2020

Agricultural Impacts of Climate Change in Indiana and Potential Adaptations

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Recommended Citation

Bowling, Laura C.; Cherkauer, Keith A.; Lee, Charlotte; Beckerman, Janna; Brouder, Sylvie; Buzan, Jonathan; Doering III, Otto; Dukes, Jeffrey; Ebner, Paul; Frankenburger, Jane; Gramig, Benjamin; Kladivko, Eileen J.; and Volenec, Jeffrey J., "Agricultural Impacts of Climate Change in Indiana and Potential Adaptations" (2020). *Agriculture Publications.* Paper 1.
https://docs.lib.purdue.edu/agriculturepub/1

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Agricultural impacts of climate change in Indiana and potential adaptations

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Received: 8 January 2020 / Accepted: 5 November 2020 / Published online: 28 December 2020 # Springer Nature B.V. 2020

Abstract

While all sectors of the economy can be impacted by climate variability and change, the agricultural sector is arguably the most tightly coupled to climate where changes in precipitation and temperature directly control plant growth and yield, as well as livestock production. This paper analyzes the direct and cascading effects of temperature, precipitation, and carbon dioxide (CO2) on agronomic and horticultural crops, and livestock production in Indiana through 2100. Due to increased frequency of drought and heat stress, models predict that the yield of contemporary corn and soybean varieties will decline by 8–21% relative to yield potential, without considering CO2 enhancement, which may offset soybean losses. These losses could be partially compensated by adaptation measures such as changes in cropping systems, planting date, crop genetics, soil health, and providing additional water through supplemental irrigation or drainage management. Changes in winter conditions will pose a threat to some perennial crops, including tree and fruit crops, while shifts in the USDA Hardiness Zone will expand the area suitable for some fruits. Heat stress poses a major challenge to livestock production, with decreased feed intake expected with temperatures exceeding 29 °C over 100 days per year by the end of the century. Overall, continued production of commodity crops, horticultural crops, and livestock in Indiana is expected to continue with adaptations in management practice, cultivar or species composition, or crop rotation.

Keywords Climate change Agriculture Indiana Livestock Horticulture Row crops

This article is part of a Special Issue on "The Indiana Climate Change Impacts Assessment" edited by Jeffrey Dukes, Melissa Widhalm, Daniel Vimont, and Linda Prokopy

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Introduction and background

1.1 Agriculture in Indiana

Indiana’s soils, topography, ample rainfall, and favorable temperature patterns contribute to its comparative advantage in agricultural production. Nationally, Indiana ranks 10th in the total value of agricultural products sold. It ranks fifth in corn production, third in soybean production, and among the top ten for production of blueberries, peppermint, processing tomatoes, cantaloupe, watermelon, snap beans, and cucumbers. In livestock, Indiana is also among the top ten in hog, chicken, turkey, duck, and egg production. According to the 2017 Census of Agriculture, 49% of the cropland in Indiana has subsurface drainage, 38% has no-till, and another 31% has other forms of conservation tillage. Seven percent of the cropland reported cover crops in 2017.

Between 1974 and 2007, following the national trend, Indiana experienced a 58% reduction in middle-sized farms and growth in smaller and larger farms (by 40% and 241%, respective- ly). During this period, Indiana farms also became more specialized (less diversified), which can increase vulnerability to climate-related risks (Ortiz-Bobea et al. 2018).

This paper explores the direct and cascading impacts of projected climate trends on Indiana’s agricultural productivity and environmental quality. Changes in precipitation, temperature, and atmospheric carbon dioxide (CO2) levels can directly impact the growth of crops, forages, livestock, and other agricultural products. Both crops and livestock can suffer from temperatures that are either too low or too high, with maximum growth occurring within their ideal growth range (Takle and Gutowski 2020). In addition, consistent, sub-freezing temperatures induce dormancy in perennial plants and improve winter hardiness. Similarly, crops exhibit negative responses to both too much and too little water. Carbon dioxide is the substrate of photosynthesis, so increased CO2 concentrations can stimulate photosynthetic rates directly, especially in cool-season species known as C3 plants.

Changing air temperature and precipitation can also indirectly impact non-crop species and soil and water resources in agroecosystems. Changing moisture and temperature conditions may expand suitable ranges of non-crop species such as weeds, pathogens, and insects, while warmer winter soils and reduced soil frost depth improve overwintering success for some species, resulting in increased persistence of pest infestations. Projected yield losses from pests and pathogens range from 17 to 30% globally across five major crops (Savary et al. 2019), with implications for global food security. There is the potential for multi-level changes to agricultural production through the cumulative influence of the direct climate impacts and adaptations in management to environmental quality. The emphasis of this study is on field- level changes impacting agricultural production, the downstream impacts of potential changes in land use, nitrate leaching, soil erosion, and water availability are addressed in other studies (e.g., Cherkauer et al., this issue).

1.2 Overview of climate impacts in Indiana

- Our analysis reveals numerous changes that will impact Indiana's agricultural production, under both the intermediate and worst-case emissions scenarios:
- Warmer growing season temperatures (very high confidence, Fig. S1);
- Increased duration of extreme heat through mid-century (very high confidence) and end of the century (high confidence); Longer frost-free period (very high confidence);
- Increased variability in winter (DJF) temperature resulting in more freeze/thaw cycles (medium confidence);
- Increased frequency of high-intensity precipitation events (low confidence, Hamlet et al., this issue);
- Increased winter and spring precipitation (very high confidence), with increased soil saturation early in the growing season (very high confidence);
- Little to no change in growing season precipitation (low confidence, Fig. S2); and Reduced plant available water (medium confidence), due to longer periods between rain events coupled with increased evaporative demand.
- These impacts are consistent with the key findings of the Midwest Chapter of the 4th National Climate Assessment (NCA4/Midwest; Angel et al. 2018) while providing more specificity regarding expected rates of change in Indiana.

2 Methods

Impacts through the end of this century are based on the down-scaled and bias-corrected projections from six global climate models from the 5th Phase of the Climate Model Intercomparison Project (CMIP5) for two different Representative Concentration Pathways (RCP 4.5 and RCP 8.5). RCP 4.5 is considered an intermediate scenario, where CO2 emissions begin to decline after 2045. In contrast, for RCP 8.5, emissions continue to rise throughout the twenty-first century, so it is considered a worst-case scenario (van Vuuren et al. 2011). An overview of climate changes in Indiana under these scenarios is provided in Hamlet et al. this issue and the Supplementary Information (SI). The direct impacts of projected climate on corn, soybean and winter wheat yield were simulated using a version of the CropSyst crop growth model, coupled with the VIC hydrology model. The coupled VIC-CropSyst models were evaluated through comparisons with observed streamflow (Cherkauer et al., this issue), observed corn, soybean and wheat yield, and observed subsurface drainflow for three sites in Indiana. Details regarding the model setup and evaluation of yield and drainflow are provided in the SI.

US grain yields have been increasing steadily over time due to improvements in germ- plasm, increasing nutrient inputs, management improvements, and in some cases, positive weather conditions. Observed corn, soybean, and wheat yields from 2004 to 2013 were detrended prior to model calibration and bias-correction, so can be considered representative of 2008 varieties in Indiana. Following simulation of future yields, the trend for each Indiana crop reporting district (CRD) was added back to give an estimate of yield change if varietal improvements continue at this rate. If the observed yield trend is influenced by positive weather conditions, this could be a source of over-estimation of the projected trends. Westcott and Jewison (2013) explicitly accounted for weather effects in their calculation of US grain yield trends for 1988–2012. Their weather adjusted trends for corn (0.123 t/ha/year) and soybean (0.03 t/ha/year) are very similar to the rates calculated for Indiana (0.06–0.13 t/ha/ year for corn and 0.02–0.03 t/ha/year for soybean), so it was not considered necessary to remove a weather signal. Future trends in yield potential are very uncertain (Alston et al. 2009; Edgerton 2009), and so all yield results are presented as relative to the projected trend referred to as “yield potential” in the absence of future climate change.

Averaged output from the six VIC-CropSyst model runs is referred to as the ensemble-mean. The CropSyst model predicts the cumulative impact of the projected increased temperature and decreased moisture availability on the biomass accumulation and yield. The temperature projections could trigger earlier planting in the model, and increased productivity early in the growing season, followed by decreased growth as temperatures approach 30 °C. The potentially positive impacts of increased CO2 concentrations on photosynthesis and the negative impacts of excess moisture stress in the early growing season on crop yield were not represented. The IPCC five point confidence scale (Very high confidence, High confidence, Medium confidence, Low confidence, Very low confidence) has been used to express the level of confidence for each of our key findings (USGCRP 2018). Following Janzwood (2020) assessment of confidence is based on the formulaic interpretation of the intersection of the consistency of evidence and the level of scientific agreement. The consistency in direction of change of the mean between the six ensemble members was used to quantify the consistency of evidence (6 agree = robust, 5 agree = medium, 4 = agree limited). Level of scientific agreement was assessed based on the presence of supporting evidence of different types outside of this study, for example inclusion as a key point in the 4th national assessment (low, medium, high).

3 Direct impacts

3.1 Agronomic crops

3.1.1 Row crops

A longer frost-free season (see Hamlet et al., this issue) implies increased agricultural productivity and the possibility for multiple plantings; so in theory, increased annual temperatures can benefit crop production in the Midwest (Wuebbles and Hayhoe 2004). However, an increase in average temperatures also implies more frequent and intense extreme heat events, which may negatively affect crop yield (Goldblum 2009). The rate of increase of summer daily maximum temperatures has been lower in the Midwest than the global average due to the so-called “warming hole” associated with increased cropland evapotranspiration (Pan et al. 2004; Mueller et al. 2016). Indiana is on the edge of this zone of suppressed temperature change. Enhanced evapotranspiration is supported by increased spring precipitation (Feng et al. 2016). Our ensemble-model predictions project a 14% (17%) increase in Indiana-average spring precipitation for RCP 4.5 (RCP 8.5) by mid-century in Indiana. Patricola and Cook (2012) also project likely wetter conditions over Indiana in May, with greater than 66% model agreement. In addition to the direct influence of extreme heat, increased summer temperatures and decreased vapor pressure increase projected crop water use. This coupled with the projected 3–5% decrease in growing season rainfall by the end of the century will also result in lower summer soil moisture.

As described in the “Methods” section, the direct impacts of projected climate on corn, soybean, and winter wheat yield were simulated using a version of the CropSyst crop growth model, coupled with the VIC hydrology model. Across the Indiana CRDs, simulated ensemble-mean maize yield decreased from 7 to 14% (8 to 17%) relative to yield potential by mid-century, for RCP 4.5 (RCP 8.5) (Fig. 1). Simulated ensemble-mean soybean and wheat yield is less sensitive to projected climate changes, with projected yield decreases of 2–8% and 0–8% by mid-century (Figs. S6 and S7). The NCA4/Midwest projected maize yield declines of 5 to 25% across the Midwest by mid- century. For soybean, they project declines as high as 25% in the southern half of the domain, with increases in the northern half (Angel et al. 2018).

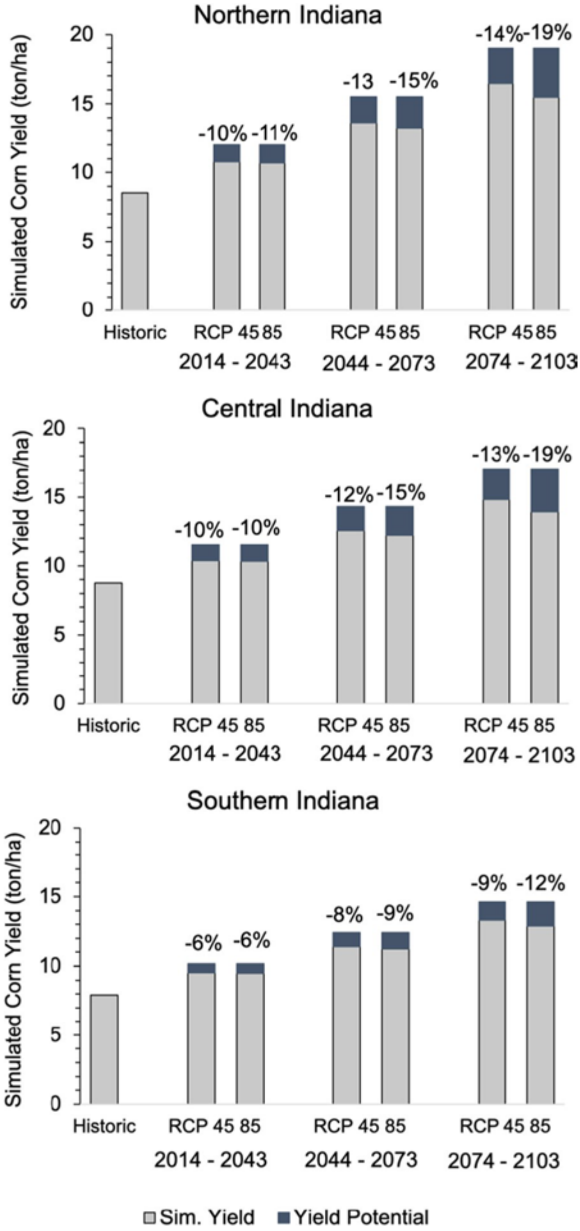

Fig. 1 Simulated corn yield differences relative to yield potential for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 for early, mid-, and late century for Indiana Crop Reporting Districts 1–3 (top), 4–6 (middle), and 7–9 (bottom). De- spite the positive influence of temperature on plant productivity, yields decline relative to potential in all scenarios due to increased heat and drought stress. Yield potential is projected to increase based on a linear projection of the observed historic yield trend

The simulated yield declines are due to both heat stress and water limitation. Future projections show a steady increase in the difference between irrigated and non-irrigated yields, with simulated corn and soybean yields being 36% and

17% higher than non-irrigated by mid-century. The model simulations assume that water is always available for irrigation.
The potential positive impact of increased CO2 concentrations on yield may be small for corn but is more positive in C3 plants such as soybeans (Angel et al. 2018). Leakey et al. (2006) observed that the productivity and yield of maize were not affected by the open-air elevation of CO2 concentrations (550 ppm) in the absence of drought in IL, USA. Stomatal conductance was reduced by 34%, and soil moisture was increased by 31% when compared with corn under ambient CO2 concentrations (370 ppm), which may improve crop-soil water balance. However, tissue temperatures were higher in the elevated CO2 environment leading to reduced rates of photosynthesis and increasing dark respiration and photorespiration. Collectively, this leads to reduced growth and yield (Long et al., 2006). Jin et al. (2017) simulated a similar decline in corn yield whether or not elevated CO2 was taken into account. In contrast, simulated soybean yields increased in some locations in the future when elevated CO2 was taken into account.

In addition to extreme daytime temperature stress, warming nighttime temperatures have been linked to decreased corn and soybean yields at a rate of − 8%/°C and − 1%/°C, respectively, based on a global analysis of reported crop yields, and observed temperature and precipitation (Lobell and Field 2007). In Indiana, observed corn grain yields are lower in recent years where July nighttime temperatures are warm (Fig. 2a). Using this relationship (see SI for details), corn yield is projected to decrease by about − 3%/°C or 1 t/ha by the end of the century due to the projected change in July minimum temperatures alone (Fig. 2b). The reduction in yield associated with elevated nighttime temperatures has been linked to increased respiration, and accelerated phenological development which reduces the time available for grain fill (Cantarero et al. 1999 and Badu-Apraku et al. 1983).

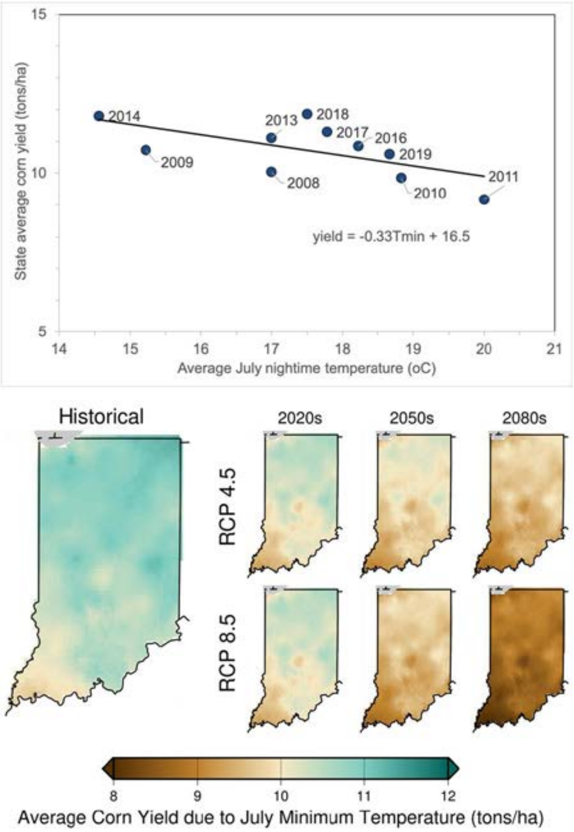

Fig. 2 (Top) Regression of observed state average maize yield (2004–2013) versus minimum nighttime temperature, (bottom) map of potential corn yield (tons/hectare) given correlation with July daily minimum temperature. This empirical model represents a potential mechanism of yield decline that has not been explored with current-generation crop models

Increased high-intensity precipitation and surface ponding also have negative impacts on crop yield. The observed frequency of extreme precipitation events (daily totals > 21.8 mm/ day) has increased in Indiana at a rate of 0.2 days per decade (Widhalm et al. 2018), but changes in summer convective storms are not captured by the large-scale climate models used in this study. Insurance claims for crop losses due to excess water or deficit water conditions have been about equal in Indiana in recent decades. Few current-generation crop growth models represent the impacts of excess precipitation, but Rosenzweig et al. (2002) predicted 6% maize yield losses due to excessive precipitation and related events by 2030 in the Midwest. The NCA4/Midwest reported that excess moisture is emerging as a major source of crop loss in the region (Angel et al. 2018).

3.1.2 Forages and pastures

Climate change impact on pasture and forage in temperate climates, such as Indiana’s, will be lower than in some southern states. Many beef cattle operations are located in Southern Indiana, which will be more vulnerable than those in the north of the state. Additionally, pasture-based systems and their animals may be more vulnerable to extreme weather events compared to indoor production systems. In some cases, a longer growing season may produce additional forage quantities. However, perennial forage crops are under a greater risk of winter injury with climate change because of a greater frequency of above-freezing temperatures during winter (Chilling Hours, see Fig. 3 and SI). These warm temperatures reduce inherent plant winter hardiness, while eliminating snow cover that insulates the soil against temperature fluctuations and shifting precipitation towards rainfall (Hamlet et al., this issue). Return of winter conditions exposes plants to freezing temperatures, encases them in ice that results in smothering, and heaving can push overwintering parts above the soil surface exposing them to killing temperatures (Bélanger et al., 2001).

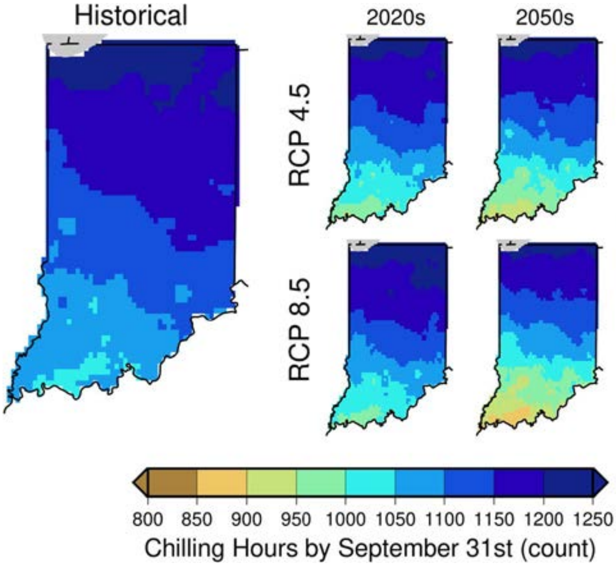

Fig. 3 Maps of accumulated annual chilling hours (hours with air temperature between 1.7 and 7.2 °C) from October 1 to September 31 for the historic period (1980–2010), and for three future periods (2014–2040, 2041– 2070, 2071–2100) for RCP 4.5 and 8.4 emissions scenarios

These negative effects may be mitigated, in part, by developing cultivars with greater fall dormancy that will respond less quickly to a brief warm spell in late winter. Unfortunately, dormant plants tend to have slow growth rates and low yields (Lu et al. 2017), and because they stop growing in early autumn, cannot exploit the advantage of a longer growing season.

Forage composition, including protein and fiber concentration, can change with environment. As a result, changes in composition rather than yield may be a greater concern to forage- livestock producers. For a C3 cool-season legume, N concentration (protein) declined with temperature when grown in an environment with elevated temperatures and high CO2 (Fritschi et al. 1999; see Fig. S8). Based on the Fritschi et al. (1999) relationship, forage nitrogen content is projected to decrease to between 1.5 and 1.6% by mid-century (Fig. S8). Neutral detergent fiber concentrations generally increased with temperature and CO2. High fiber makes animals feel full longer and generally reduces dry matter intake, translating to slower animal growth rates and lower meat and milk production. Dry matter intake rates of 3% of body mass or greater per day are preferred. Forage digestibility generally declined in the high CO2 environment, which exacerbates low intake by further reducing animal performance.

3.2 Horticultural and specialty crops

Dormancy is the primary mechanism woody fruit-producing plants like apples, peaches, grapes, and blueberries use to protect themselves from winter damage. The date of the killing frost is one potential factor impacting fruit production; another more complicated factor is the chilling requirement. The fruit chilling requirement is the minimum number of accumulated chilling hours needed for a fruit-bearing tree or vine to blossom. Different species must experience a sufficiently cold period before they can break dormancy in the spring. Fruit tree chilling hours accumulate most effectively at the 1.7–10 °C temperature range early in the dormant period. The accumulation of hours can also be reversed by temperatures above 15.6 °C, and chilling hour accumulation ceases or resets somewhere below − 1.1 to 1.1 °C (Luedeling et al. 2015). The outcome of insufficient winter chill is erratic bloom, resulting in both reduced crop yields and fruit quality (see Table S3).

The majority of Indiana fruit crops require 150 to 1700 chilling hours (Table S3); Indiana usually accumulates 1050 to 1200 chilling hours based on the simple chilling hour model that accumulates all hours between 1.7 and 7.2 °C (Fig. 3; see SI). This is projected to decrease by 50 to over 200 chilling hours by the end of the century. The killing frost (− 3.9 °C) that initiates this vernalization period is projected to occur approximately 25 days later in the fall by the end of the century (Fig. S9). This delay in the start of chilling hour accumulation may be one factor that could change which varieties of apple, peach, and grape are grown in much of Indiana by the end of the century (Fig. S10). Many perennial crops must accumulate a certain number of chilling hours in order to break dormancy (Table S3), so shifts in the number of hours accumulated may influence the selection of crop variety.

A related concern shown in Fig. 3 is that in areas that do accumulate enough chilling hours, the chilling hours will be achieved earlier in the year because of warmer winter temperatures. In the northern part of the state, the Julian day by which 1000 chilling hours are accumulated moves forward by 1–2 weeks by the end of the century. Should fruit plants bud out too early because chilling hours have been achieved, there is an increased risk of a frost that kills buds, as was observed in 2007 and 2012, resulting in region-wide crop loss. Figure S11 illustrates that the number of freeze/thaw transitions in February (periods when daily air temperature transitions from below to above freezing) is projected to increase from 2 to 6 events in the month to 4 to 7 events as the spring frost-free date moves earlier in the growing season, thus increasing the likelihood of bud-killing frosts.

A separate issue is the sensitivity of horticultural crops to extreme high and low temperatures, with cold extremes being a primary determinant in the geographic distribution of perennial plants and their cultivation. Due to increases in winter minimum temperatures, the USDA Hardiness Zone, which reflects the ability of cold-tender plants to withstand extreme cold temperatures, is shifting northward. By mid-century, there is no longer any area of zone 5b in the state, and there is no area of zone 6a by the end of the century. By mid-century, the state shifts from being primarily 6a/6b to 6b/7a (Hamlet et al., this issue). This would actually expand the peach production area (and include pluots and nectarines), while potentially changing the apple, peach, and grape varieties planted, and even allowing the planting of brambles not previously considered hardy for Indiana, like boysenberry and tayberry, if these crops are not lost due to early spring freezes.

However, increased summer temperatures with or without concomitant rains are devastating to horticultural crops, impacting fruit set and quality, both of which are determined by pre-harvest environmental conditions. Temperature directly impacts photosynthesis, respiration, and plant hormones, which in turn, changes the production and ratios of sugars, organic acids, and flavonoids. All of these, in turn, impact fruit ripening, firmness, and other parameters of quality, and dictate which varieties consumers prefer, and where those varieties are grown. Climate change will not remove fruit production from Indiana; what it may force is a change in varieties grown, with a greater reliance on Braeburn, Gala, or Fuji (which have little requirement for chilling hours) and loss of Midwest apple favorites like Golden Delicious and Honeycrisp. For growers who invest tens of thousands of dollars for trees that are expected to live 25 years, any changes could mean a loss on their investment. For peach growers, who need a minimum of 700 chilling hours, high winter temperature fluctuations that reset the accumulation of chilling hours may preclude production even in Indiana, as well as southern states like Georgia and the Carolinas.

3.3 Livestock and poultry production

Vulnerabilities to climate change and/or extreme weather events vary across the different food animals. Increased average seasonal temperatures (e.g., Fig. S1) coupled with the increased number of days under heat stress (Figs. S12, S13) pose challenges to all Indiana livestock and poultry producers. To varying degrees, all species, and breeds within species, are susceptible to heat stress and its effects on growth/production rates. These effects are largely attributed to decreased feed intake. On average, animals decrease feed intake by 3–5% for every 1 °C increase above 30 °C (NRC 1980).

On a macro level, decreased feed intake translates to decreased nutrients necessary for growth and other physiological processes. For example, for milking cows, the effects of decreased feed intake are compounded by increased energy needs for milk production and the shunting of already reduced energy reserves away from the udder and towards cooling processes. Energy requirements of a 635-kg cow producing 36 kg/milk per day increase by 22% as ambient temperature increases from 16 to 32 °C (Chase 2006). Using the model of Wolfe et al. (2008), milk production declines of up to 4 kg/cow/day are projected for Indiana (Fig. S14), relative to a normal production level of 32 kg/day at a temperature-humidity index of 72. Similar effects are seen in other species (Habashy et al. 2017; White et al., 2015).

The impact of heat stress goes beyond the reductions in performance associated with reduced feed intake (Angel et al. 2018). Heat stress often reduces fertility rates across species. Reproductive impacts are often seen in both males and females. Heat stress can also affect the animal's response to disease challenge and clearing of infections. Finally, by definition, heat stress is an animal well-being challenge with extreme heat events potentially resulting in the death of the animal (see Renaudeau et al., 2012 for review).

Feed costs account for the largest percentage of recurring costs in food animal production (USDA-NASS 2013). This is especially true for confined feeding operations where, in most cases, all nutrients must be supplied to the animal. In Indiana, livestock feeds utilize corn and soybeans on some level as energy and protein sources and production efficiencies rely on the affordability and accessibility of these feedstuffs. The predicted yield losses in corn and soybean (Figs. 1, 2, and S6) may introduce additional scarcities or, at least, increases in feed costs.

4 Diseases and pests

Climate affects the organisms that cause plant disease in a complex fashion.

Outbreaks of bitter rot, a disease of apples, have been reported to become epiphytotic when summer temperatures rise above their 30-year average (Jones et al. 1996). In 2016, growers in Indiana and surrounding states suffered 20–100% loss on Honeycrisp and Gala when the temperature deviation was 1.1 °C above normal. By mid-century, mean growing season air temperature is projected to increase more in the Midwest than anywhere else in the USA (Angel et al. 2018) and in Indiana by 3 to 4 °C (for RCP 4.5 and 8.5, respectively), with greatly increased variability suggesting more frequent departures above normal. However, temperature alone is not the only environmental factor impacting plant pathogens. Fruit pathogens like apple scab, gray mold, and brown rot, in addition to Phytophthora root rots, are favored by the increased frequency and duration of soil and leaf wetness (Beckerman et al. 2016; Rosenzweig et al., 2001). Brook (1977) demonstrated that the incidence and severity for bitter rot infection increased with continuous moist conditions following inoculation. Infection can occur very early in the growing season, so there may be increased infection risk due to increased spring precipitation, despite the projected decrease in summer and fall precipitation. Warmer, wetter weather will increase the likelihood of fire blight outbreaks in apples and pears, which thrive in a moist climate, spread rapidly, and cause significant economic damage.

Powdery mildew, which infects all temperate fruit varieties, thrives in drier conditions, and increased winter temperatures may facilitate higher populations of pathogens to overwinter in fruit buds. Many plants are asymptomatic after infection, with disease developing upon heat, drought, or flood stress; this stress may also predispose plants to infection by opportunistic root rots like Armillaria spp. and Phytophthora spp.

In addition to pathogens, the increase in plant stress predicted with climate change will lead to reduced plant resistance to insect herbivores and an increase in loss. For example, increased CO2 levels can increase soybean losses from Japanese beetle (Hamilton et al. 2005). In vegetable systems, drought is a key predisposing factor to aphid-vectored virus diseases (Rosenzweig et al., 2001), which compose over 50% of the insect-vectored viruses (Nault, 1997). An altered climate regime in Indiana could invite an entirely new suite of invasive insects. Diffenbaugh et al. (2008) quantified the potential climate change impacts on a suite of Indiana corn pests. In particular, the migratory taxa, armyworm and corn earworm, were projected to become more prevalent in the future climate. This expansion is driven by decreases in the occurrence of severe cold events, allowing these taxa to overwinter in Indiana.

Many diseases associated with livestock production do not have a known association with climate. There is strong evidence, however, of climate affecting the spatio-temporal shifts in transmission of some diseases, especially parasites and arthropod-borne diseases (see Altizer et al. 2013). In the Eastern USA, including Indiana, milder climates have led to increased black-legged tick populations, believed to result in more rapid transmission of Lyme disease (Altizer et al. 2013; Filippelli et al., this issue). Chronic and acute helminth-associated diseases have increased 3 to 4-fold in European climates where these phenomena have been more systematically studied. The climates studied are similar to those of Indiana (Skuce et al., 2013), suggesting that pasture-based cattle and small ruminant farms in Indiana are potentially vulnerable. Indoor production systems are also not without risks. Red mite infestations in poultry production are linked to heat waves (Skuce et al. 2013), which are predicted to increase in frequency and length (Figs. S12 and S13). Likewise, the emergence of several new viruses affecting Indiana pork and poultry over the past 10 years shows that indoor systems with heightened biosecurity protocols are not impervious to new diseases.

Indiana’s changing climate will permit new weed species to reproduce and may limit the growth or competitiveness of other species currently in the state, affecting the economic costs associated with weeds and the strategies used to manage them. Since the widespread adoption of genetically engineered herbicide-resistant crops, herbicide application has largely controlled weeds in Indiana’s row crops. Recently, several common weeds in Indiana have become resistant to the dominant herbicide, glyphosate (Westhoven et al. 2008), increasing the potential for weeds to again influence crop yields in the state. The changing climate will permit new weed species to reproduce in Indiana and may limit the growth or competitiveness of other species currently in the state. For example, McDonald et al. (2009) suggest that damage to maize from *Abutilon theophrasti* may decrease in southern Indiana by later this century, while damage from johnsongrass (*Sorghum halepense*) may increase. Just as some species have evolved to tolerate herbicides, some are thought to be evolving to tolerate broader ranges of environmental conditions (Clements and DiTommaso 2011), potentially expanding the regions in which weeds reduce crop yields.

Climate change will affect competition between weeds and plants through a diverse suite of mechanisms, such as photosynthetic pathways (e.g., Blumenthal and Kray 2014; Peters et al. 2014; Ziska and Dukes 2011). Current monoculture cropping strategies also play a role; year-to-year weather variation can favor weeds in large areas with a single crop genotype that has a limited set of environmental tolerances. Breeding and genetic engineering may be used to develop crops that grow well across wider ranges of climatic conditions, but at the same time, natural selection will be driving the weed flora to be more competitive. Faster seedling growth under warmed conditions has been observed for problematic weeds in Indiana such as Palmer amaranth (*Amaranthus palmeri*), common waterhemp (*Amaranthus rudis*), and redroot pigweed (*Amaranthus retroflexus*; Guo and Al-Khatib 2003). As CO2 concentrations increase, some perennial weeds allocate more carbon to tissues below ground. This change in allocation helps Canada thistle (*Cirsium arvense*) tolerate glyphosate, potentially requiring increased herbicide application rates (Ziska 2016). This mechanism may be common to many Indiana weeds, but few studies have examined this issue.

5 Impacts on soil and water resources

5.1 Water resources

Agricultural water resources in Indiana are highly influenced by the practice of agricultural subsurface drainage which impacts about 50% of cropland in the state. These perforated pipes installed approximately 1 m below the surface in poorly drained soils help to remove excess water in the spring. At the same time the drainage water tends to be high in nitrates, leading to Indiana's high contribution to hypoxia in the Gulf of Mexico. The timing and volume of subsurface drainage in Indiana is primarily driven by precipitation in the non-growing season (October 1–April 30). The ensemble-mean annual subsurface drainflow is projected to increase by up to 50% by the end of the century, particularly for the higher emissions scenario (Fig. 4). It is expected that this increase in drainage volume will lead to an increase in annual nitrate losses, since nitrate concentration has historically been relatively constant with drainage volume. As the drainage season shifts earlier in the spring/winter, a larger portion of drainflow occurs in the non-growing season, especially in northern and central Indiana (Fig. S15).

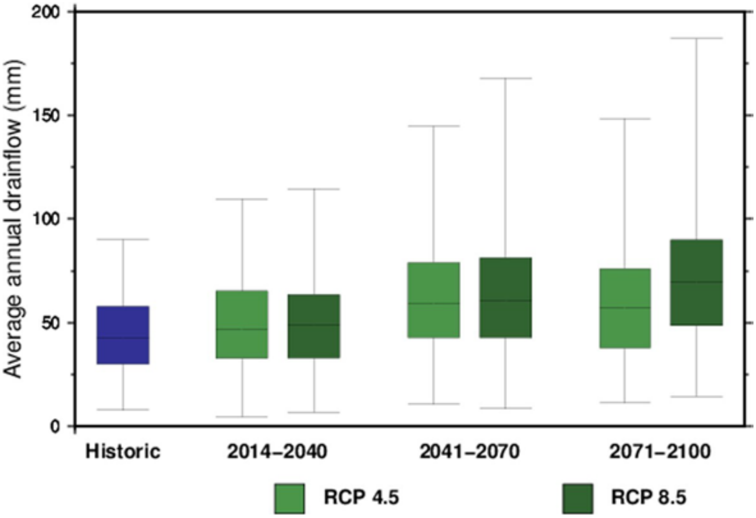

Fig. 4 Simulated subsurface drain flow for the historic period (1981–2010) and projections for early, mid-, and late century for RCP 4.5 and RCP 8.5. The amount of subsurface drainage is important for water resources since historically, the nitrate load released to surface water has been directly proportional to the drainage

volume. Box plots show the distribution of data across all model grid cells and all 6 ensembles. The horizontal line represents the median, box height shows the interquartile range, and whiskers extend to the data minimum/maximum

Indiana water resources are expected to be further impacted by potential increases in water demand for irrigation from the agricultural sector. Future projections indicate that the median growing season water deficit (difference between growing season precipitation and water demand for a well-watered reference crop) which may influence irrigation rates, will increase from approximately 10 to 30 mm for the near future period (Fig. S16). The potentially larger impact is increased adoption of irrigation, which is discussed in the "Soil health" section.

5.2 Soil health

By serving as a binding agent, soil organic matter is an important component of soil aggregate formation. The structure provided by soil aggregates increases the effective soil pore space, allowing greater rates of water movement into the soil, meaning more plant available water, and less overland flow and erosion. Organic matter also holds nutrients in the soil. Carbon and nitrogen are lost from soil through organic matter decomposition. For these reasons, enhanced sequestration of carbon is considered an important tool for both mitigation and adaptation to climate change.

The relative rates of soil decomposition generally increase with temperature but are constrained by other factors (Davidson and Janssens 2006; Giardina and Ryan 2006; Black et al. 2017). Observed total soil respiration was higher in elevated CO2 and temperature plots, but lower in plots with elevated temperature and ambient CO2 (Black et al. 2017). Root respiration and microbial decomposition of soil organic matter (SOM) is also subject to water limitation (Davidson and Janssens 2006). Saturated conditions can lead to anaerobic conditions that slow carbon decomposition, while excessively dry conditions can also slow decomposition.

The amount and rate of microbial transformations of soil organic matter N to inorganic N are also influenced by temperature, soil moisture, and soil organic carbon. Denitrification increases with soil water content and available carbon, but the ratio of N2 to N2O produced decreases for high NO3 concentrations (Weier et al. 1993). Soils with higher SOM generally have higher N2O fluxes (Li et al. 2005).

The Q10 is a measure of the increase in decomposition that can be expected with a 10- degree increase in ambient temperature. A common rule of thumb is that Q10 equals two, meaning that decomposition rates double for every 10-degree increase in temperature, at least for relatively labile carbon at current temperatures (Davidson and Janssens 2006). Substrate availability, quality, soil moisture, and temperature acclimation could offset future Q10, so that the Q10 may decrease as ambient temperature gets higher (Atkin et al. 2005; Post et al. 1982). Based on our simulations, monthly soil temperatures are projected to increase between 1.4–3.2 °C (RCP 4.5) and 1.9–4.2 °C (RCP 8.5) (see Fig. S17), suggesting a 44 to 57% increase in carbon decomposition for Q10 = 2, with no other changes. Recent efforts to emphasize soil health with farmers have resonated, but warmer soil temperatures imply that building organic matter will be a balancing act between increased plant productivity and increased rates of decomposition.

Because SOM is concentrated in the upper soil horizons, erosion is another important mechanism by which SOM is lost (Lal 2004). Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, the most direct of which is the change in the erosive power of rainfall (Nearing, 2001; Pruski and Nearing, 2002a). Nearing (2001) estimated increases in average US rainfall erosivity of 17–29% by mid-century. Pruski and Nearing (2002a) projected that erosion increased by a factor of 2.38% for every 1% increase in daily precipitation intensity for a site in West Lafayette, IN. They simulated a 71–78% increase in soil erosion in corn systems for four soils in the West Lafayette area between 1990 and 2099, despite projected decreases in annual runoff (Pruski and Nearing 2002b). Across Indiana, both the frequency of high- intensity precipitation events and the amount of rain that falls during the highest 1% of events are projected to increase (Widhalm et al. 2018), meaning that good soil management to protect against erosion is going to be even more important in the future.

Overall, soil carbon sequestration has the capacity to reduce CO2 in the atmosphere and store it in the soil. There is uncertainty about the speed and permanence of carbon capture in the soil, which makes a policy of paying for soil carbon sequestration difficult (Gramig 2012). Receiving credit for carbon capture would require some certainty that it took place. Secondary benefits such as soil health (fertility, water holding capacity, etc.) might induce society or individuals to pay for or adopt practices for soil carbon capture.

6 Adaptation

6.1 Agronomic and horticultural crops

Adaptation measures for agronomic crops include changes in the cropping system (double cropping, expanded rotations, cultivar choice, cover crops) and infrastructure changes (investment in irrigation, increased drainage intensity), as summarized in Tables S5 and S6.

Many things determine a farmer’s crop mix and cropping system. These include the resources available (machinery land, labor), the climate, management capacity, and the returns that the farmer might receive from different crops. Based on a habitat mapping approach, Lant et al. (2016) projected a decrease in land suitability for corn, soybean, and winter wheat across the Midwest by the end of the century, including a substantial loss of area in Indiana. While climate change will change the yields and management of different crops, the primary drivers of land use and crop mix are the relative prices of crops that can be grown. Climate change can bring about adaptations that make different crop mixes and cropping systems both possible and potentially more resilient. One such adaptation that looks favorable in the central and northern areas of Indiana and surrounding states is a rotation of corn followed by winter wheat and then double-cropped soybeans (Lant et al. 2016). The key issue is profitability, and the main constraint is low wheat prices (Pfeifer and Habeck 2002). One past constraint has been the length of season, and this is lessened as growing seasons have already lengthened and are projected to lengthen by 3.5 to 4.5 weeks by mid-century (Hamlet et al. this issue), although this could be affected by planting delays (see the “Field and environmental management” section).

Irrigation is often cited as a method of adaptation to climate change. Corn is especially sensitive to drought stress during pollination (June or July), so supplemental irrigation during this period can stabilize corn yields (Apland et al. 1980). Schauberger et al. (2016) found that irrigation can mitigate potential heat stress caused by temperatures above 30 °C, but that detrimental effects still occurred for temperatures above 39 °C, even with irrigation. Historically, Indiana has received abundant growing season precipitation to support rainfed crop growth; however, it is not uncommon for the same fields to experience stress from excess water in the spring and deficit water later in the growing season. This can lead to yield benefits from supplemental irrigation in some years. Irrigated area in Indiana has increased by ~ 160% between 1987 and 2007. As discussed in the “Agronomic crops” section, the future soybean and corn yield deficits relative to the projected potential simulated with the VIC-CropSyst model could be reduced in Central and Southern Indiana if producers switch to irrigation (Fig. S18).

Groundwater is the most common source of irrigation water but is only available in sufficient quantities for irrigation in part of the state (Cherkauer et al., this issue). Ponds or reservoirs could also be used to store and recycle drainage water from periods of excess and provide supplemental irrigation to offset water stress due to climate change. Additional water could also be provided by increasing water storage in the field, for example through controlled drainage.

As revealed by the simulated corn and soybean yields alone, irrigation is found to mitigate yield losses from projected climate change in soybeans in Central and Southern Indiana and in corn throughout the state. Mitigating yield losses comes at the cost of investment in an irrigation system (fixed costs of purchasing, installing, and financing) and the annual operation and maintenance costs that include labor, energy, and water distribution costs attributed to irrigation. The varied effectiveness of irrigation in mitigating yield losses in different CRDs is reflected in the economic investment analysis. The calculated net present value (NPV) of the difference in gross margin between investing in irrigation and farming without irrigation is negative in the northern tier of the state but is increasing in the time period for both RCPs in the central and southern regions of Indiana. Despite the NPV of irrigation becoming more positive over time in the projected period in the central and southern parts of the state, the economic value of investment remains lower than not investing until mid- to late century in the central, west central, and southern CRDs (see Fig. S19). We find that adopting irrigation is not expected to be a beneficial adaptation in the northern or east central CRDs. Considerably higher future prices than we are experiencing today, a lower opportunity cost of investment, or higher yield response to irrigation could, individually or in combination, lead to a different economic finding. While irrigation is often discussed as a potential adaptation to climate change in historically water-abundant areas, in practice, only a limited number of areas in the state may have physical and/or economically feasible access to groundwater for irrigation. The economic costs of operating an irrigation system assumed in this study are largely drawn from the USDA Farm and Ranch Irrigation Survey based on Indiana farms that were already irrigating as of 2012, and thus overcome such economic and physical barriers to adopting irrigation.

Increased installation of subsurface drainage at closer spacing is also possible over the next decades as farmers with existing drains add additional lines and historically undrained fields are drained to combat increasing heavy precipitation events. In addition, both no-till and cover crops have the potential to increase trafficability compared to tilled soil and increase soil organic matter over time, as do the general principles of soil health management being promoted by the USDA.

Pesticide and herbicide efficacy is also contingent upon climatic conditions, but there are few studies on how climate change may affect chemical control (Coakley et al. 1999). Any increases in duration, frequency, or intensity of rainfall will inversely impact the effectiveness of pesticides and herbicides and could increase the cost of dealing with weeds in some years by harming young crops and/or making dates unavailable for management. Rain, directly through wash-off, is a primary factor that impacts fungicide persistence on fruit and leaf surfaces; however, rain also drives plant growth. Warming temperatures accelerate growth of weed seedlings, shortening the time window for effective application of herbicides. As plant surfaces (both leaves and fruit) expand, new growth is unprotected (in the case of protectant fungicides) or “diluted” in the case of systemic fungicides. Currently, Indiana fruit growers apply 10–20 applications of fungicide per season, on average. The more frequent rainfall events predicted by climate change models could result in farmers finding it difficult to keep fungicide residues on plants, triggering more frequent applications.

6.2 Livestock

Adaptation measures for Indiana livestock producers largely center around temperature control (Table S7). Indiana livestock producers already implement practices to mitigate the effects of heat stress. As temperatures continue to increase, however, the cost of implementing these practices may increase. Adaptation-associated cost estimates by species are still rare. Based on decreased crop and forage yield alone, however, Weindl et al. (2015) estimate that climate adaptation practices will account for 3.0% of total agricultural production costs by 2045.

Confined feeding operations create micro-climates within the facilities primarily with ventilation. With increases in seasonal temperatures and the number of consecutive heat stress days (Fig. S13), maintaining optimal micro-climates may require improved or expanded ventilation systems or increased energy, operating, and maintenance costs. Thus, alternative systems may be required with additional costs. Dairy operations using confined feeding programs may incur the highest percentage of these costs (Key et al. 2014). Pasture-based systems may also incur costs of additional/new shelters or other environmental buffers to account for increased frequency of extreme weather events and increased intensity of solar radiation.

There is a great deal known on dietary interactions with heat stress. For example, the impact of heat stress in ruminants can be partially mitigated with feeds containing lower amounts of dry matter, which reduces heat generated through rumen fermentation. The efficacy of different types of supplementations (e.g., probiotics) in reducing heat stress markers in different species is also being investigated (see Renaudeau et al., 2012). The adaptation by the livestock industry to the use of dried distiller’s grains with solubles in the face of rising corn prices and reduced accessibility demonstrates the capacity of producers to adapt and develop comparably effective diets with new feedstuffs.

As most food animals in Indiana are raised indoors in micro-climates, breeding programs have not traditionally focused on incorporating heat tolerance for all species. Heat-tolerant traits can be found and selected for within different species (see Nienaber and Hahn, 2007 for review). There is often some antagonism, however, between heat tolerance and other important production traits such as feed efficiency and reproductive traits. For instance, heat-tolerant cattle breeds often adapt more quickly to heat events by decreasing milk production (Berman 2011). The capacity to make widespread genetic changes also varies across the different livestock industries. Such changes, when possible, are more easily facilitated in poultry industries based on the extensive integrated nature of poultry production and the comparatively short breeding cycle of birds. On the opposite end of the spectrum is beef cattle production, where there is limited integration and longer breeding cycles.

6.3 Field and environmental management

Producers responding to changes in working conditions may benefit from changes in field management. Earlier occurrences of the last spring frost (e.g., Sinha and Cherkauer 2010) may result in earlier planting dates, but increased spring moisture may still delay planting despite warmer temperatures (Dohleman and Long, 2009; Rogovska and Cruse 2011). Days suitable for fieldwork (DSFW) are the number of days available to perform work in agricultural fields. A day is not suitable for field work when it is too wet for farm machinery to enter fields. Based on 1980– 2010 NASS Crop Progress Data for Indiana, there has been a statistically significant decrease of 0.5 days per week in the mean DSFW/week during planting for 1995–2010 relative to 1980– 1994. Our climate change projections suggest an increase in average spring (March, April, May) precipitation during the spring field preparation and planting period, but this is balanced by the earlier arrival of warming and drying weather conditions leading to a median decrease in the number of DSFW during April, May, and June of just one day by mid-century (Fig. S20a). By improving soil aggregate stability and allowing greater rates of water movement into the soil, soil health management can be an important management adaptation to improve field access (see the “Soil health” section and Table S7). Other management adaptations that may be necessary in some years include purchasing equipment that can enter fields under wetter soil conditions (e.g., continuous tread/track tractors), larger equipment capable of covering more acres in less time, or increased drainage intensity capable of removing higher volumes of water more quickly. The harvest period is also very important to optimize crop quality and field dry down that minimizes drying costs. A slight increase in the DSFW is projected for fall (Fig. S20b), which is consistent with the observed statistically significant increase in the mean DSFW/week during harvest for 1995–2010 relative to 1980–1994.

Heat stress is a life-threatening condition that also inhibits human and animal physical activity (Haldane 1905; Brunt 1943). Here, we estimate agricultural labor capacity based on the Simplified Wet Bulb Globe Temperature, which assumes that people are in direct sunlight exposure (Buzan et al., 2015). We use a labor capacity function that factors in different levels of metabolic output relative to different levels of heat stress to calculate the change in annual total labor capacity (Dunne et al. 2013; Buzan and Huber, 2020). The multi-model mean annual total labor capacity for Indiana is projected to decrease from 92 to 94% for the 1986–2005 time period to 82–88% with an increase of mean annual temperature of 3 °C (Fig. S22), broadly consistent with a previous work (Dunne et al. 2013; Smith et al. 2016). Summertime work will need to be adjusted to evenings with the cessation of daytime activity for outdoor work.

7 Conclusions and future work

The first goal of this work was to better constrain quantitative estimates of the range of climate impacts expected for Indiana. This was accomplished using down-scaled and bias-corrected climate projections from an ensemble of six GCMs selected for their ability to reproduce historic Indiana climate, to run the coupled VIC-CropSyst hydrology and dynamic crop growth model adapted to Indiana’s poorly drained landscape at high spatial resolution. Model simulations were supplemented by more extensive results available in a review of the literature, within the range of changes anticipated in Indiana. Secondly, this assessment provides a strategy for adaptation, based on our experiences with agricultural management in the state.

Due to increased frequency of drought and heat stress, models predict that corn yield will decline relative to yield potential (very high confidence) and our models project declines of 7– 14% (RCP 4.5) and 8–17% (RCP 8.5) by mid-century. These losses could be partially compensated by adaptation measures such as changes in cropping systems, planting date, crop genetics, soil health, and providing additional water through supplemental irrigation or drainage management. Soybean yield declines are projected due to heat and drought stress (very high confidence) by 2–8% (RCP 4.5) and 0–8% (RCP 8.5) by mid-century. These declines may be compensated in large part by increased productivity due to CO2 enhancement. In addition, double cropping of soybeans is increasingly viable in southern Indiana. Forage quantity may be impacted by variable winter conditions, but the biggest threat to forages is decreasing quality due to rising temperatures (very high confidence), including decreases in protein content to 1.5 or 1.6% by mid-century (for RCP 4.5 and 8.5, respectively) and higher neutral detergent fiber levels. These negative effects may be mitigated, in part, by developing cultivars with greater fall dormancy.

An additional threat to perennial crops, including tree and fruit crops, is changes that affect winter hardening (low confidence) and dormancy (very high confidence). In the southern part of the state, the annual cumulative chilling hours is projected to decrease by over 200 h, reducing the suitability for some apple, peach, and grape varieties. In the northern part of the state, chilling hours will be accumulated about a month earlier by mid-century (both RCPs), putting early-budding fruits at greater risk for frost damage. Shifts in the USDA Hardiness Zone will expand the area suitable for peach, pluot, and nectarine production and may allow the planting of brambles not previously considered hardy for Indiana, like boysenberry and tayberry (high confidence).

A major threat to livestock production in the state is increased heat stress, with decreased feed intake expected when temperatures exceed 29 °C (very high confidence). By the end of the century, temperatures will exceed 29 °C for 99 (RCP 4.5) to 129 days/ year (RCP 8.5) and will stay that high for over a week at a time. Increasing winter and spring precipitation will increase soil saturation, increasing risk of soil erosion, disease infestation, and planting delays. Despite an earlier frost-free season, traditional planting dates may not change dramatically because the number of days suitable for field work is not projected to change (low confidence).

The impact of weeds, pests, and diseases is difficult to predict. Overall, there are concerns regarding increasing disease and pest pressure due to changes in overwinter survival, warm wet springs, and hot summers. Due to greater genetic diversity than single-species row crops, weeds have greater tolerance of a wide range of environmental conditions.

This assessment focused on field-scale impacts to soil and water resources. The cumulative impacts of future changes to watershed scale water quality are addressed by Cherkauer et al. (this issue). There is the potential for increases in annual nitrate leaching load to surface water due to a 50% increase in subsurface drainage volume. A greater proportion of this drainage is occurring during the non-growing season, increasing the potential benefit of controlled drainage as a conservation practice.

Agriculture is a major emitter of greenhouse gasses (CO2, nitrous oxides, and methane). However, it can play a role in mitigating its own greenhouse gasses and even storing CO2 from the atmosphere. To get this done usually requires a policy that puts caps on greenhouse gas emissions and creates a market where those who can reduce or capture greenhouse gasses at the lowest cost can be paid to do so.

Overall, climate impacts to the agricultural sector in Indiana are variable and complex. There is the potential for large negative impacts to current agricultural production practices in the State of Indiana. The overall economic impacts of projected changes to the agricultural sector in Indiana were not evaluated as part of this assessment. While climate change will change the suitability for different crops (Lant et al. 2016), their yields and their management, the primary driver of system choice and crop mix will be the relative prices of crops that can be grown. This further influences the distribution of future land use in Indiana, which was beyond the scope of this study. Overall there is still great potential for continued production of commodity crops, horticultural and livestock in Indiana with adaptations in management practice, cultivar or species composition, or crop rotation. In many cases, producers have already begun to make the shifts needed to better manage the increased variability and risk in our production system. There is a need for continued applied research into climate-adaptive management systems and extension education programming to provide Indiana's producers with the science-based information needed to make informed decisions regarding their options to minimize risk to themselves and the environment.

Supplementary Information The online version contains supplementary material available at https://doi.org/ 10.1007/s10584-020-02934-9.

Acknowledgments This paper is a contribution to the Indiana Climate Change Impacts Assessment (INCCIA). The INCCIA is organized and financially supported by the Purdue Climate Change Research Center.

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