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A Crop Stress Index to Predict Climatic Effects on Row-Crop Agriculture in the U.S. North Central Region

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Corn (*Zea mays* L.) and soybean (*Glycine max* L.) are major U.S. grain crops with 38.6 million and 31.0 million ha (95.4 and 76.5 million acres) planted in 2013, respectively (NASS 2014a). These two crops support both local demand and international agricultural exports and greatly contribute to the U.S. economy. The value of production for corn and soybean in the United States has increased markedly in recent years and for 2012 was estimated at $77.4 billion and $43.2 billion, respectively (NASS 2014b). Corn accounted for 41% of the value of production of all U.S. field crops in 2012 (NASS 2014b). The United States is the world's largest exporter of corn, exporting 46.6 Tg (1.8 billion bushels) from the 2010 harvest of 317 Tg (12.5 billion bushels) (ERS 2011a). The U.S. North Central Region (NCR) (Fig. 4.1), often called the Corn Belt due to the success of its dominant crop (Hudson 1994), contains some of the most productive cropland in the world, growing over 80% of U.S. corn and soybean. The agricultural importance of this region will only continue to grow as demand for food, fuel, and fiber increases across the globe.

Natural vegetation in the NCR ranges from eastern deciduous forest in the north and east to tallgrass prairie in the central portion to shortgrass prairie in the west (Bailey 1998). Today, much of the NCR has been transformed to croplands (Fig. 4.1). Of its 228 million ha (563 million acres), 39.8% are row crops; corn and soybean account for 34% and 29%, respectively, of this area (NASS 2009a). The Kellogg Biological Station Long-term Ecological Research Site (KBS LTER) lies in the middle of the latitudinal range of the Corn Belt (Robertson and Hamilton 2015, Chapter 1 in this volume) and thus represents the climate stresses typical for row crops such as corn and soybean. The geographic position of KBS provides an
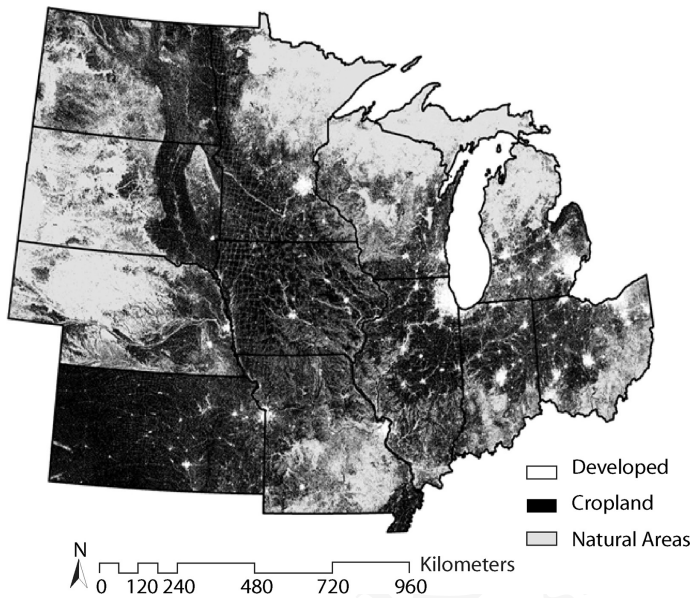
Figure 4.1. Land use or cover in the North Central Region (NCR) of the United States. Created from the USDA NASS Cropland Data Layers (NASS 2009b). States in the NCR include Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.

opportunity to investigate trends and patterns of crop production ranging from local to regional scales within the NCR.

As in any other ecosystem, production in cropping systems is determined by abiotic and biotic factors. Climate, soils, and nutrient availability can be abiotic constraints to producing a profitable crop. Biotic constraints include the yield potential of a given crop cultivar plus potential losses to weeds, insect herbivores, and plant pathogens. Management practices such as tillage, irrigation, fertilizers, and pesticides are attempts to attain crop yield potentials by overcoming limitations of climate, soil fertility, and pests and to favor agriculture in settings where it might otherwise be less productive. These practices have economic consequences for both growers and consumers, and often come at an environmental cost (Matson et al. 1997, Tilman et al. 2002, Robertson et al. 2004).

Climate regulates crop growth and productivity. Heat and precipitation are two important climatic drivers that operate at multiple spatial scales and are the principal physical determinants of crop yield. In this chapter, we present a simple Crop Stress Index (CSI), based on data sets of temperature and precipitation, which captures the main effect of climate on crop yields. We also compare the relationship between CSI and crop yields at county and regional levels. We end the chapter by addressing the implications of climate change projections for row-crop production in the NCR. In an era of incipient climate change impacts (IPCC 2013, Walsh et al. 2014) that will affect the NCR in ways not yet fully understood, it is crucial to have

an understanding of how temperature and precipitation patterns have historically influenced crop productivity. Because trends cannot be understood in the absence of historical context, we begin the chapter with a brief historical background of the NCR, including the rise of corn and soybean as important crops, the industrialization of agriculture, and the advent of agricultural ecology as a scientific discipline.

A Short Agricultural History of the North Central Region

Land Transformation

The western movement of U.S. agriculture during the nineteenth century was facilitated by three primary factors. First, some 30 million immigrants came to the United States between 1815 and 1914, mainly from Germany, Italy, Ireland, and Austria-Hungary. Second, the cleared forest lands in much of the eastern United States had low productivity and were unable to produce sufficient yields for the increasing human population. And third, vast tracts of potential agricultural land— stretching from the Ohio Valley to the Rocky Mountains—were identified by expeditions such as those of Lewis and Clark in the early 1800s (DeVoto 1953). These areas were made accessible by mid-century transportation advances that included water routes such as the Erie Canal, which opened the Great Lakes portion of the NCR to westward expansion, and railroads that provided access to southern regions of the NCR.

The increasing availability of arable land to newcomers provided a huge incentive to establish row-crop agriculture in the NCR. Wheat (*Triticum aestivum* L.) was a dominant early crop because it was readily adaptable to the region's soils and climate. As the vast bison (*Bison bison*) herds in the western part of the NCR were harvested and replaced by domestic cattle and hogs, corn was grown to fatten grazed animals before transport to the emerging livestock markets in Chicago. Corn–livestock agriculture was well established in the southern states of the NCR by 1850 (Hudson 1994).

Corn–livestock agriculture spread slowly from southern states northward and by 1880 reached well into Michigan's southern peninsula, southern Wisconsin, and southern Minnesota (Hudson 1994). In the year 1890, the 41 packing houses in Chicago slaughtered 13 million head of livestock, accounting for 50% of the U.S. urban wholesale meat business (Hudson 1994). By the 1920s, the center of the NCR corn-growing region had shifted northward with the availability of high-yielding corn varieties adapted to more northern latitudes (Hudson 1994). And northern Ohio, Indiana, Illinois, and Iowa had rich soils well suited for growing corn closer to the Chicago livestock markets.

As agriculture expanded into the northern wooded portion of the NCR, trees were cleared to open farmland and provide other parts of the Midwest with lumber for buildings and furniture. Thousands of small sawmills were erected on waterways of Michigan and Wisconsin to process logs from vast inland stands of white pine and hardwood. In eastern Michigan, for example, the Saginaw River alone supported over 100 sawmills along a 56-km (35-mile) reach (Kilar 1990).

After working the land during the growing season, Michigan farmers often were employed to cut and haul timber to riverbanks, so the spring runoff could transport logs to Lake Michigan for subsequent shipment to the thriving Chicago market (Cronon 1991). The interplay between forest and agricultural resources played an important historical role in the growth and sustainability of the emerging farm-steads in the northern NCR: the availability of timber provided an initial source of income and made it possible to construct farm buildings such as barns, silos, and houses.

The Advent of Hybrid Corn and the Rise of Soybean

Open pollinated corn (i.e., corn that is naturally pollinated and produces fertile seeds) reached a yield plateau by 1900 in Illinois (Hudson 1994). Efforts to increase yield further by selecting seed from the best corn plants led to corn yields of only 4.4 Mg ha^{-1} (70 bushels per acre) in 1920 under ideal growing conditions. The discovery of hybrid vigor in corn led to single cross hybrids by 1934 that produced consistently higher yields (Weaver 1946). By 1940 hybrid corn was widely adopted and resulted in more than just increased yields (Hudson 1994): corn hybrids also hastened the shift to mechanization on account of greater stalk strength and increased demands for nitrogen and other nutrients that could more conveniently be supplied with fertilizers than with leguminous cover crops or manure (Robertson and Vitousek 2009). Fertilizers made yields profitable on even poor-quality soils. The widespread use of hybrids enabled more corn production west of the Mississippi River, enhanced by government-supported irrigation subsidies. In addition, northern corn production increased because hybrids performed well during a short growing season with long day length. These advances stimulated greater production and caused major overproduction of corn, depressing its market value.

After World War I, consumers' food preferences changed, causing an increased demand for vegetable oils rather than lard or "pig fat" (Hudson 1994). This cultural shift—combined with overproduction of corn and hogs—reduced demand and value and stimulated government subsidies for corn and hog farmers to reduce production. Disincentives for corn led the way for soybean, introduced to the United States by Benjamin Franklin, to become a new cash crop for the Corn Belt region, quickly replacing oats as a rotation crop (Hudson 1994). Soybean futures trading began in Chicago in 1936. Soybean oil meal was used by livestock and poultry producers as well as pet food manufacturers because of its high protein content (Hudson 1994). Other uses were also explored—for example, in 1936 Henry Ford Farms established 4900 ha (12,108 acres) of soybean in Michigan to explore soybeans for use in both food and industry, including soy-based plastics that could be used in cars. Ford had developed a laboratory to discover industrial uses for farm products ("chemurgy") then used mainly for food, with the aim of making farming more profitable (Lewis 1976).

Soybean adoption in the NCR was helped by the fact that farmers could plant soybeans at about the same time as corn with only minor adjustments in farming equipment. By the 1940s—even though no one in the United States had grown the crop commercially before 1920—soybean had become established

as the second most profitable cash crop and was grown on the best lands in the NCR. Today, NCR soybean acreage is about the same as corn acreage, although the proportion can be affected by fluctuating corn ethanol prices (Feng and Babcock 2010).

The Industrialization of North Central Region Agriculture

By 1950 corn and soybean farming underwent post–World War II industrialization. Larger equipment was being used to plant, till, spray, and harvest crops. In addition, new varieties were developed to suit large-scale corn and soybean production, and new fertilizers and application methods were deployed. The advent of the insecticide DDT in the 1940s heralded the chemical era that grew exponentially during the 1960s and 1970s as the use of biocides expanded (Van Den Bosch 1978). Insecticides targeted insects such as rootworms (*Diabrotica* spp.), stalk worms including the European corn borer (*Ostrinia nubilalis* Hübner), and various insect defoliators. Herbicides also came into widespread use, with multiple types and formulations developed to combat both grass and broad-leaf weeds. And new types of fungicides were developed to attack plant diseases like root rot, mildew, and foliar pathogens.

Government subsidies for irrigation and advances in irrigation technology allowed cropland to expand west of the Mississippi. The Ogallala Aquifer, which underlies much of the Great Plains region, was tapped to supply water to row crops. Over 170,000 wells were drilled to enable corn production on land that without irrigation was ecologically suitable only for wheat. By 1977, 1.4 million ha (3.5 million acres) were irrigated by center pivot irrigation systems in Nebraska, Kansas, Texas, and Colorado. This enabled the development of both corn feedlots for cattle and decentralized, regional slaughtering facilities in these states (Hudson 1994), and led to the demise of the Chicago stockyards, most of which closed by 1970.

Increased international demand for corn also drove up production. This demand in the mid-1970s was met, in part, by abolishment of the Soil Bank—a government subsidy program initiated in 1956 that took agricultural land out of production to reduce crop surplus. As a result, millions of acres of land were put into corn production. For example, nearly 163,000 ha (402,721 acres) of corn were newly planted on drained wetlands in Michigan's Saginaw Bay watershed between 1969 and 1978.

Currently, corn is the largest U.S. crop in both volume and value. Iowa, Illinois, Nebraska, and Minnesota account for more than 50% of U.S. corn production. Other major corn-producing states include Indiana, Wisconsin, South Dakota, Michigan, Missouri, Kansas, Ohio, and Kentucky. Today's U.S. corn crop has three principal uses: animal feed, ethanol, and direct human consumption. Of the 13.13 billion bushels of corn used during the marketing year of September 2010 through August 2011, uses included: 38% for ethanol production; 38% for livestock feed and residual; 14% for export; 8% for high-fructose corn syrup, glucose, dextrose, and starch; and ~2% for cereals and other products (ERS 2011a). By 2015 about half of the 2009-equivalent corn crop is expected to be used for ethanol, with important environmental implications (Robertson et al. 2011).

Insect and Disease Influence on Corn and Soybean Production

The intensification and mechanization of grain production can increase crop susceptibility to plant pathogens and insect infestations because it provides extensive resource opportunities for these organisms. Major disease outbreaks are rare but can have significant impacts on corn production in the NCR. In 1970, for example, the Southern Corn Leaf Blight—caused by the fungus *Helminthosporium maydis* (Nisikado & Miyake)—resulted in a 10% reduction in national corn production, the largest decrease in corn yield due to a pathogen in U.S. history. The outbreak was limited to 1 year and was attributed mainly to an uncommon combination of favorable environmental conditions for the fungus (Tatum 1971).

Soybean production in the United States has been largely unaffected by disease, although a recent arrival introduces the potential for significant harm. Asian Soybean Rust, caused by the fungus *Phakopsora pachyrhizi* (Syd. & P. Syd. 1914), was present for many years in Asia before spreading to Africa and South America (Miles et al. 2003). This fungus was found in 2004 at a research farm in Louisiana (Schneider et al. 2005). Isard et al. (2005) produced a soybean rust aerobiology predictive model that guided soybean rust scouting operations after its initial discovery. Predictions of soybean yield decline are as high as 80% in the absence of effective management strategies, such as fungicide sprays now common in Brazil. Major research efforts are under way to develop more effective fungicides and disease-resistant soybean varieties. Although its impact in the United States thus far has been limited, this disease remains a significant threat to soybean production.

Insect pests have also affected corn and soybean yields. The European corn borer has plagued corn producers, who have waged major pesticide assaults against the insect. The borer can also be managed by rotating crops to break the insect's life cycle, and by cutting cornstalks close to the soil surface at harvest to remove overwintering habitat. Corn varieties with genes inserted to produce the bacterial toxin *Bacillus* thuringiensis (Bt), fatal to the larvae of moths and other lepidopterans, provide protection for 65% of U.S. corn acreage (ERS 2011b) at a disputed environmental cost not fully resolved (Rosi-Marshall et al. 2007, Beachy et al. 2008, Parrott 2008, Jensen et al. 2010, Tank et al. 2010).

The western corn rootworm (*Diabrotica virgifera virgifera* LeConte) is another serious corn pest responsible for severe root damage and subsequent yield loss when large populations are present. Insecticides applied to soil can reduce infestations but are costly. Although crop rotation can also be effective at reducing infestations, the rootworm has adapted to the normal rotation of corn and soybean in the NCR (Levine et al. 2002), so rotating into soybean is no longer an effective control technique. Bt genes have also been inserted into root tissue to combat rootworm, offering another pest management option for farmers. While such genetically modified crops have provided benefits to both agriculture and the environment, weed herbicide resistance is an important emerging problem (NRC 2010a) and questions remain regarding the long-term ecological effects of using genetically modified crops (NRC 2008, NRC 2010a).

In soybean, insect pests have been relatively rare until recently. In 2000 the soybean aphid (*Aphis glycines* Matsumura) invaded the NCR and has required widespread insecticide application (Landis et al. 2008). Major efforts are under way to understand biological regulation of this pest (Landis and Gage 2015, Chapter 8 in this volume). Other soil-inhabiting organisms such as the soybean cyst nematode also can reduce soybean yields and increase the cost of soybean production (Kaitany et al. 2000) by requiring management such as crop rotation, resistant varieties, nematicide application, or other cultural practices.

The Emergence of Agricultural Ecology

Many plant pathogens and insect pests flourish in large-scale crop production systems and are favored by the reduced use of crop rotations (Oerke 2007). Crop surveillance is a key factor in the early detection and control of such outbreaks. Although more farmers are beginning to apply principles of ecosystem management, such as scouting, to their cropping systems, there is limited coordination of such activities at regional scales (Isard et al. 2005).

In the 1970s, after years of attempting to manage agricultural insect pests with an arsenal of chemical inputs such as the insecticide DDT, the environmental risks of pesticide use were discovered. This, along with publications by Carson (1962) and others (Pimentel 1971, Van Den Bosch 1978), stimulated the need for a shift from indiscriminate pesticide use and the development of new approaches to pest control.

In response, insect ecologists developed the paradigm of Integrated Pest Management (IPM)—based on the greater use of ecological understanding and biological methods for pest regulation, such as intensive scouting prior to chemical use and using natural enemies of pests for biocontrol (Radcliffe et al. 2008). Integrated Pest Management challenged industrial agriculture's assumption that reliance on chemicals was the only effective means to manage and maintain production and economic capacity (Pimentel 1981). The controversy over chemical vs. biological pest management raged during the 1970s, at a time when corn and soybean production was vastly increasing on account of export demand. In the 1980s, the concepts of Sustainable Agriculture (Robertson and Harwood 2013) and Integrated Farming Systems emerged. Finally an ecosystem perspective became a lens through which to examine agriculture, and agricultural ecology had begun to mature as a scientific discipline (Tivy 1990, Soule and Piper 1992, Altieri 1987).

Climate and Crop Yields in the North Central Region

Patterns of Corn and Soybean Yield

Figure 4.2A shows the county-level percentage of NCR land area classified as suitable for agricultural production (i.e., arable land) without regard to water availability. Soil water-holding capacity (Fig. 4.2B) provides additional information about crop production potential.
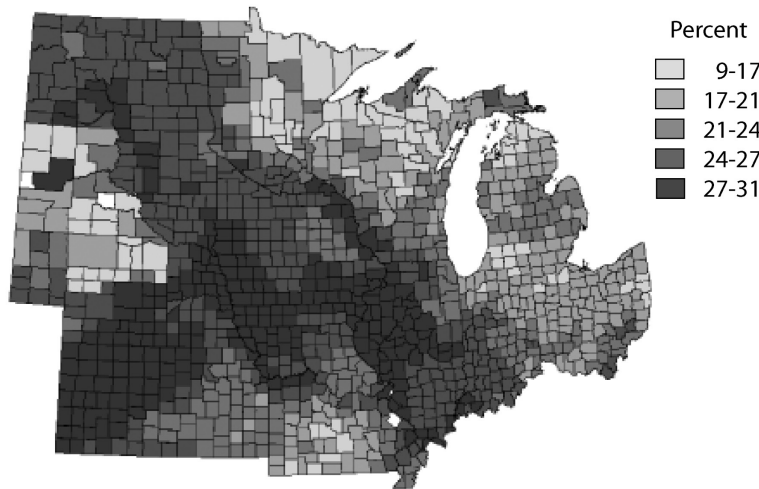
(A) Arable Land
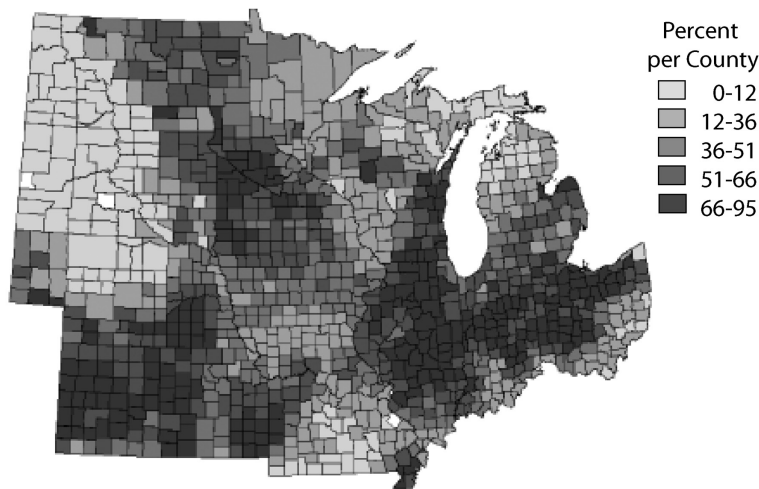
(B) Water Holding Capacity

Figure 4.2. Distribution of (A) percentage of arable land and (B) soil water holding capacity by county in the NCR. Water holding capacity is the amount of water that can be held in a soil between its field capacity (drained upper limit) and the wilting point of the vegetation, expressed as the volumetric water content (% of total soil volume). This is a function of soil texture and is expressed for the upper 250 cm of the soil profile. Data from NRCS (1991).

Statewide 30-year patterns of rain-fed crop yields for corn and soybean range from 3–7 Mg ha^{-1} (48–112 bu acre^{-1}) for corn and 1.4–2.6 Mg ha^{-1} (21–39 bu acre^{-1}) for soybean across the NCR (Fig. 4.3). Corn and soybean yields for this time period (1971–2001) were highest in Iowa and lowest in North Dakota. The upward trends in corn and soybean yields for the NCR since 1971 (Fig. 4.4) reflect improvements
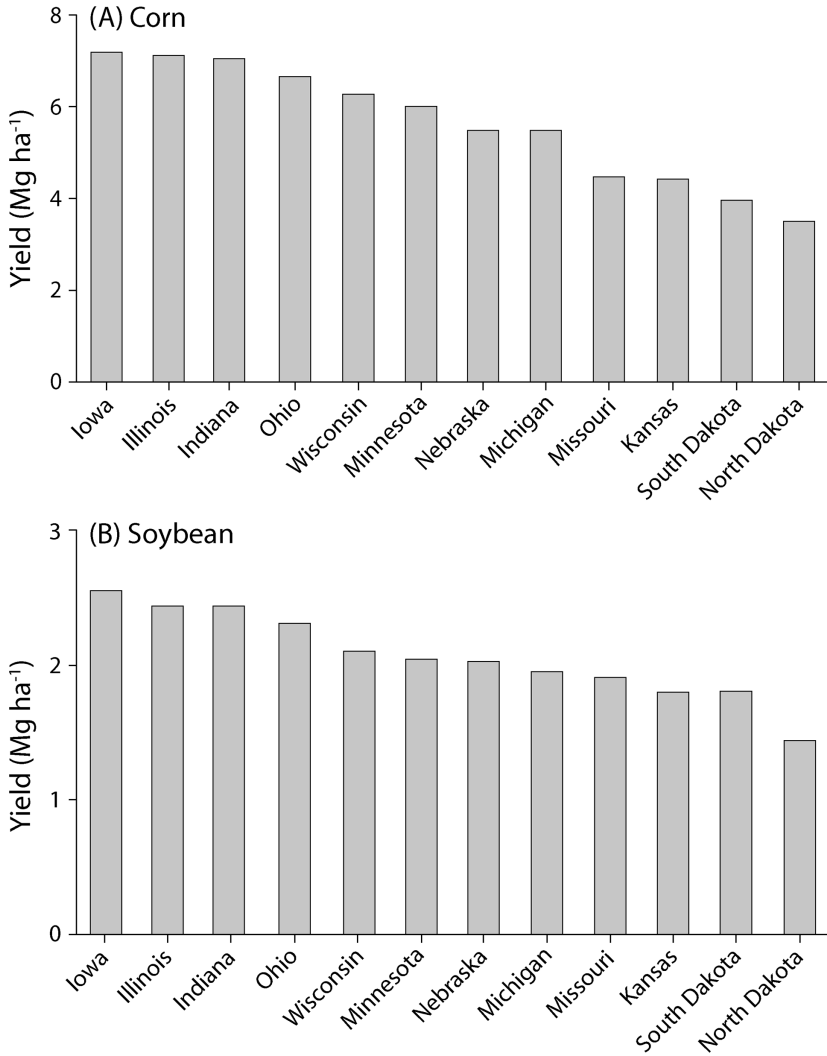
Figure 4.3. Mean non-irrigated (rainfed) grain yields (Mg ha^{-1}) for 1971–2001 for (A) corn and (B) soybean crops by state in the NCR. The regional crop dataset was compiled by the NCR Climate and Crop Committee (USDA and Cooperating States) from NASS (2011).

both in varieties (genetic improvement) and agronomic management—especially in the use of nitrogen fertilizers (Robertson and Vitousek 2009)—as well as favorable climate conditions (Twine and Kucharik 2009). Annual variability in yield largely reflects variation in climate. Although regional variability exists, the spatial pattern of corn and soybean yields provides an outline of the Corn Belt: a band of higher yields stretching from central Ohio through Indiana, Illinois, Iowa, and southern Wisconsin and Minnesota (Fig. 4.5).
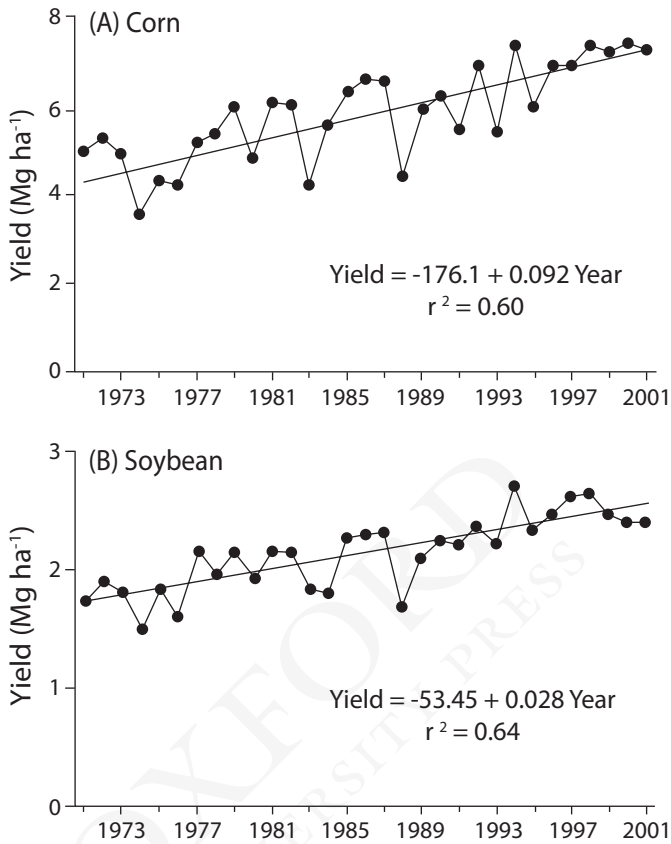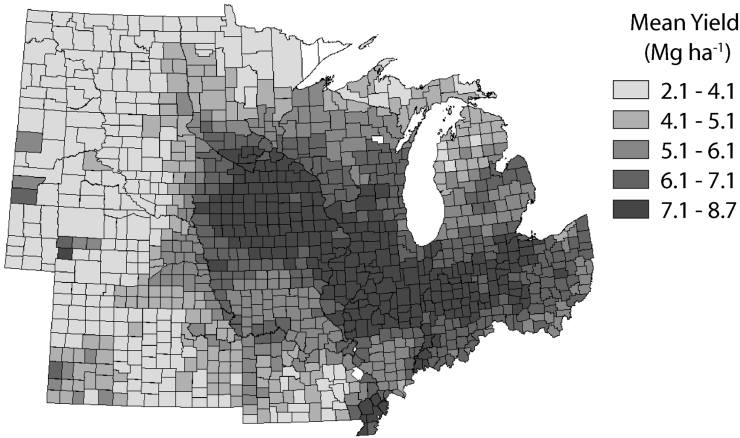
Figure 4.4. Trends in mean grain yields (Mg ha⁻¹) for non-irrigated (A) corn and (B) soybean in the NCR (1971–2001). See Fig. 4.3 legend for data source.

Crop Stress Indices

One of the stresses affecting corn and soybean growth and productivity—and plants in general—is a moisture deficit. Moisture deficits can cause physiological stress in plants and, when coupled with the additional stress of increasing temperatures, can lead to significant crop loss. Several indices have been derived to relate weather to crop stress and crop loss. Jackson et al. (1988) reexamined the theoretical basis of the crop water stress index and showed that measures of canopy temperature, wind speed, crop canopy resistance, evapotranspiration, solar radiation, and other factors are important considerations. In a review of drought indices, Heim (2002) noted that the Palmer Drought Index (PDI), despite some deficiencies, is still the most widely used index. However, the PDI requires data on precipitation, evapotranspiration, soil moisture loss and recharge, and runoff (Heim 2002), a range of variables for which few regions in the world have data.
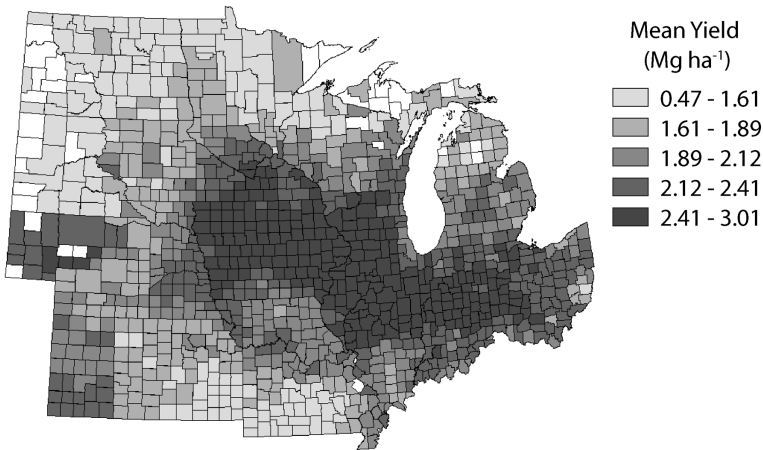
(A) Corn

(B) Soybean

Figure 4.5. Distribution of mean grain yields (Mg ha^{-1}) for non-irrigated (A) corn and (B) soybean by county in the NCR (1971–2001). See Fig. 4.3 legend for data source.

The Crop Stress Index (CSI) is a simpler index to use and requires less data than the PDI. The CSI is estimated by the equation

$$CSI = D_{10}/(P + 1)$$

where D_{10} is degree-day, or the average daily air temperature as degrees in excess of 10°C ([(maximum temperature + minimum temperature)/2]–10°C) summed over a month-long period, and P is the amount of precipitation (mm) accumulated during the same month. Commonly, 10°C is used as the base temperature to calculate agricultural growing degree-days. The CSI has been correlated with wheat yields and

grasshopper populations in Saskatchewan, a cotton pest in Australia, and regional drought in the NCR (Gage and Mukerji 1977, Hamilton and Gage 1986, Gage 2003). The CSI is relatively easy to compute at any scale—from local to global—since it requires only daily maximum and minimum temperature and precipitation data, which are generally available.

Patterns of Heat, Moisture, and Crop Stress

Coupling NCR databases of temperature, precipitation, and crop yield offers a powerful means for examining the relationship between yield and climate. The analyses that follow cover a 30-year period (1971–2001) for 1053 of the 1055 counties in the NCR where data were available, and incorporate more than 11 million daily climate records and over 35,000 rain-fed crop yield records. Figure 4.6 represents the structural organization of datasets used to compute the Crop Stress Index (CSI) from monthly records. The annual crop dataset shown in the lower panel of Fig. 4.6 illustrates the extraction of the rain-fed component of the crop database. The resulting database used in the analysis is the integration of the monthly climate and rain-fed crop datasets.

May through July degree-day accumulation, shown as means over the 30-year period, ranged from 334 in the northern NCR to 1258 degree-days in the south, a 3.8-fold difference (Fig. 4.7A). Precipitation (May through July) ranged from 177 mm in the western NCR to a high of 383 mm in the south central NCR, a 2.2-fold difference (Fig. 4.7B). Of interest is that the patterns of heat and precipitation are not consistent across the region. Accumulated degree-days increase from north to south, while precipitation tends to increase toward the central portion of the NCR, with highest accumulation in Iowa and lowest accumulation in western states. The CSI integrates these two patterns, and likewise varies across the region, as illustrated in Fig. 4.8. Monthly growing season patterns in the CSI (Fig. 4.8) show that sustained stress is concentrated in the southwestern part of the region in May, June, and July, but that May stress is also high in the northwest (Fig. 4.8A). In June, crop stress is high in the south central NCR (Fig. 4.8B), whereas in July it shifts primarily to the western NCR (Fig. 4.8C). The 3-month sum of average CSIs for each county shows that the western and southern parts of the NCR have the highest probability of crop stress (Fig. 4.8D), which is why most of the corn and soybean fields in these areas are irrigated.

A monthly distribution of the CSI illustrates the dynamics of stress over the 30-year period (Fig. 4.9). Although climate may affect crop growth and yield throughout the entire growing season, plants are most susceptible to stress, as measured by yield loss, during the critical months of May–July in the NCR (Fig. 4.9). The potential for crop stress differs over this period and tends to be greatest in July, followed by June and May The most intense crop stress occurs in late July when grain has already set and growth is beginning to slow; however, stress early in growing season can reduce crop yield quickly because young plants are more susceptible to moisture deficiency as they have not fully tapped into the belowground moisture. This was the case during the 1988 drought in the Corn Belt region (Gage 2003).
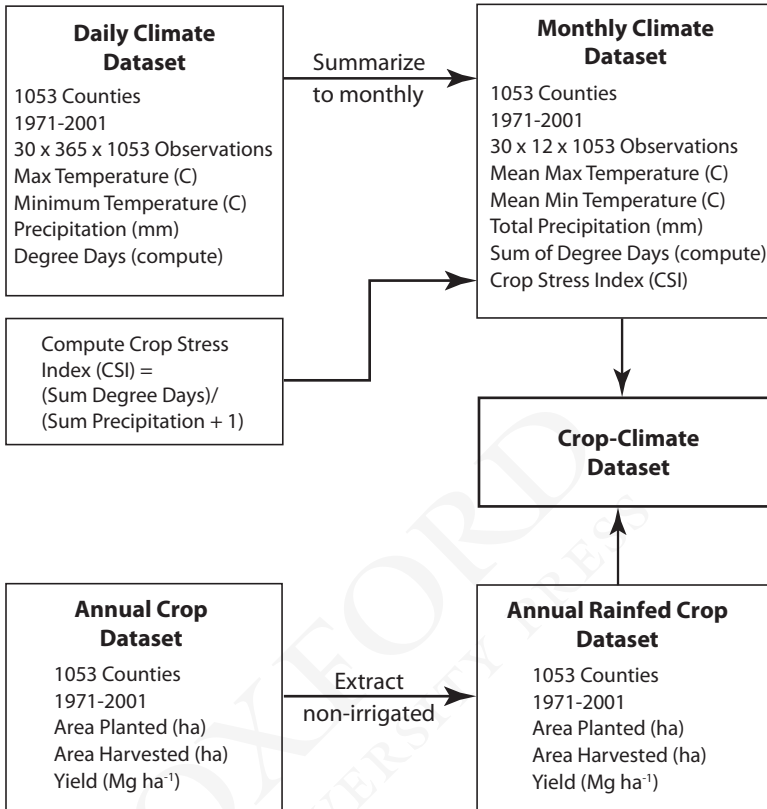
Regional Data Processing

Figure 4.6. Structural organization of the regional database linking daily and monthly climate variables with annual yields of corn and soybean crops. Growing season degree-days are based on the average daily temperature (°C) - 10 °C. The climate data set is from the National Weather Service Cooperative Observer Network. Extrapolations to the 1053 of 1055 counties in the NCR where data were available were computed by the Midwestern Regional Climate Center (MRCC) and compiled by the North Central Regional Climate and Crop Committee (USDA and Cooperating States). See Fig. 4.3 legend for regional crop dataset source.

Crop Stress and Yields

Over the 30-year period of this analysis, technological advances—including new varieties, nutrient subsidies, soil management, and pest control—have improved yields of both corn and soybean. Regional yields of both crops trend upward during this period and have similar degrees of fit ($r^2 = 0.60$ for corn and $r^2 = 0.64$ for soybean, Fig. 4.4). Regional yields of both crops decline, however, with increasing crop stress (Fig. 4.10). The steeper negative slope for corn compared to soybean suggests that corn has a greater sensitivity to climate stress than soybean. This is consistent with the differential responses of these crops to heat stress: high
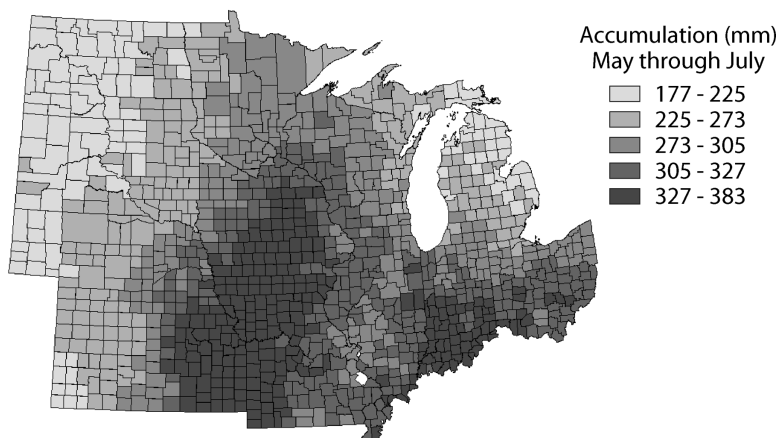
(A) Growing Degree-Days
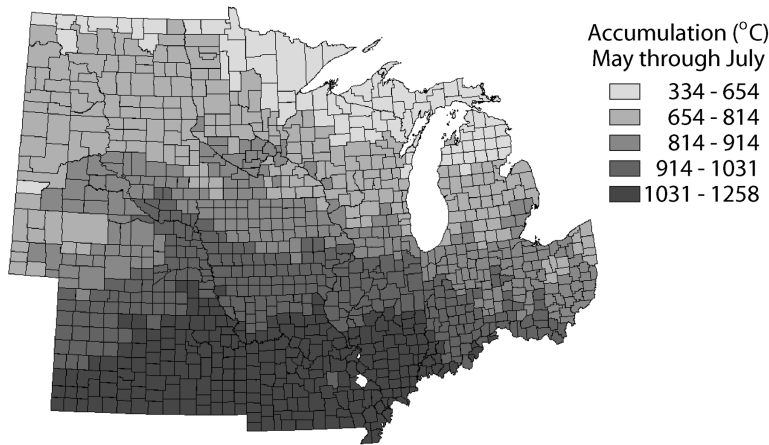
(B) Precipitation

Figure 4.7. Distribution of accumulated (A) growing season degree-days and (B) precipitation (mm) by county in the NCR from May through July (1971–2001). See Fig. 4.6 for data sources.

temperatures during flowering and pollination depress yields in both, but because corn has a shorter reproductive period—on the order of only 1 week—corn is especially sensitive to short-term heat waves (Hatfield et al. 2011).
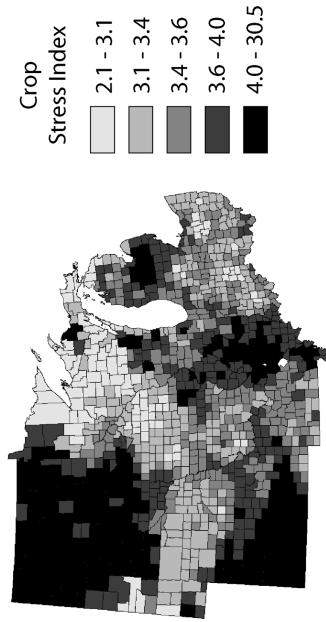
Incorporating both year and climate into multiple regression analyses significantly improves the prediction of corn ($r^2 = 0.80$) and soybean ($r^2 = 0.79$) yields in the NCR:

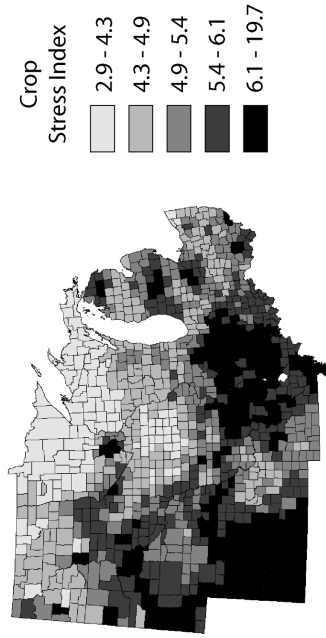$$\text{Corn yield} = -135 + 0.0717 \text{ year} - 0.0955 \text{ CSI}$$

$$\text{Soybean yield} = -43.2 + 0.0230 \text{ year} - 0.0238 \text{ CSI}$$

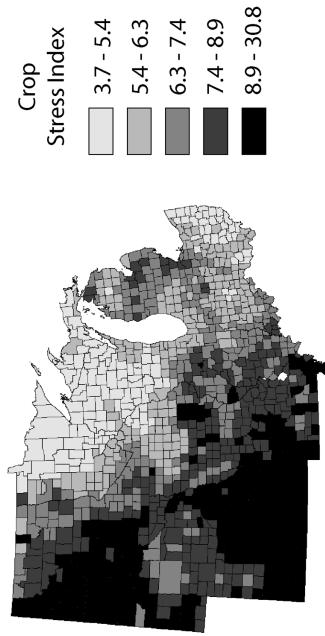where year = calendar year and CSI = Crop Stress Index.
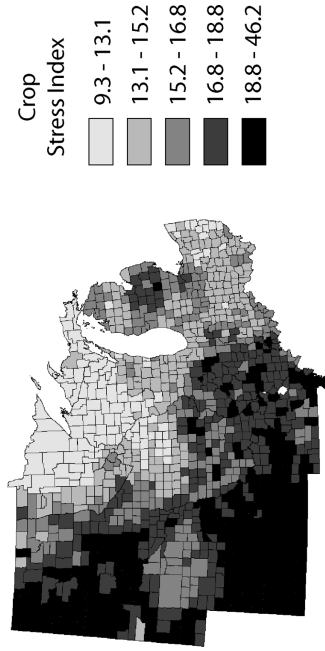
Figure 4.8. Distribution of the mean Crop Stress index (CSI) by county in the NCR during (A) May, (B) June, (C) July, and (D) the mean CSI sum for May—July from 1971–2001. See Fig. 4.6 for data sources.

Figure 4.9. Month by year distribution of the Crop Stress Index (CSI) for the NCR (1971–2001). See Fig. 4.6 for data sources.

Figure 4.10. Average annual grain yields of non-irrigated (A) corn and (B) soybean in the NCR as a function of the May–July Crop Stress Index (1971–2001). See Figs. 4.3 and 4.6 for data sources.

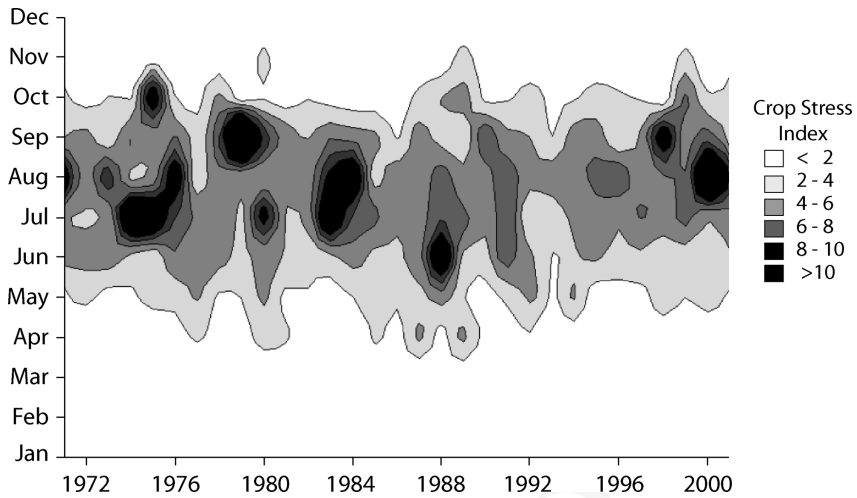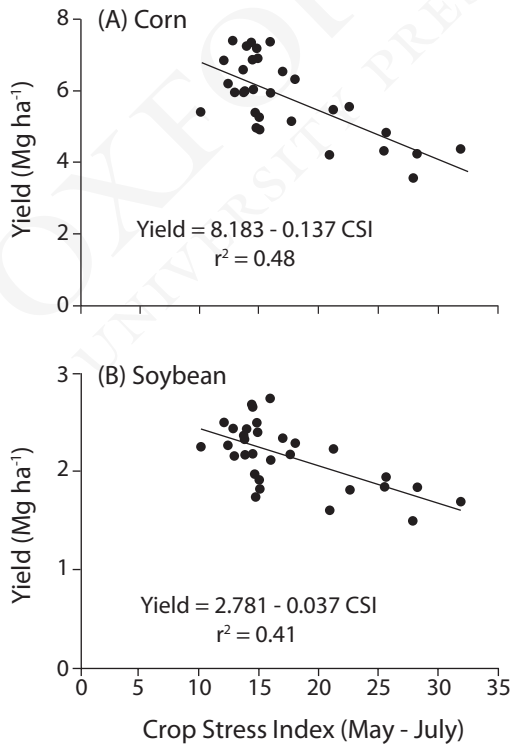The same approach can be used to examine the combined effect of year and climate on crop yield at the local scale. For example, Fig. 4.11 shows yield increases in corn and soybean in Kalamazoo County, Michigan—the location of the KBS LTER—during the 1971–2001 period, with slopes of 0.094 ($r^2 = 0.47$) and 0.042 ($r^2 = 0.51$), respectively. This yield trend also reflects technological advances, as it did at the regional level (Fig. 4.4). However, incorporating both year and climate does not improve the prediction of yield for Kalamazoo County (Fig. 4.12) as much as it did for the NCR (Fig. 4.10). At the county level, the CSI explains only 26% of the yield variance for corn (vs. 48% for the region) and 11% of the yield variance for soybeans (vs. 41% for the region).

The CSIs for Kalamazoo County during this time frame were not as extreme as they were in the NCR; in fact, locally only 1 year out of 30 had a CSI value greater than 25 (Fig. 4.12), whereas in the NCR, the CSI was greater than 25 in 5 out of the 30 years examined (Fig. 4.10). This is likely because Kalamazoo County is in the northern part of the NCR where temperatures are cooler and rainfall is greater than in the western
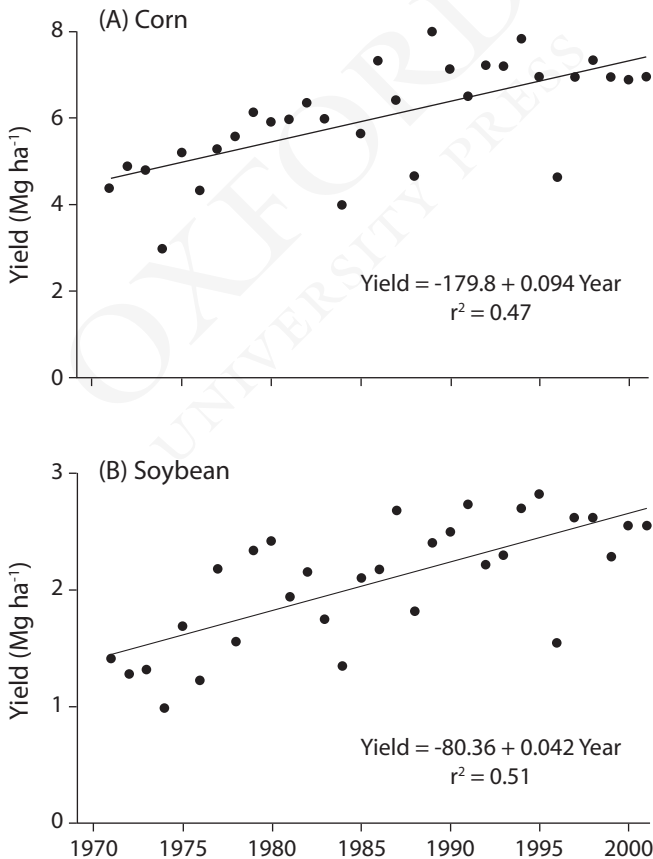

Figure 4.11. Trends in grain yields of (A) corn and (B) soybean in Kalamazoo County, Michigan (1971–2001). See Figs. 4.3 and 4.6 for data sources.
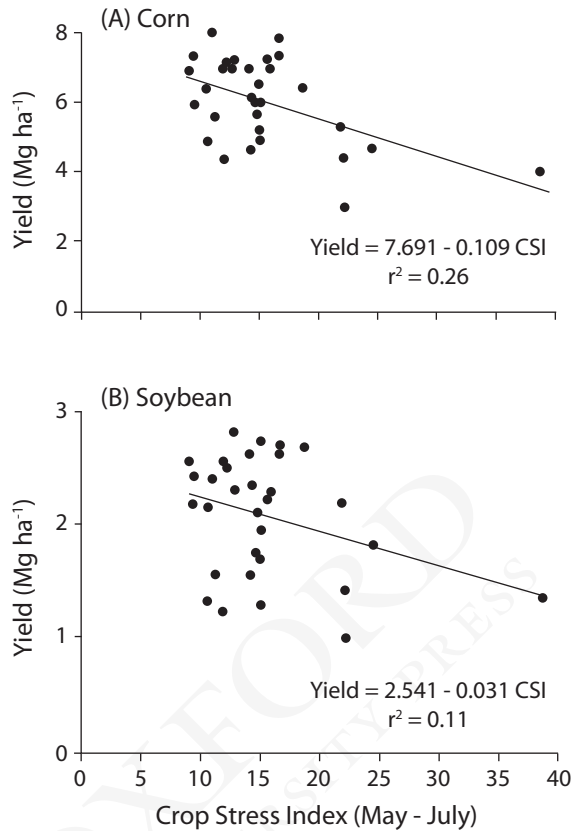
Figure 4.12. Average annual grain yields of (A) corn and (B) soybean in Kalamazoo County, Michigan, as a function of the Crop Stress Index (May–July) in Kalamazoo County, Michigan (1971–2001). See Figs. 4.3 and 4.6 for data sources.

portion. For example, in Kansas, the CSI was greater than 25 in 7 of the 30 years examined.

   Also worth noting is that the slope of increasing corn yield over this period for Kalamazoo County (0.094 Mg ha^{-1} yr^{-1}; Fig. 4.11) is almost identical to the slope for the NCR (0.092 Mg ha^{-1} yr^{-1}; Fig. 4.4), showing how closely the KBS area tracked regional trends. Interestingly, the slope of soybean yields for Kalamazoo County over this same period (0.042 Mg ha^{-1} yr^{-1}) is greater than that for the NCR (0.028 Mg ha^{-1} yr^{-1}).

Climate Change Implications

Agriculture in the NCR will be greatly affected by climate change, with important consequences for crop stress. The earth's average global surface temperature rose 0.85°C from 1880 to 2012, with each of the last three decades being successively

warmer than any decade since 1850 (IPCC 2013). In the Midwest, the largest temperature increases have occurred at night and in the winter (Pryor et al. 2014), and the length of the frost-free season has increased by 9 to 10 days across the NCR, leading to a longer growing season (Walsh et al. 2014). Since 1991, precipitation has increased across most of the NCR by 8 to 9%, as has the frequency of heavy downpours, especially in the Midwest and northern portion of the Great Plains region (Walsh et al. 2014). Heat waves have also increased, with three times the long-term average number of intense heat waves in 2011 and 2012 across the United States (Walsh et al. 2014).

Temperature trends in Michigan reflect global patterns with a cooling period from 1930 through 1980 followed by a warming trend beginning in the early 1980s (Andresen 2012). The warming has been concentrated in the winter months and mostly reflected in higher minimum temperatures. Mean precipitation has generally increased since the late 1930s—but with dry conditions in the late 1950s and early 1960s—as has the number of days with measureable precipitation, which is associated with more cloudiness (Andresen 2012). The decreasing amount and duration of ice cover on the Great Lakes have significant implications for Michigan's climate as the Great Lakes tend to moderate the local climate downwind of the lakes (Andresen 2012).

Climate Projections

For the next two decades, warming of 0.3 to 0.7°C in global mean surface air temperature is projected under a range of greenhouse gas scenarios, and even if greenhouse gas emissions are stopped, changes in the climate will continue for many centuries (IPCC 2013). By the end of the twenty-first century, projections of warming range from 0.3°C to 4.8°C depending on greenhouse gas emissions and other drivers, with projections showing a 1.5°C increase as likely under most emission scenarios (IPCC 2013). The highest rates of warming are expected to be over land, with more warm days and nights and fewer cold days and nights. Increases in the frequency of heat waves and heavy precipitation events are likely, with the contrast in precipitation between wet and dry regions of the globe increasing (IPCC 2013).

Climate change projections for specific regions are generally much more uncertain than global projections, and regionally focused studies are not yet available for every location (NRC 2010b). However, models consistently agree with projections of warmer annual temperatures for the NCR for both summer and winter months (IPCC 2013, Walsh et al. 2014), and the trend of longer frost-free and growing seasons is projected to continue for the region (Walsh et al. 2014). There is greater uncertainty in precipitation projections. For the northern half of North America, projections show increases in mean annual precipitation over winter and spring months, but models do not agree on summer or fall precipitation changes (IPCC 2013, Walsh et al. 2014), making it difficult to predict regional effects on agriculture. There is, however, high certainty that heavy precipitation events will increase in frequency and intensity, and the number of consecutive dry days is projected to increase (Walsh et al. 2014).

Implications for Row-Crop Production

Changes in climate greatly impact row-crop agriculture: temperature, precipitation amount and distribution pattern, cloud cover, and carbon dioxide (CO_2) levels affect plant growth, field practices, pests, and plant diseases, sometimes in conflicting ways (Tubiello et al. 2007, Hatfield et al. 2011, Hatfield et al. 2014, NRC 2010c). Over the last forty years, agricultural production in the United States has been affected by more climate disruptions, a trend that is expected to continue (Hatfield et al. 2014). The magnitude of the impacts on crop yields depends on location, the agricultural system, and the degree of warming (NRC 2010b) as well as the availability of water to the crop. We have used the CSI as a metric to assess the effects of changes in temperature and precipitation on corn and soybean yields in the NCR. While other factors will also affect crop yield, including rising atmospheric CO_2 levels, weed pressure, herbicide efficacy, and the spread of pests and diseases (Tubiello et al. 2007, Hatfield et al. 2011), there are too few data to develop an index that incorporates these effects.

A recent global analysis showed that from 1980 to 2008, corn and wheat yields were suppressed 3.8% and 5.5%, respectively, in many important agricultural countries because of increasing temperatures (Lobell et al. 2011). The United States was a notable exception, showing no detectable yield loss due to climate change. In fact, for the years 1982–2002, increased corn and soybean yields in the central and eastern United States were attributed to favorable climate conditions: a combination of more precipitation, longer growing seasons, and decreased summer average temperatures (Twine and Kucharik 2009). These favorable climate trends may have contributed 20–25% to the observed U.S. yield increases over this period. Kucharik and Serbin (2008) examined the variability of past temperature and precipitation county-level trends and their effect on crop yields in Wisconsin during 1976–2006. Yield trends were suppressed 5–10% in counties that had warmer summer temperatures. This negative impact was, however, counterbalanced by increases in precipitation that favored crop yields.

Our work shows that, in the 30-year period we analyzed, most periods of crop stress in the NCR have been short-term events in May through July (Fig. 4.9) that were characterized by high temperatures and below-average precipitation. For every unit increase in the CSI, yields decreased 0.14 Mg ha^{-1} for corn and 0.04 Mg ha^{-1} for soybean (Fig. 4.10). During this period, there were few years with back-to-back severe crop stress events (Fig. 4.4). Further back in the region's recorded climate history, however, severe continuous crop stress events helped create the 1930's Dust Bowl and depressed yields to near zero for several years in succession, illustrating the vulnerability of agricultural systems to prolonged and repeated climatic stress.

To date, U.S. agriculture has been effective at adapting to climate change (Hatfield et al. 2014), and under local temperature increases of up to 2°C adaptation has the potential to offset projected crop yield declines in North America (IPCC 2014a). At temperature increases of 4°C or more, however, the effectiveness of adaptation will be reduced and large risks to food security at global and regional scales are likely (IPCC 2014a,b). Climate disruptions are anticipated to have an increasingly negative impact on most U.S. crops by mid-century (Hatfield et al.

2014). Increased temperatures result in higher rates of soil water evaporation and crop transpiration, which could lead to an increase in soil water deficits (Hatfield et al. 2011). If climate change leads to longer periods of warmer and drier weather, producing high yields without irrigation will be increasingly challenging. While increased levels of CO_2 improve water-use efficiency for some plants (Hatfield et al. 2008), the benefit will be tempered by heat-related stresses that increase water demand (NRC 2010c). Moreover, NCR aquifers that provide irrigation water are already under stress because of unsustainable withdrawal rates (Kromm and White 1992) and are increasingly showing contamination by nitrate and pesticides. The IPCC projects an overall net negative impact of climate change on freshwater ecosystems (IPCC 2014a).

Recent studies have suggested that the effect of future warming on grain crops may be worse than previously recognized (Hatfield et al. 2011). For example, Kurcharik and Serbin (2008) found that for each degree of future warming, with no change in precipitation, corn yields could decrease by 13% and soybean by 16%. The authors note that while warmer and drier conditions during spring planting and fall harvest could help boost yields in some NCR states, higher summer temperatures will likely temper yield benefits. Likewise, Schlenker and Roberts (2009) estimated decreases in U.S. crop yields for corn, soybean, and cotton ranging from 30 to 46% by the end of the century under a slow warming scenario and 63 to 82% under a rapid warming scenario. By mid-century under conditions of increased temperatures and precipitation extremes, U.S. crop yields and farm profits are expected to decline while annual variation in crop production increases (Hatfield et al. 2014).

Agriculture will be affected both by changes in absolute values of temperature and precipitation and by increased climatic variation (Hatfield et al. 2011, 2014), and adaptive measures will be needed. Adaptation is not new to agriculture, and the analyses presented in this chapter highlight the extent to which agriculture has already adapted to trends and variability in temperature and precipitation. The challenge for the future is to adapt to more rapid and extreme climatic changes in the face of other environmental and social pressures and stresses (Easterling 2011, Hatfield et al. 2014), including increasing demands for agriculture to provide biomass for ethanol production (Robertson et al. 2008). Adaptive measures for agriculture include (1) relying on natural resources and inputs (e.g., water, energy, land); (2) technological innovation (e.g., breeding and genetic modification, water and soil conservation, pest management); (3) human ingenuity (e.g., relocating crop and animal production areas, improved agronomic practices); and (4) information and knowledge (e.g., environmental monitoring systems, risk management) (Easterling 2011). Although these measures have been effective in increasing crop yields to their current levels, it is not clear if further adaptation of agronomic practices and technologies—alone or in combination—will meet the challenge (Easterling 2011).

Uncertainties in climate projections for the NCR, coupled with varying climate trends at local levels (e.g., Kucharik and Serbin 2008), make adapting and planning for the future difficult. Agronomists are given the challenge of making cropping systems more resilient to climatic change (Hatfield et al. 2011) and using an ecosystem approach to agriculture (Robertson and Hamilton 2015, Chapter 1 in this volume) may help. Strategies such as cover and companion crop integration

and no-till farming, which are included in the alternative crop management systems at the KBS LTER, can reduce the need for chemical subsidies and help manage crops under heat and/or water stress (Snapp et al. 2015, Chapter 15 in this volume). Increasing the organic matter content of soil increases soil water retention and reduces the need for water subsides, which will likely be required as the climate warms. Designing landscapes to optimize natural regulation of crop pests can reduce both crop loss and pesticide use (Landis and Gage 2015, Chapter 8 in this volume). Not only would such practices help agricultural ecosystems become more resilient and adaptable to climate change, they also have the potential to mitigate future climate change by sequestering carbon and by reducing the footprint of agronomic chemical use (Paul et al. 2015, Chapter 5 in this volume; Gelfand and Robertson 2015, Chapter 12 in this volume).

Because corn is more sensitive to heat stress than soybean (see Fig. 4.10), an immediate concern is whether the NCR will be able to sustain corn production under climate projections of increased heat and less water. How can farming in the NCR adapt to such projections? Formulating an answer to that question requires a long-term perspective based on the integration of both climate and crop production, such as in the development of the CSI—because if you cannot measure it, you cannot manage it. Interpreting and using indices such as the CSI will only become more important as an unprecedented global population places even greater demands on agricultural ecosystems for food, fuel, and fiber.

Summary

Since its conversion from prairie and forest following European settlement in the 1800s, the North Central Region (NCR) of the United States has become one of the most important crop-producing areas in the world. Government subsidies, economic forces, industrialization, and consumer preferences combined to shape the current agricultural landscape of the NCR. Temperature and precipitation patterns help to drive yield trends at regional and local scales. A simple Crop Stress Index (CSI) based on temperature and precipitation records across the region shows the strong climatic influence on yield of rain-fed corn and soybean over 1971–2001; each unit increase in the CSI results in a yield penalty of 0.14 and 0.04 Mg ha^{-1} for corn and soybean, respectively.

Overall yield trends for Kalamazoo County over 1971–2001, the location of KBS, are similar to those for the NCR, but crops in Kalamazoo County were less affected by climatic variability than crops in drier areas in the NCR. At both local and regional scales, few stress events spanned multiple years during this period. With projected changes in temperature and precipitation from human-induced climate change, crop stress is likely to increase, and with serious potential consequences. Climate uncertainties make adaptive measures both crucial and challenging to implement. A regional understanding of agriculture coupled with an ecosystem-level approach is needed to determine how interacting and ever-changing socioeconomic, climatic, and ecological forces will impact agriculture in the region.

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