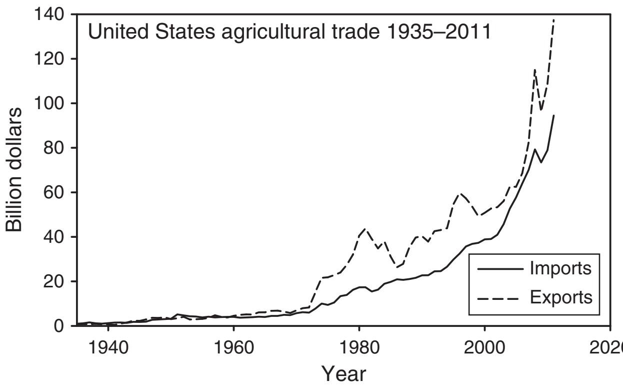

Fig. 2. Import and export of agricultural commodities of the United States from 1935 through 2011. Source: www.nass.usda.gov/quickstats.

3 million hectares to total 38 million hectares in 2012. Much of this increase occurred in the Midwest at the expense of soybean acreage, but nationwide soybean acreage also increased by 1.6 million hectares through expansion in the northern plains states (Wallander *et al.* 2011). This expansion of soybean production is partly due to improved crop genetics and partly due to warmer spring weather in this region, consistent with a warming climate. Concordant with expansion of these two major crops, other crops have declined, particularly small grains, cotton and hay. The Midwest states have shown increased acreages with consecutive years of corn. The trend of increased corn-on-corn acreage increases the risk of nitrogen (N) leaching loss. Nitrogen fertiliser rates may be increased by producers to account for the likelihood of wet spring weather conditions, and decomposition of the prior year's corn crop also consumes mineral N leading to larger N rate recommendations under a continuous corn rotation compared to the corn–soybean rotation (Sawyer *et al.* 2006). Donner and Kucharik (2008) illustrated how expanded corn acreage in the Midwest increases potential risks for nitrate-N losses to the Mississippi River and the Gulf of Mexico. Despite these expanded acreages, large grain surpluses in the USA seem a thing of the past, and the trend of increasing biofuel production has led towards the recent intensification of row-crop agriculture.

Climate trends in the United States

Climate has been changing in the USA throughout the past 100 years and across the USA there has been regional variation in this change, as shown by Karl *et al.* (2009). The regional variations have occurred in temperature and precipitation. The expectation for the next decades is that the variation in both temperature and precipitation will increase on daily, monthly, and annual scales.

Temperature

Projected temperature increases for the USA vary depending on which emission scenario for greenhouse gases is used in climate simulation models (Karl *et al.* 2009). Projected temperature increases range from 1.0 to 1.5°C over next 20 years to 3–5°C by 2100 (IPCC 2007). Projected changes in the summer temperatures for the USA are shown in Fig. 4. These changes are projected to include a strong trend of increasing minimum temperatures rather than maximum temperatures, and an increase in the occurrence of extreme heat events (Karl *et al.* 2009). The frequencies of extreme events are important to agriculture because of the stress on both plants and livestock production. Clearly, extreme summer temperatures will have more negative impacts than unusually warm temperatures during autumn or winter.

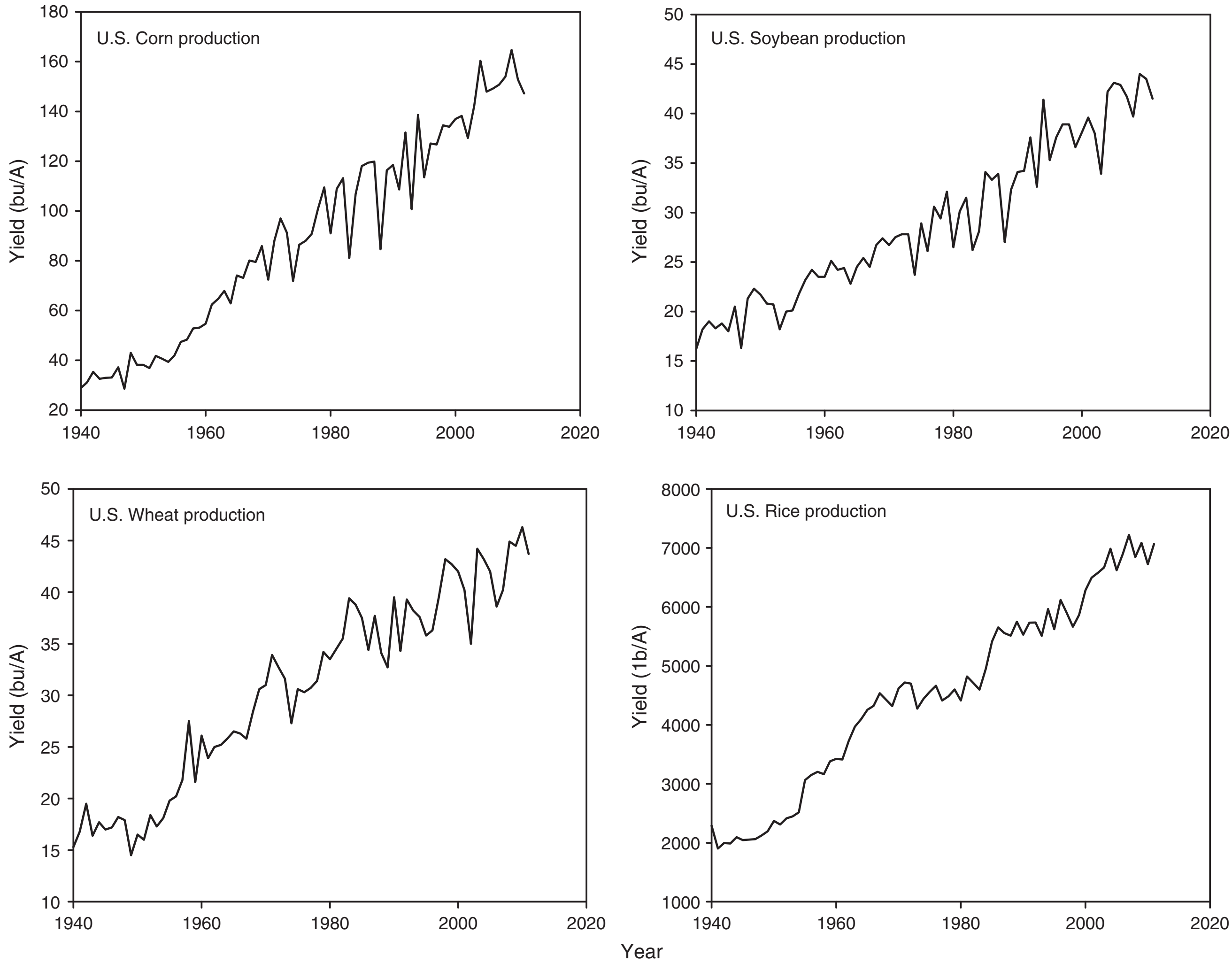

Fig. 3. Trends in corn, soybean, wheat, and rice yield for the United States from 1940 through 2011. Source: www.nass.usda.gov/quickstats, accessed 2 May 2012.

Precipitation amounts and frequency of large events

Precipitation is the most variable climatic parameter. Over the past 100 years, there has been a large amount of annual variation, as illustrated for Ames, Iowa (Fig. 5). However, annual precipitation doesn't reveal as much variation compared with seasonal changes; Karl *et al.* (2009) projected that a shift in the seasonal patterns should be anticipated with a tendency towards a greater frequency of extreme precipitation events. Projections from an ensemble of climate models suggest that the upper Midwest should become wetter in the spring, but that the whole USA should expect drier summer months. These changes are already evident in the record with increased spring precipitation across the Midwest, typified by the observations from Ames, Iowa (Fig. 5). The greater spring precipitation has decreased the number of days for agricultural field operations by 3.5 days, when comparing the average from 1994 through 2010 to the period from 1979 to 1993. This trend puts pressure on spring planting operations and increases the risk that operations will occur when soils are too wet, which poses a long-term threat to the hydrologic functioning of soils due to the risk of compaction.

There has also been a marked increase in the number of days across the Midwest with 'heavy' rainfall (defined for this region as more than 30 mm in a 24-h period). The number of days per year falling into this category has more than tripled in the past 50 years. These events are linked with increasing spring precipitation and occur when cropped fields typically have the least amount of ground cover, therefore, increasing the risk of erosion.

Drought

Drought carries different definitions and thresholds depending upon the region and whether hydrologic or agricultural impacts are of concern. The frequency of drought is expected to increase in the coming decades, concordant with decreased precipitation being projected during summer months. Drought could also occur when precipitation is inadequate to recharge reservoirs for irrigation, which is of greatest concern in the western USA where below-average mountain snowpacks are becoming more common due to increased climate variability. The impact of agricultural drought depends on soil conditions that influence soil water storage capacities. Maintaining soil organic matter levels is

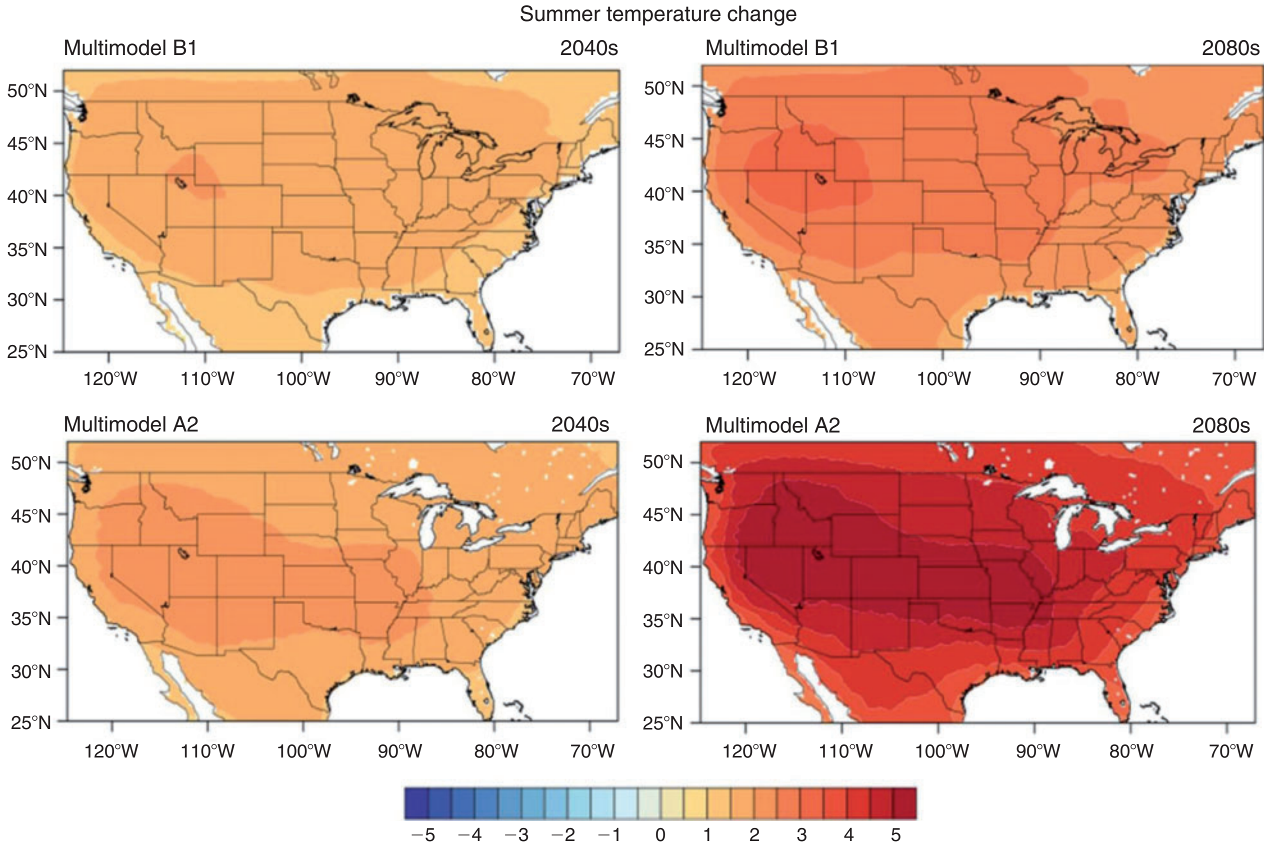

Fig. 4. Projected changes in summer temperatures in the USA for the 2040s and 2080s, based on two differing scenarios of atmospheric CO2 increase (i.e., B1 and A2) using a multimodel approach. Source: National Center for Atmospheric Research, CMIP3 results (Meehl *et al.* 2007).

critical to maintain water holding capacities. If degradation of soil leads to limited water holding capacity, then more frequent precipitation will be required to recharge soil water available for crop uptake. The expected trend towards drier summers reinforces the importance of practices that enhance soil organic matter contents (outlined below), as this will increase agriculture's resilience in drought situations. Projected trends of increased variation in precipitation and more frequent extreme events will also result in lesser impacts where soils are least degraded.

Variability in temperature and precipitation is expected to increase over the next decades, for all seasons of the year. Agriculture will have to contend with this increased variation as part of the production system. In order to cope with these changes, adaptation practices will have to be implemented to reduce the potential stress on the agricultural system. Some of the options have been provided in a recent review by Easterling (2011).

Vulnerability of USA agriculture to climate change

Agriculture is a complex system and has shown itself to be extremely fluid in adapting to climate change (Hatfield *et al.* 2008). Producers have continually adapted management practices in response to changing climate through the use of longer-maturing crop varieties, earlier planting dates, or changing the type of crop altogether. The impact of climate change on agriculture has been detailed in recent reviews, for crops by Hatfield *et al.* (2011) and for pasture and rangeland by Izaurralde *et al.* (2011). These reviews detail the responses of agricultural systems to climate change and discuss potential future adaptation strategies. Evidence for the increasing impact of climate on agriculture has been the marked increase in crop loss over the past 15 years related to climate events, e.g. floods, droughts, hail, and freezes (Table 2). Climate change has already been implicated in reducing crop yields of wheat and maize globally (Lobell *et al.* 2011). The heat wave experienced by Russia in 2010 imposed a significant food security concern (Wegren 2011) and moved world grain markets rapidly upward; crop prices rose rapidly and have remained high. Increasing climatic variation may continue to occur in the next decades, threatening to exacerbate the recent variability in production.

Implications of warmer temperatures

Increasing temperatures will affect all aspects of crop production. The detailed reviews by Hatfield *et al.* (2011) and Izaurralde *et al.* (2011) provide insights into the impacts of temperature on crop growth and development. Hatfield and Prueger (2011) described how temperature increases tend to increase crop water use, assuming adequate soil water. Where soil water is inadequate, crop water stress will lead to decreases in crop growth and yield. Crops with genes that increase drought resistance may help minimise this impact, but poor soil management will exacerbate it.

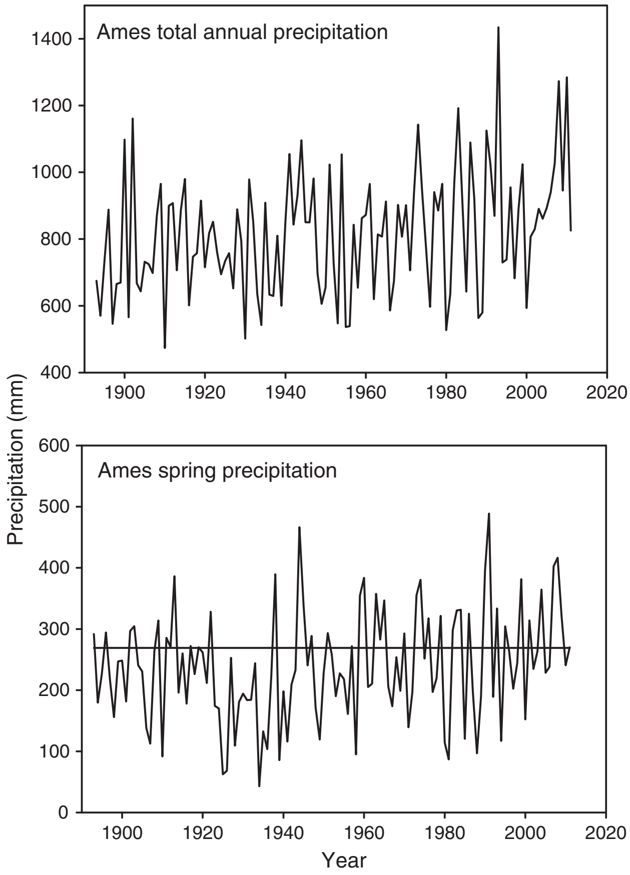

Fig. 5. Total annual precipitation (top) and annual spring precipitation (bottom) for Ames, Iowa, from 1893 through 2011. Mean annual precipitation over the period is 812 mm. Source: Iowa State University, Climate Science Program.

One impact that has not been fully considered is the role of the increasing minimum temperatures on crop growth and development. Warmer overnight temperatures are likely to hasten the phenological development of plants, leading to smaller plants and decreased yields. This negative impact of increased night-time temperatures on crop growth and yield may, in fact, be more detrimental than increased daytime temperatures. The effect of minimum temperatures on plant growth has been observed in the small grains (Prasad *et al.* 2008): night-time temperatures above 20°C decreased kernel size and counts of grain for wheat and rice (*Oryza sativa* L.). In the Midwest USA, temperature effects on pollination and kernel initiation in corn may become critical. Photosynthesis in corn is optimum at 33°C but reduced above 38°C (Crafts-Brandner and Salvucci 2002). Pollen viability decreases at temperatures above 35°C (Herrero and Johnson 1980; Schoper *et al.* 1987; Dupuis and Dumas 1990). Corn plants exposed to temperatures above 30°C have shown impacts on cell division, grain kernel development and yield (Commuri and Jones 2001; Jones *et al.* 1984). In soybean, night air temperatures above 23°C reduce seed growth, and crop pollination has shown declines above 30°C (Baker *et al.* 1989; Salem *et al.* 2007). Increasing temperatures at night affect all plants, affecting fruit quality along with quantity.

Intensive agriculture requires management of pest and nutrients and the production increases shown in Fig. 3 would not be possible without advances in all aspects of crop management. Further increases in production will require that effects of climate change on agricultural pests be fully understood and addressed. The expectation is that warmer winter temperatures will increase the ranges of many insects and diseases. Invasive weeds may become more problematic where climate change increases the physiological stresses on cultivated crops and pasture/range grasses. The result may be greater use of agrichemicals to control weeds, insects and diseases with accordant risk of their loss to aquatic systems.

Livestock are often overlooked when assessing the impact of climate change on agriculture. The increased potential for extreme temperature events, both cold and hot, will place a stress on animal production (Mader *et al.* 2009). Extreme temperatures disrupt animal metabolism and more energy is needed to maintain core body temperature. The result is reductions in rate of gain for meat, milk, or egg production. This impacts feed utilisation, meaning that more grain may be required to maintain animal production.

Direct effect of increased CO_2

Concentrations of CO_2 continue to increase and have reached levels not experienced in recorded history, with the expectation for concentrations to reach 450 μmol mol^{-1} by the mid to late 21st century. Increasing CO_2 has a positive impact on plant growth and has been shown to decrease crop water use (Bernacchi *et al.* 2007). The effects of increasing CO_2 somewhat offset the negative impact of increasing temperatures. Fleisher *et al.* (2011) discussed interacting effects of temperature and CO_2 on crops. One concern, however, is that weed species are showing larger growth responses to rising CO_2 than many crops and this increases the potential problem with weed management in future agricultural systems. Understanding of how crops will respond to climate change will not be adequate until the interacting effects of increasing CO_2, changing temperature, and water availability are known. Research on these interactions may be critical to developing effective adaptation strategies to cope with climate change.

Implications of increased precipitation amounts and variability

Water is critical to agricultural production, whether from precipitation and/or irrigation – the sufficiency and stability of the water supply determines agricultural productivity. The increased variability in precipitation and even the form of precipitation, i.e. rainfall versus snow in the western USA, will impact production because the timing of snowmelt in early summer determines irrigation supplies. Lettenmaier *et al.* (2008) discussed the implications of climate change on the water resources of the USA and the implications of the seasonality changes in precipitation. These changes also have implications for the conservation of soil resources, as discussed below.

Soils: a changeable resource in a changing climate

The fact that a civilisation's survival depends on soil is now becoming recognised. There are multiple examples of civilisation collapse due to degradation of soil resources (Hillel 1991;

Table 2. Extreme event, location, and economic impact for the United States
Source: National Climate Data Center, 2011

Year	Event	Location	Economic impact on agricultural sector (unless noted as Total) (2011 $, Billions)
2011	Upper Missouri River flooding	Upper Midwest (MT, ND, SD, IA, KS, MO)	2.0
2011	Mississippi River flooding	Lower Mississippi River (AR, TN, LA, MS, MO)	1.9 (3–4 Total)
2011	Heat/Drought	Southern Plains/South-west	10.0
2009	Drought	South-west/Great Plains (TX, OK, KS, AZ, NM, CA)	5.3
2008	Drought	South and West (CA, TX, GA, TN, NC, SC)	2.0
2008	Flooding	Upper Midwest (IA, IL, IN, MO, MN, NE, WI)	15.8 Total
2007	Drought	Great Plains and Eastern USA	5.5
2007	Freeze	East and Midwest USA	2.2
2007	Freeze	California	1.5
2006	Drought	Central USA	6.7
2005	Drought	Central USA (AR, IL, IN, MO, OH, WI)	1.2
2003	Storms and hail	Southern Plains and lower MS valley	1.6
2002	Drought	30 states, Western, Great Plains, and Eastern USA	12.5
2000	Heat/Drought	South-Central and South-eastern USA	5.2
1999	Heat/Drought	Eastern USA	1.4

Montgomery 2007*b*), as healthy soils perform multiple life-supporting ecosystem services that are critical to society. Soils serve as the growth medium for plants and food production; soils also sequester carbon, store water and nutrients for plant uptake, act as a filter to maintain the quality of water resources, and host an abundant diversity of microbial species, insects and arthropods. Given their biological diversity and physical–chemical properties, soils also decompose organic materials and provide treatment of wastes that are applied to land.

These beneficial soil properties and their potential to provide ecosystem services vary across and among landscapes, and often dramatically. Soil properties exhibit considerable spatial variability, across the landscape, and vertically within the soil profile. The uppermost layer of surface soil (the A horizon) typically has the greatest organic matter content and nutrient availability. This is the layer most affected by atmospheric conditions and processes, and is also most impacted by human activities, with agricultural activities being particularly important. Agriculture covers ~37% of the earth's land surface (United Nations Food and Agricultural Organization 2003), and these areas typically exhibit the most productive soils that are critical to the global food supply. Prior to agricultural settlement, today's agricultural soils were covered by perennial vegetation that protected the soil surface. However, today's agricultural systems replaced the perennial cover with annual crops. To efficiently produce food from these annual crops, soils have been tilled, and amended with fertiliser, manure, and several agrichemicals. These activities expose the soil surface to the forces of weather to a much greater extent than occurred under native perennial vegetation. As a result, transport of eroded sediment and agricultural amendments from farmed soils affect wide areas including riparian lands, and freshwater and marine aquatic systems.

Climate effects on soil

There are combinations of climate and soils that have historically provided the full suite of ecological services upon which each unique human culture has been based, including food production, water supplies, and other benefits. However, climate and soils both are subject to change in space and time. Because climate is a fundamental factor impacting the course of soil formation (Jenny 1941), change in climate is certain to directly and indirectly impact soils, and therefore food production. There is often a focus on direct climate factors, such as increasing frequency of high-intensity storms (Karl *et al.* 2009), as the key driver affecting soil resources. And while the connection between extreme climatic events and accelerated soil degradation is clear (Lal and Stewart 2012), indirect effects of climate change may be a more dominant factor affecting soil resources, and one that needs greater recognition (Table 3).

Higher commodity prices have resulted from biofuel production and disruptive weather events, and in turn farmers modified practices, attempting to capture profits resulting from the climate-influenced grain market. As commodity prices increase, the cost associated with compensating farmers for implementing conservation practices increases dramatically. Practices that provide soil conservation by placing highly erodible land under perennial cover, into programs such as USDA's Conservation Reserve Program, become much less popular with farm producers (Secchi *et al.* 2008). The result is exposure of larger areas of vulnerable soils to rainstorms of increasing intensity and frequency (Karl *et al.* 2009), which obviously threatens aquatic resources. Soil erosion increases by a factor of ~1.7 relative to increased rainfall rates (Nearing *et al.* 2004). Therefore, reduced surface cover and increased soil disturbance associated with farmers attempting to capture greater profits, coupled with elevated frequency of extreme rainfall events, is particularly troublesome. As farmers expand acreage by converting conservation cover to annual row cropping, as corn acreage expands, and as weather gets wetter, producers have a smaller window of time to plant more acreage. This time pressure leads to less care for soil protection and landscape management considerations. The time it takes to farm around grassed waterways and chronically wet spots becomes more inconvenient for famers,

Table 3. A summary of climate-change trends and impacts on soils in the USA Midwest, with potential consequences for aquatic ecosystems

Although milder winters provide a few mitigating effects (upward arrows), other weather trends have deleterious effects (downward arrows) on soil and aquatic resources and could exacerbate potential soil quality problems. Specific conservation practices that can mitigate impacts of each climate change trend are listed in the right-most column

Climate change effect on weather	Direct responses of farm producers and/or commodity markets	Direct effect on soils and crops	Indirect on-site effects	Impacts on: Soils and crops	Impacts on: Aquatic ecosystems	Conservation practices that can reduce effects and mitigate impacts
Wetter Springs	Pressure increases to conduct spring field operations on wet soils	Soil compaction	Increased runoff, decreased infiltration Increased soil resistance to root growth	↓ Poorer soil conditions	↓ Flashier streams	Winter cover crops, Perennial vegetation in areas prone to runoff and inundation Wetland restoration
More frequent high-intensity rain events		Surface sealing due to raindrop impacts. Storm damage to crops	Increased runoff, decreased infiltration	↓ Poorer soil conditions ↓ Decreased yield	↓ Flashier streams	Minimal tillage (no tillage or zonal tillage) Contour strips Filter strips
Warmer soils		Increased rates of soil organic matter decomposition	Decreased capacity of soils to hold water and nutrients	↓ Poorer soil conditions, decreased yields	↓ Flashier streams, Eutrophication	Cover crops, Rotations including perennials
More frequent drought stress and flooding of crops	Increased commodity prices due to pressures on grain supply		Marginally productive lands taken from conservation cover into row-crop production	↓ Less stable production	↓ Sensitive sites removed from conservation cover reduce habitat and stream buffers	Use of rotational crops or faster maturing crops to spread production risk
Milder winters	Earlier planting	Longer growing season Less soil freezing	Rain on snow runoff events become rarer Increased nitrification if fertiliser fall applied Increased survival of insect pests and diseases	↑ Increased production ↑ Could reduce soil erosion ↓ Greater N leaching ↓ Production less stable, more costly	↑ Could reduce eutrophication ↓ Eutrophication	Winter cover crops Improve timing and rate of fertiliser application Crop rotation Integrated weed/pest management

creating more pressure to increase subsurface drainage and farm through ephemeral waterways. These trends deter farm producers' natural motivation to protect soil and water resources through conservation.

Soil organic matter

Soil organic matter (SOM) is highly dynamic and is a critical soil constituent that enhances soil quality, agricultural productivity, soil ecosystem function, and the hydrologic behaviour of soils. The water storage capacity of soil increases with SOM content; Hudson (1994) showed that a 1% increase in SOM increased soil water storage capacity by 3.2–4.7%, on a soil volume basis, depending on soil texture (i.e. relative proportions of sand, silt, and clay). This means that in a 30-cm-thick surface horizon, a 1% increase in SOM will increase water storage by up to 14 mm, therefore potentially decreasing runoff volume from any given precipitation event. This has huge implications for flood hydrology and delivery of runoff-carried contaminants to streams and rivers in agricultural watersheds.

Whether SOM is accumulated or lost over time depends on the net balance among climatic factors and a set of soil processes that are impacted by management practices. Organic matter increases occur where conditions are favourable for growth of plants, as decaying plant material is the source of most organic matter found in soils. In contrast, two critical climate-dependent processes influence SOM loss: SOM oxidation and soil erosion. Processes impacting both accumulation and loss occur concurrently. The balance between SOM loss and accumulation is therefore influenced by management. Yet, conditions that maximise processes that affect SOM accumulation behave in contrary ways; warm weather increases plant growth that supplies SOM, but also increases rates of microbial decomposition of SOM. The reverse holds true for cold weather. Not only are plant physiological processes affected by temperature (discussed above), oxidation of soil organic matter is also temperature dependent and accelerates as temperature increases. However, unlike plant growth that slows above an optimum temperature, chemical reactions associated with oxidation of SOM double in rate for each increase of ~8–9°C and do not display a temperature optimum. Therefore, temperatures greater than that optimum for plant production increasingly favour net SOM loss (Jenkinson and Ayanaba 1977).

Standing plant biomass is not necessarily an indicator of SOM stocks. Huge stores of SOM are found in northern tundras where plants grow slowly but SOM does not decompose. In contrast, tropical soils can host a standing biomass of plants that is unmatched anywhere in the world, but at the same time contain very little SOM. Temperate zones in the middle latitudes provide our agricultural produce from soils with intermediate SOM concentrations. These temperate regions have had most favourable temperature and soil conditions for plant growth and soil organic matter accumulation will likely experience greater SOM oxidation rates as global temperatures rise. This suggests that degradation of our most productive soils through SOM loss is a distinct possibility. Not only will temperatures likely increase, the seasonal duration of warm temperatures is also expected to lengthen, thereby extending the SOM oxidation period. Most agricultural soils have already lost significant stores of SOM due to aeration by tillage, stimulation of SOM decomposition by fertiliser additions, and erosion (Montgomery 2007*a*).

Water: infiltration versus runoff

As soil degradation proceeds, the loss of SOM not only decreases soil water storage capacity, but the water infiltration capacity of soil decreases, leading to increased water runoff (Bot and Benites 2005). Increasing runoff reduces plant-available water, implying that more frequent and intense periods of plant water stress are likely, resulting in lower yields. Water runoff carries a variety of agriculturally applied and naturally occurring molecules and compounds that degrade water quality. The pollutants found in agricultural runoff include, but are not limited to, sediment, nutrients from fertiliser and manure, pesticides and their degradation products, and potentially pathogenic bacteria in applied manure. The impacts of degraded soils are thereby propagated from agroecosystems to aquatic ecosystems, through runoff losses of materials that are only beneficial (or kept harmless in the case of manure-borne bacteria) when they stay where applied.

While soil degradation negatively impacts agricultural production and water resources, the potential implications of climate change coupled with a degraded soil system are much more serious (Lal and Stewart 2012). As the increased frequency and magnitude of both rainfall and heat/drought events is anticipated (IPCC 2007), the soil's ability to buffer plants from more intense water stress periods and to absorb increasingly intense rainfall will be increasingly necessary. Global trends in soil degradation, however, suggest that our soil resource base is losing its ecological service capacity (UN FAO 2011). Soils are eroding considerably faster than they are forming (Cox *et al.* 2011; Montgomery 2007*a*) and SOM in agriculturally active areas has decreased by 50% or more globally compared to preagricultural conditions (Lal 2004). Of even greater concern, once a soil begins the degradation process, it becomes more susceptible to further degradation. A soil with reduced infiltration capacity has greater runoff potential, leading to increased soil erosion and larger water impairment implications.

Implications for aquatic systems

The challenges to maintaining soil-based ecosystem services under a changing climate also have inherent implications for managing water resources. One implication concerns changes in the hydrology of Midwestern rivers, which have seen increases in average discharge rates during the past 50 years (Schilling and Libra 2003). There is debate as to whether these increases have been mainly caused by changes in climate or agriculture. There are both empirical and modelling studies to suggest that shifts in climate since the 1970s, including increased precipitation and humidity, are responsible for increases in river discharge and nutrient loads (Tomer and Schilling 2009; Nangia *et al.* 2010). However, the corn–soybean rotation became dominant in Midwestern agriculture during the same time and is also associated with water quality changes. Hatfield *et al.* (2009) found that increased nitrate-N concentrations in the Raccoon River since 1970 were related to shifts in crop production that replaced small grains and hay with corn and soybean crops. Combined, these changes result in increased discharge rates and nitrate-N concentrations that are correlated with one another, particularly where agricultural subsurface drainage is extensive (Schilling and Lutz 2007; Tomer *et al.* 2008). In the end, there is a clear implication that recent changes in climate, combined with historical soil degradation, have helped to trigger the hydrologic and water quality changes associated with hypoxia in the Gulf of Mexico.

The hypoxic zone in the northern Gulf of Mexico (Rabalais and Turner 2001; Rabalais *et al.* 2002; United States Environmental Protection Agency 2007) has been linked to agriculture practices through multiple studies, particularly in the Upper Mississippi River Basin of the USA Midwest (United States Environmental Protection Agency 2007). Stream nutrient loads have been repeatedly tied to increased fertiliser applications and broad-based agriculture being practiced across the landscape. Nutrient transport mechanisms are dominated by leaching and subsurface tile drainage of water, carrying nitrate-N (Jaynes *et al.* 2001; Singer *et al.* 2011) and dissolved phosphorus (Jacobson *et al.* 2011), and surface runoff carrying sediment enriched with phosphorus (Kleinman *et al.* 2011). The combined effect of artificial drainage, wetland loss, and agricultural nutrients on Midwest aquatic ecosystems was recently reviewed by Blann *et al.* (2009). If climate change trends continue as projected, expected precipitation patterns will further increase agricultural runoff and its impacts on aquatic systems unless land management practices are adapted to improve soil functions and thereby mitigate these trends.

Debate around hydrology and water quality in the Midwest has also been on the ultimate source of nitrate in the region's surface waters. Because of the large concentrations of organic matter in Midwestern agricultural soils, there is reason to question whether the dominant source of nitrate in the region's surface waters has been from fertiliser or SOM. This debate does not seem essential, because most fertiliser N is taken up by crops and that portion not removed in the grain harvest is cycled back into SOM, and fertiliser N is therefore inherently part of carbon cycling in agricultural soils (Russell *et al.* 2009).

Cycling of C and N in soil–plant systems is complex and mediated by many processes, most of them carried out by soil microorganisms. However, to the extent that nitrate losses originate from native SOM stocks, those nitrate losses represent a net loss of SOM, which carries risks of decreased soil functionality, as described above. Losses of nitrate into the region's streams have commonly been reported to exceed 25 kg ha^{-1} $year^{-1}$ (Schilling and Lutz 2004; Tomer *et al.* 2008). If C : N ratios average 12 : 1 (Karlen *et al.* 2008), then every 5 kg ha^{-1} $year^{-1}$ of nitrate-N that, in fact, originates from native SOM represents an annual loss of 60 kg ha^{-1} $year^{-1}$ of organic C (or ~96 kg SOM ha^{-1}). This is not a rate of SOM decline that can readily be measured in field studies of soils, but it indicates the slow but steady rate of SOM loss that may be occurring in Midwest agricultural soils. Montgomery (2007*b*) proposed that agricultural soils managed through annual tillage can remain productive for, at most, ~500 years given SOM decline that tillage induces. One repercussion of SOM decline is that soil microbes have less capacity to cycle N into SOM reserves that are not readily susceptible to leaching. This trend will decrease the nutrient supply capacity of soils, with consequences of increased risks for eutrophication in freshwater systems and hypoxia in the Gulf of Mexico. Hence debating the source of nitrates leached from soils misses the critical point that losses from both sources need to be minimised if sustaining soil resources and agricultural systems, and protecting downstream water quality are long-term goals.

The cross-dependency of SOM and soil nutrient supply suggests that nutrient management needs to be part of agriculture's strategy for the climate adaptation. Changing precipitation patterns, combined with effects of increasing temperature on plant growth, mean that nutrient uptake patterns will change as agricultural systems adapt to a new climate. The increased susceptibility of nutrients to runoff and/or leaching resulting from climate change needs to be recognised and considered through changes in current nutrient management practices, including better timing of appropriate application rates (Nangia *et al.* 2008), better targeting of fertiliser rates to match the distributions of soil and crop conditions within fields (Delgado and Berry 2008), intensification of plant water use through incorporation of cover crops (Kaspar *et al.* 2007) or perennials (Randall *et al.* 1997), and implementation of conservation practices that are able to trap and treat nutrient losses downstream of cropped fields (e.g. nutrient removal wetlands) (Tomer *et al.* 2012). These practices benefit soil quality as well as water quality. Table 3 lists climate change impacts on soil and water resources, and suggests specific conservation practices that can help mitigate each impact. Baker *et al.* (2012) have gone further to suggest that perennial crops be combined with well engineered water management systems, which would allow spring drainage volumes (which are projected to increase) to be stored and subirrigated during summer (which are projected to be warmer and drier), thereby helping agriculture adapt to emerging food security, environmental, and climate change issues. Delgado *et al.* (2011) discussed the opportunities for agriculture to mitigate climate change through conservation practices that can sequester carbon, reduce greenhouse gas emissions, and conserve the energy resources expended in agricultural production. Their review focused on management of crop residue and SOM, use of perennials and diversification of crop rotations, development of technologies to target practices, capture nutrients, and reduce emissions, and obtaining synergy from complementary conservation efforts including agroforestry and riparian practices. These assessments all suggest that there is no single solution; rather, integrated practices and landscape-specific solutions offer the best opportunity to maintain the productivity and enhance the environmental performance of agriculture under a changing climate.

Soil conservation practices (e.g. minimal tillage, grassed waterways, contour filter strips) that control soil erosion in fields can have wide benefits for aquatic systems, including even stabilised discharge. With increasing variability in climate, impacts of flood and drought on aquatic systems should be anticipated. However, reduced tillage (specifically ridge tillage) has been shown in a long-term small-watershed study to increase average stream discharge while decreasing its variability (Tomer *et al.* 2005). Thus, wider efforts in agricultural conservation could provide some stabilisation of flows through aquatic systems under increasingly variable precipitation patterns.

A final point concerns the linkage between agricultural conservation practices and the conservation of river corridors and aquatic habitat. Studies that have evaluated sources of sediment in rivers of the central and Midwest USA have concluded that stream bank and bed erosion is a dominant source of suspended sediment (Kessler *et al.* 2012; Wilson *et al.* 2008). This is partly because increases in discharge can increase bank erosion, but also clearly results from historical sediment accumulation, which originated from croplands that were eroded at very large rates in the decades before the soil conservation movement in the USA (before 1940). While the story of changes in Midwestern rivers is somewhat complicated (Simon and Rinaldi 2006), the management of rivers and riparian corridors is germane to management of sediment and water quality in the Midwest. The fact that key ongoing challenges to river corridor management result from agricultural erosion that occurred long ago illustrates the importance of linking management of river corridors and agricultural practices. Climate and land use trends put both soil resources and river corridors at risk, and coordinating efforts to mitigate risks to both upland soils and riparian zones should improve the resilience of Midwestern agroecosystems. This could be accomplished by increasing the role of watershed analysis and planning in active conservation efforts.

Conclusion

Despite the promise that conservation practices hold for adapting to climate change, economic incentives that farmers respond to today do not align well with soil and water conservation goals. Current trends relative to land use and agricultural practices suggest that agricultural management practices are not shifting in ways that will protect the soil and water resources, despite the threats that observed shifts in climate have brought. Rather, current pressures on agricultural producers in the region are towards removing conservation cover wherever economically feasible and increasing annual crop production for short-term economic benefit, at perhaps significant risk to long-term agricultural security (Secchi *et al.* 2008). If these land use trends hold into the future, anticipated changing climate will amplify challenges related to crop productivity and hydrologic functioning of soils, as listed in Table 3. Approaches to meet these challenges through integrated management of soil and water resources within our agricultural landscapes need not only to be recognised, but implemented at broad scales in the coming decades.

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