13 | Climate Sensitivity of Agricultural Energy Crop Productivity

Benjamin L. Preston[1], Matthew Langholtz[1],
Laurence Eaton[1], Chris Daly[2], and Mike Halbleib[2]

[1] Oak Ridge National Laboratory
[2] Oregon State University

13.1 Introduction

Bioenergy, including biofuels and biopower, has received significant attention as a technology for increasing U.S. energy security and offsetting greenhouse gas (GHG) emissions from fossil energy (Schneider and McCarl 2003; Adler, Grosso, and Parton 2007; Campbell et al. 2008; Field, Campbell, and Lobell 2008). However, the potential effect of climate change on biomass production has received comparatively little attention (Jones and Dalton 2012; Wilbanks et al. 2012; Tuck et al. 2006; Schröter et al. 2005; Haberl et al. 2011; Poudel et al. 2011; de Lucena et al. 2009; Dominguez-Faus et al. 2013). For example, recent assessments of the implications of climate change for U.S. energy systems acknowledge the potential climate sensitivity of biomass (CCSP 2007; Wilbanks et al. 2012), but contain little discussion of the timing and magnitude of future climate effects on different biomass resources.

As with all agricultural and forestry production, biomass resources for bioenergy are highly exposed and sensitive to weather and climate (Wilbanks et al. 2012), and thus, they may be more vulnerable than other energy sources to climate change (Eaves and Eaves 2007). Given projections that some extreme weather events will increase in frequency, duration, and/or intensity (Ortman and Guarneri 2009), climate risk to biomass derived from agricultural and forest enterprises would also be expected to increase. Yet, future changes in climate could also create opportunities for enhanced yields of particular energy crops in areas that are not currently climatically suitable for production of those crops. Greater attention to the implications of climate change for the production of biomass resources is therefore warranted.

This chapter differs from other chapters in this report in that it evaluates the effects of climatic changes on potential future biomass production, rather than evaluating environmental effects of biomass production. Thus, it does not apply the production scenarios evaluated in the other chapters. The objective of this chapter is to assess the sensitivity of U.S. cellulosic biomass to climate change by presenting initial empirical estimates of the implications of alternative climate-change scenarios for a number of illustrative energy crops. In doing so, the chapter seeks to address the extent to which future changes in climate variables (e.g., temperature and precipitation) are projected to drive significant changes (positive or negative) in the yields of energy crops at the national, regional, or county level. In addition, this chapter addresses the implications of those changes for biomass production, as well as key knowledge gaps arising from this assessment and its methods, which could be addressed with future research. Because this chapter analyzes the climate sensitivity of biomass without consideration for changes in management practices, other changes in environmental conditions, or the economics of production, results should not be treated as future predictions. Rather, the biomass projections based on particular climate scenarios help in (1) identifying the areas where production of different energy crops is anticipated to benefit or to be harmed in response to climate change and (2) prioritizing future research needs.

13.2 Methods

13.2.1 Scope of Assessment

This assessment estimates the implications of climate change for the geographic distribution and yields of potential cellulosic energy crops. Yields were modeled at the county level for the continental United States for the current climate and in response to future climate conditions as simulated by multiple Earth system models (ESMs) and model configurations (i.e., different versions of a particular ESM). The modeling also incorporates four different scenarios of future GHG concentrations in the atmosphere to capture the uncertainty in global GHG emissions. The assessment includes seven energy crops:

1. Conservation Reserve Program (CRP) mix of grasses, forbes, and legumes[1]
2. Energy Cane
3. Miscanthus
4. Poplar
5. Sorghum
6. Switchgrass (lowland and upland)
7. Willow

Forest biomass is not included in this assessment.

Yields for these energy crops were estimated for two future time periods, 2050 and 2070; that is, the assessment looks further into the future than the other modeling conducted for *BT16*. Changes in climate over shorter time frames (e.g., 2030) may be difficult to distinguish from natural climate variability. Hence, results reflect yield changes that would be anticipated in response to changes in climate conditions for U.S. counties over the long term. This long-term temporal extent enables near-term developments in biomass production to be considered in the context of long-term uncertainty in future climate change. Results do not account for changes in the intensity, frequency, or duration of extreme weather events; indirect effects of climate change such as pests or disease; fertilization effects associated with higher atmospheric carbon dioxide (CO_2) concentrations; or changes in management practices or biotechnology.

Therefore, the results reflect first-order estimates of biomass for the purpose of identifying energy crops that may be particularly vulnerable or resilient to changes in climate variables, as well as identifying possible range shifts. Also, because of inherent uncertainties in long-term economic trends and the dynamics of biomass and bioenergy markets, this assessment does not consider the economic drivers of energy crop production or interpret the results in the context of different price assumptions.

13.2.2 Description of Modeling Approach

Yields for the biomass crops were modeled using a two-stage process. First, relative yields of particular energy crops for current climate conditions were modeled using the PRISM (Parameter-elevation Relationships on Independent Slopes Model) Environmental Model (PRISM-EM) (Halbleib, Daly, and Hannaway 2012; DOE 2016). PRISM-EM is an empirical model for estimating production potential for selected energy crops under various water balance, temperature, and soil constraints based on extrapolation of field trial data. Relative yield represents the fraction of the theoretical maximum physiological yield that can be achieved for a particular energy crop in a location given environmental constraints. Relative yield values range from 0% (no production) to 100% (maximum production). Although not a direct measure of absolute yields (i.e., tons per acre) of energy crops, increases in relative yields are indicative of increases in absolute yields while decreases in relative yields are indicative of decreases in absolute yields. The two key inputs for PRISM-EM are climate conditions from the PRISM historical climate data set (Daly et al. 2008) and soil conditions from the Soil Survey Geographic database (USDA 2016). Because PRISM-EM is based on historical climate information, it does not currently model the effects of future changes in climate. To extrapolate the results from PRISM-EM into the future, the historical

[1] CRP land was not included in potential biomass production areas in the BT16 volume 1 but is a potential source of biomass described in section 13.3.2.1.

climate, soil, and relative yield information used by and generated from PRISM-EM was used to develop Bayesian statistical models for each of the aforementioned energy crops. The Bayesian models emulate PRISM-EM by using the quantitative relationships among temperature, rainfall, soil conditions, and energy crop yields to generate expected relative yields for particular crops and a given combination of environmental conditions.

Bayesian models were trained by using 30 years of PRISM-EM results aggregated to the county level in conjunction with annual average minimum temperature (T_{min}), annual average maximum temperature (T_{max}), and total annual precipitation for each year, as well as the soil conditions for each county. A comparison of county-level, aggregate-yield results from the Bayesian models indicated that they perform well in capturing the magnitude and spatial distribution of energy crop yields (see appendix A for validation and uncertainty metrics). Sensitivity analyses conducted on the Bayesian models indicated precipitation was the dominant variable influencing yield, followed by temperature. The one exception was energy cane, for which temperature (T_{min} and T_{max}) was more important. In most instances, modeled yield had a greater sensitivity to T_{min} than T_{max} (fig. 13.1). In these models, yield was rather insensitive to soil variables relative to climate variables (fig. 13.1).

In the second stage of the modeling, Bayesian models trained with PRISM-EM results were used to project relative yields of energy crops in response to alternative climate information and scenarios (see fig. 13.2), based on the assumption that the relationships

Figure 13.1 | Sensitivity of Bayesian yield models to input variables. Sensitivity was calculated as the variance reduction (expressed as a percentage) associated with each input variable (Marcot 2012). Higher variance reduction scores reflect greater sensitivity to specified input variables.

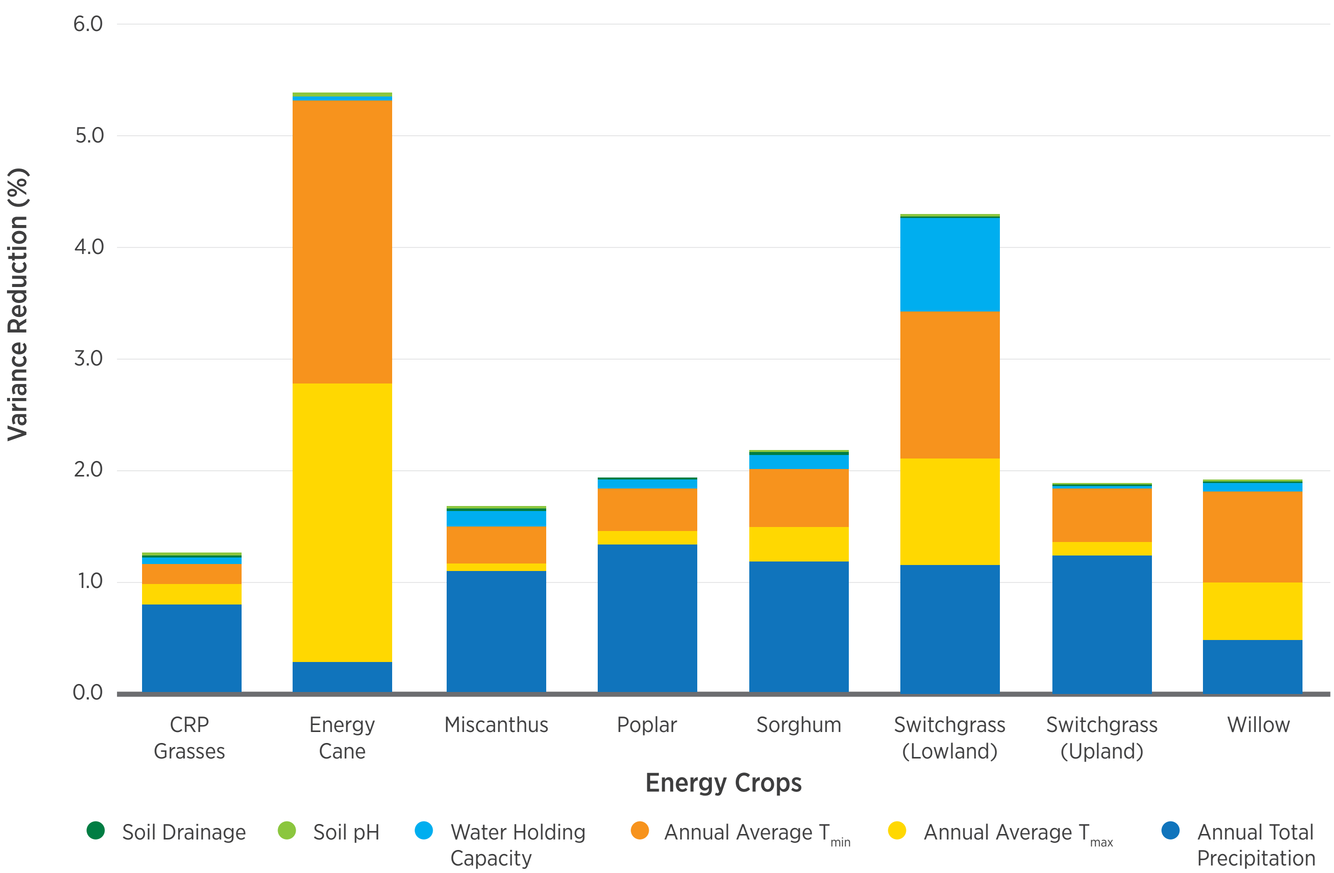
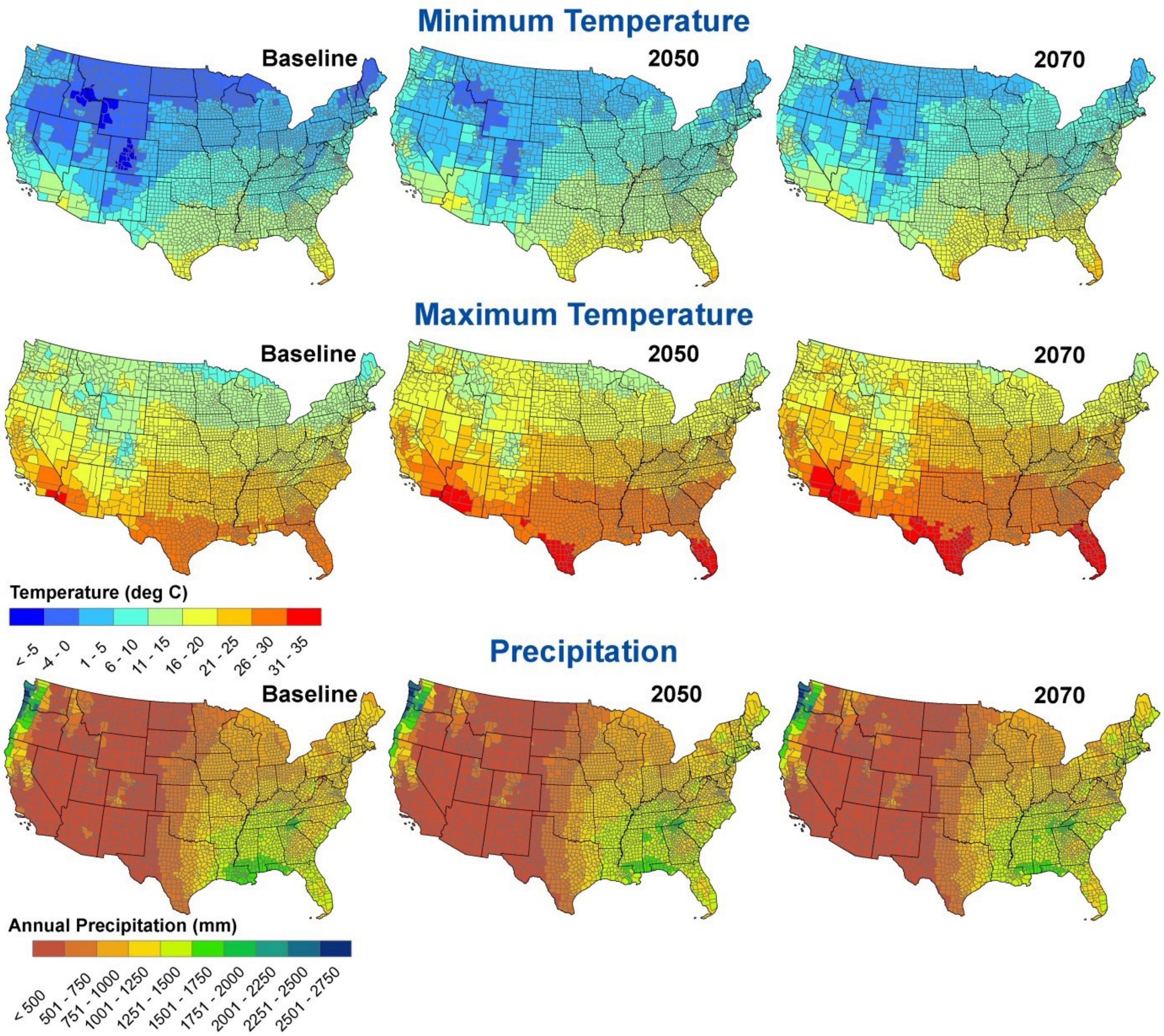


Figure 13.2 | Geographic distribution of baseline T_{min}, T_{max}, and annual precipitation for U.S. counties and projected changes for 2050 and 2070 for the Representative Concentration Pathway (RCP) 8.5 scenario. Maps represent the average of results for 11 different ESM configurations.



between climate variables and relative yields within PRISM-EM would continue to be valid into the future.

Scenarios of current and future climate from ESMs were based on the WorldClim project, which developed global, high-resolution data for historical climate conditions (Hijmans et al. 2005). The data for the current climate represent interpolated surfaces using weather stations from around the world, as well as elevation information to account for the influences of topography on climate. Variables used for modeling energy crop yields for the baseline period of 1950–2000 include annual average T_{min}, annual average T_{max}, and total annual precipitation. Annual averages for each variable in each year of the 1950–2000 baseline period were averaged to generate a 51-year climatology of baseline conditions. When aggregated to U.S. counties, the spatial gradients in temperature and rainfall across the United States are clearly visible (fig. 13.2). For example, WorldClim captures the latitudinal gradient in temperature associated with both T_{min} and T_{max}, as well as the effects of mountains such as the Appalachian Mountains in the Southeast and the Rocky Mountains in the West. In addition, the wetter regions of the Southeast and coastal Pacific Northwest are contrasted against the drier regions of the West.

For projections of future climate, WorldClim generates scenarios by downscaling simulations of ESMs from different international modeling groups using the historical WorldClim climatology. The future climate for any given U.S. county is difficult to project with confidence because of uncertainties in future GHG emissions, as well as uncertainties in how the climate will respond to those emissions. To account for this uncertainty in projections of future climate, WorldClim data for 11 different ESM configurations were used (table 13.1 and fig. 13.3). In addition, each ESM configuration was used with four different atmospheric GHG-concentration scenarios, known as the Representative Concentration Pathways (RCPs). The RCPs represent a wide range of alternative assumptions regarding future global GHG emissions and their accumulation in the atmosphere. Each RCP is identified by a number representing the radiative forcing in watts/m^2. Lower radiative forcing (i.e., RCP 2.6) is associated with lower magnitudes of future climate change relative to higher radiative forcing (i.e., RCP 8.5). WorldClim aggregates ESM simulations for two different time periods, 2050 and 2070, with each time period representing a 20-year average centered on that year (i.e., 2050 is the average of the years 2041–2060, and 2070 is the average of 2061–2080). Therefore, climate change-related relative yields for each energy crop and county include a baseline estimate for the current climate (1950-2000) as well as 44 estimates of relative yields (based on 11 ESM configurations, each using four emissions scenarios) for each county in 2050 and 2070, respectively.

Each of the 11 ESM configurations generates a different distribution of temperature and precipitation changes for U.S. counties (fig. 13.2). Most counties experience temperature increases of 4°–6°C by 2070 relative to the baseline period across different ESMs

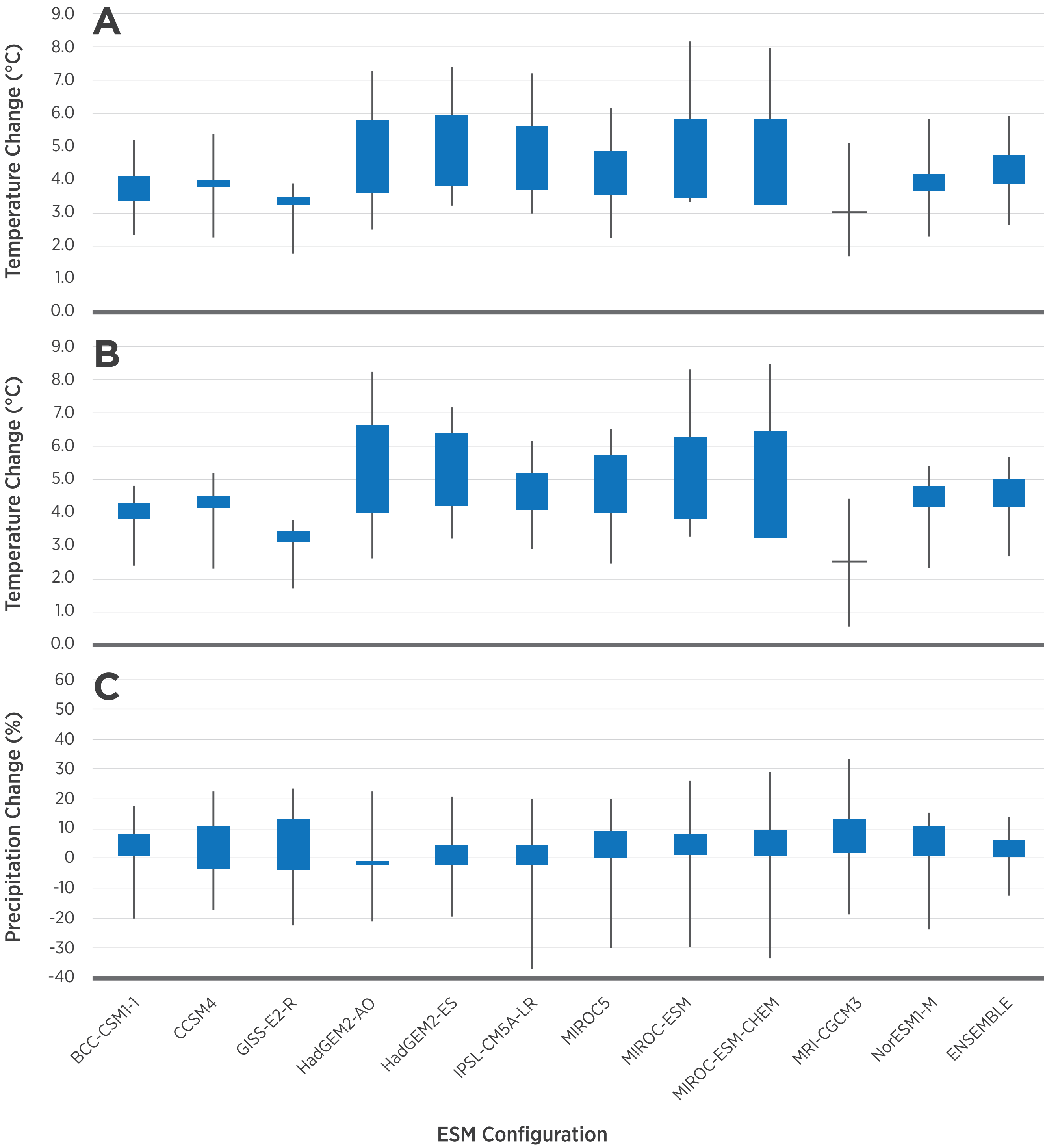
Table 13.1 | ESM Configurations Used in Estimating Energy Crop Yields in Response to Climate Change

ESM	Model Origin
BCC-CSM1-1	China
CCSM4	USA
GISS-E2-R	USA
HadGEM2-AO	United Kingdom
HadGEM2-ES	United Kingdom
IPSL-CM5A-LR	France
MIROC-ESM-CHEM	Japan
MIROC-ESM	Japan
MIROC5	Japan
MRI-CGCM3	Japan
NorESM1-M	Norway

for RCP 8.5. However, increases in temperature in excess of 8°C are projected for some counties. Meanwhile, counties closer to coastal regions experience more modest increases of 2°–3°C. For RCP 2.6, which assumes that atmospheric concentrations of GHG emissions stabilize and then decline over the 21st century, the temperature changes with respect to the baseline are similar for both 2050 and 2070. On average, climate change causes increases in both T_{min} and T_{max} throughout the continental United States. These higher temperatures, and, in particular, higher minimum temperatures, are an important factor influencing the potential future relative yields of different energy crops in different U.S. regions.

While all the ESM configurations project that temperatures increase in all counties with respect to the baseline period (fig. 13.2 and fig. 13.3), changes in rainfall vary significantly in magnitude. Furthermore,

Figure 13.3 | Comparison of the distribution of a) T_{min}, b) T_{max}, and c) precipitation for each of the 11 ESM configurations used to assess the sensitivity of bioenergy feedstock yields to climate change, as well as the ensemble average. Boxes represent the 25th and 75th percentile changes for U.S. counties in 2070 for RCP 8.5. Whiskers represent the minimum and maximum values.



the direction (i.e., increase or decrease) of change in rainfall is difficult to interpret from model results, because differences in rainfall changes among various ESM configurations are masked when results are averaged together. For example, changes on the order of ±40% by 2070 are projected in individual counties for individual models for RCP 8.5, but the average across ESMs is within ±10%. Counties across the northern United States would tend to experience increases in annual rainfall, particularly in the Northeast, while counties in the South would experience declines, particularly the Southwest. These results are consistent with other assessments of model projections of future precipitation changes (Walsh et al. 2014). However, analyses based on a different combination of ESMs generate different results. Furthermore, changes in precipitation are projected to vary among seasons (Walsh et al. 2014), which is an important factor affecting biomass yields.

To estimate future changes in relative yields, the county-level aggregate WorldClim data for each ESM configuration and RCP were used as input to the Bayesian models, resulting in maximum likelihood estimates of relative yields. Yield estimates for each ESM configuration and RCP were subsequently averaged. Analysis of variance was used to test for differences between changes in relative yields for individual ESM configurations and RCPs compared with the WorldClim baseline results. In addition, county-level results were aggregated to the national level using a weighted average, with the weights based on the area in each county identified as cropland in the U.S. Department of Agriculture's (USDA's) 2015 cropland data layer (NASS 2015).

13.3 Results

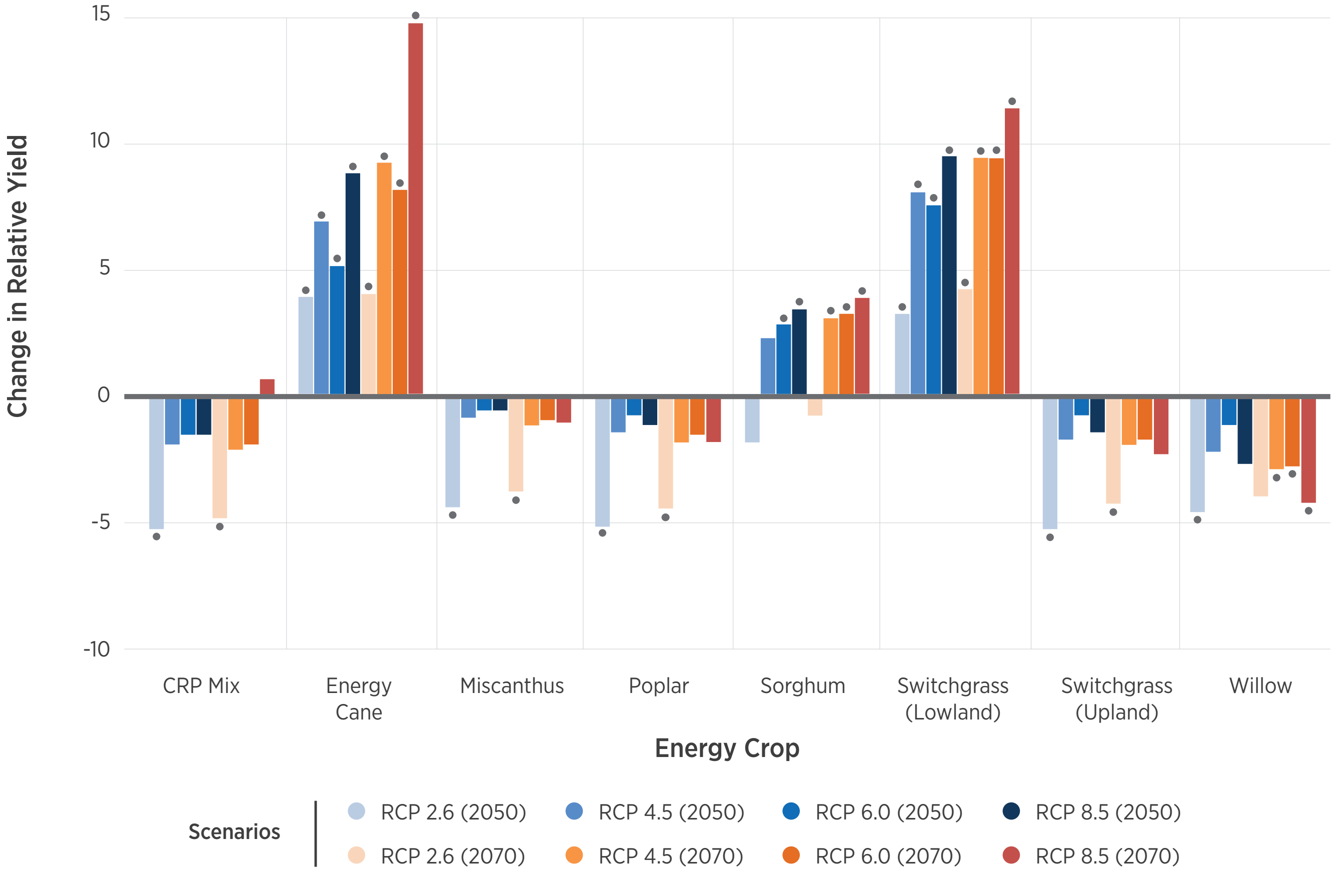
Results of the assessment of climate change effects on cellulosic-energy crop relative yields are summarized here, starting with the presentation of aggregate national results across the different crops. This is followed by the presentation of county-level results for individual energy crops to highlight regional patterns of potential yield effects.

13.3.1 National-Level Results

The aggregate national results (weighted by cropland area) reflect the geographic range of different energy crops as well as the differential sensitivities of crop yields to climate conditions (fig. 13.4). For example, because the most productive areas for energy cane and, to a lesser extent lowland switchgrass, are currently restricted to the warmer climate of the southern United States, these energy crops benefit from climate change and, in particular, higher temperatures. In addition, the benefits increase over time and/or with higher atmospheric concentrations of GHGs (i.e., RCPs). For energy cane, increases range from 4 to 15 percentage points by 2070 among the different RCPs.[2] Similarly, increases for lowland switchgrass range from 4 to 12 percentage points by 2070. These increases are attributable to large increases in yields in the southern

[2] Because relative yield is a percent value by definition, all energy crop modeling results for climate change scenarios are reported as percentage point changes in relative yields as compared with the 1950-2000 baseline.

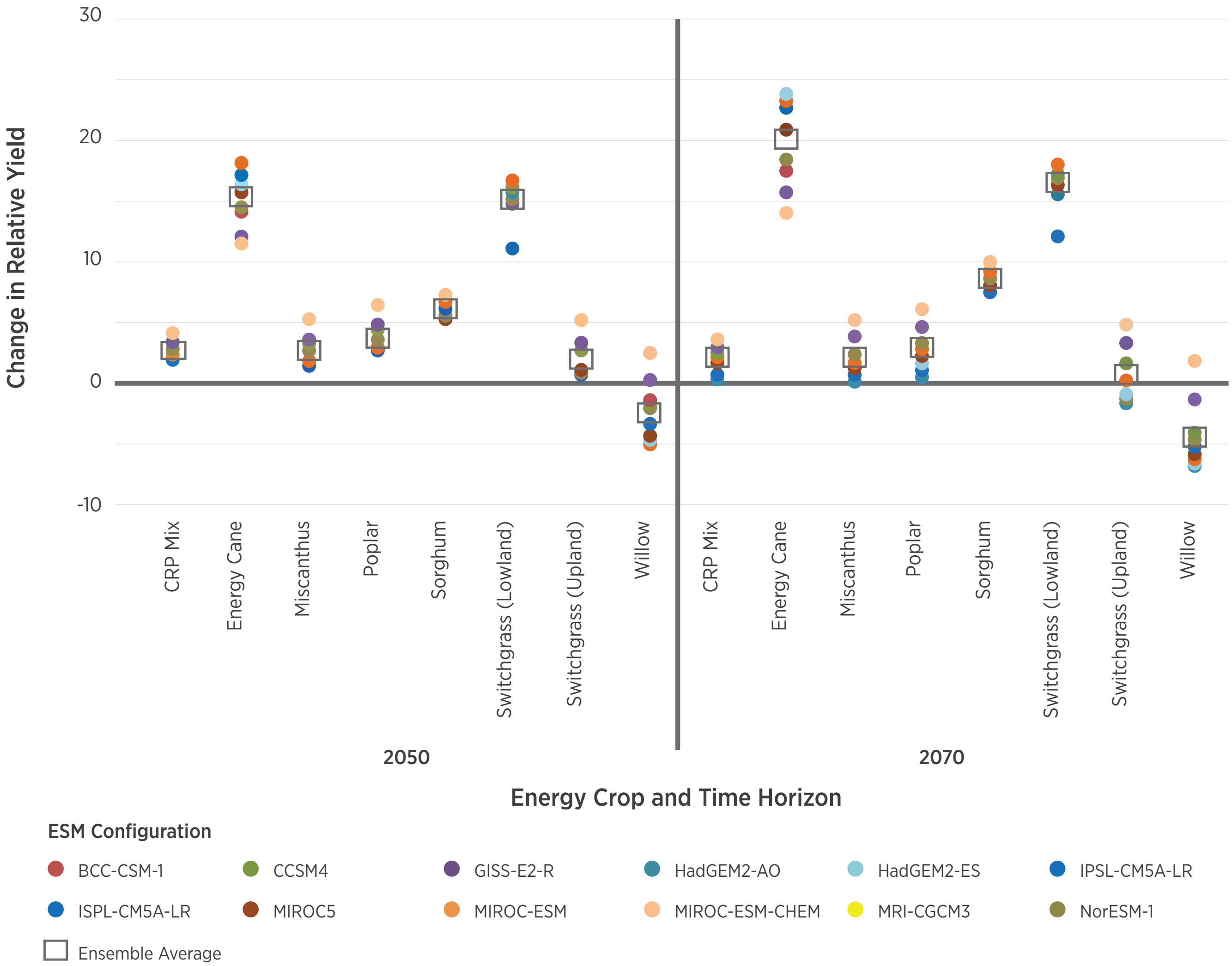
Figure 13.4 | Changes (percentage points) in aggregate national relative yields (weighted by county crop area) relative to baseline (1950–2000) estimates for alternative climate change scenarios. The grey dot (•) indicates a significant difference (p<0.05) in relative yields compared with the baseline climate.



United States, Mid-Atlantic, and Midwest (see sections 13.3.2.2 and 13.3.2.6), which reflects a general northward shift in the productive range of energy cane.

In contrast, energy crops that are restricted to cooler climates of the United States, such as upland switchgrass and willow, experience little change or modest reductions in yields. The relatively modest effects of climate change at the national aggregate level are a function of declining yields in some counties for certain energy crops being offset by increases in other counties. This suggests that the long-term changes in average U.S. climate conditions and the associated shifts in the geographic distribution of biomass yields are not necessarily a threat to biomass production at the national level. However, as illustrated in the county-level results, the suitability of a given energy crop for a particular region may change significantly over time. Furthermore, changes in seasonal conditions or changes in extreme events and disturbances may be even more related to biomass yields than long-term changes in average temperature and rainfall.

Figure 13.5 | Changes (percentage points) in aggregate national average relative yields (weighted by county crop area) compared with the 1950–2000 baseline. The figure includes results for different energy crops in response to alternative climate change conditions in 2050 and 2070 as represented by different ESM configurations for RCP 8.5.



For a number of energy crops, variability in model results existed among different ESM configurations (fig. 13.5). As a consequence, results for an individual ESM configuration could differ from the ensemble average by up to ±5 percentage points. For most energy crops, the direction of change compared to the baseline was the same among the different ESM configurations. However, for willow and upland switchgrass, different ESMs generated relative yields both higher and lower than those estimated for baseline conditions (fig. 13.5). This suggests greater uncertainty regarding the aggregate sensitivity of these energy crops to changes in climate conditions.

13.3.2 County-Level Results

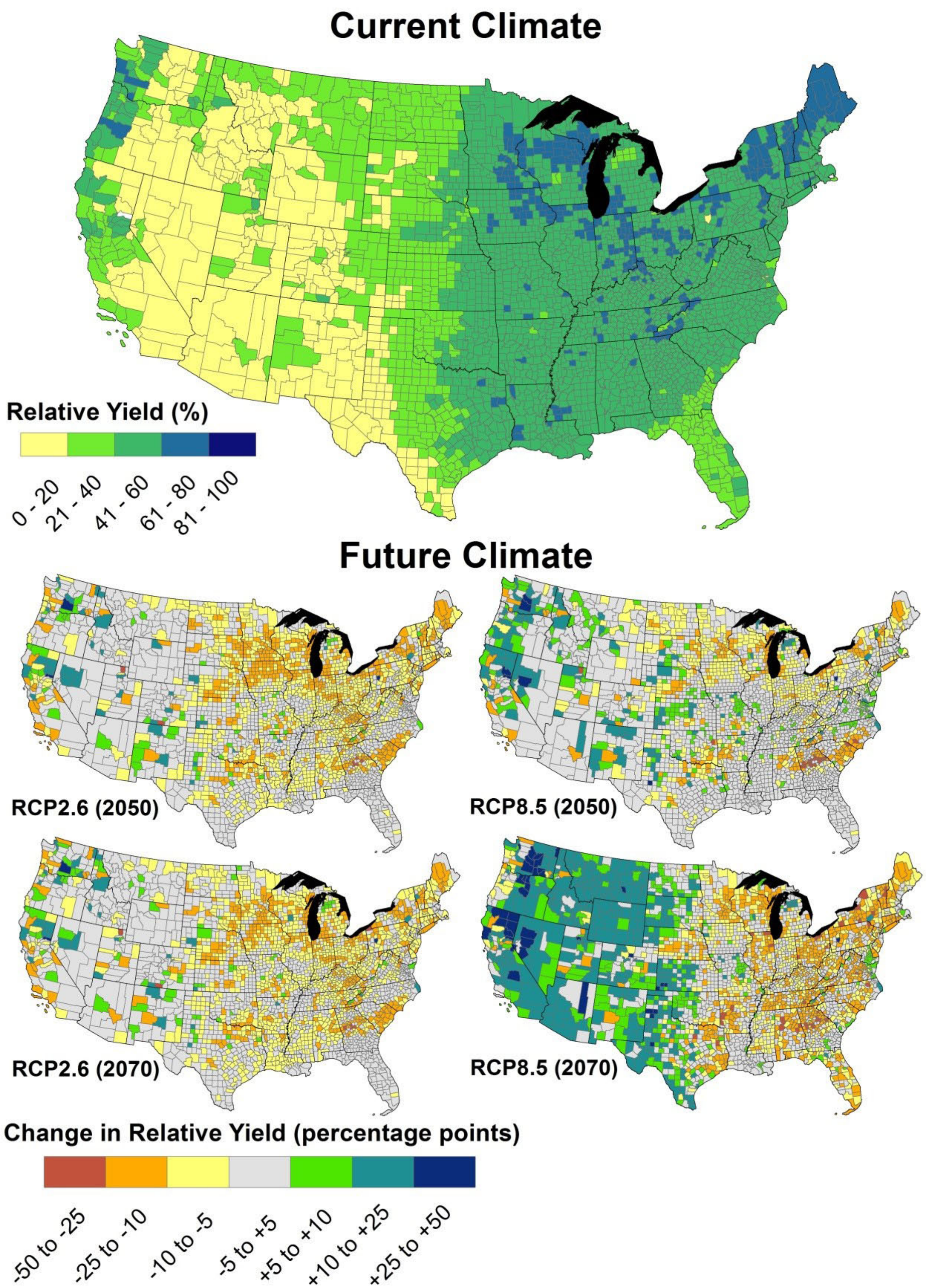
13.3.2.1 CRP Grasses

USDA's CRP encourages farmers to convert highly erodible cropland or other environmentally sensitive land area to vegetative cover. The goal of the program is to reduce soil erosion, enhance water quantity and quality, and provide habitat for wildlife. A wide variety of species and varieties of vegetation are found within CRP seed mixes, with different mixes used in different regions of the United States. Increasingly, a mix of perennial grasses is being explored as a means of maximizing biomass production on CRP lands (Zamora et al. 2013; Venuto and Daniel 2010; Mapemba et al. 2007). Such grasses could be deployed as a biomass resource on other land as well.

At present, much of the eastern United States is conducive to relatively high yields from CRP grasses, as is much of the coastal Pacific Northwest (fig. 13.6). This suggests that areas with higher rainfall and temperature are most conducive to the development of high-yield CRP mixes. The climate change projections reflect a clear east-west division with respect to changes in yields of CRP grasses. For RCP 2.6, relative yields across much of the United States are within ±10 percentage points of baseline values (fig. 13.6). However, yield reductions of 10–25 percentage points are projected in isolated areas of the South (e.g., coastal Carolinas and central Georgia), as well as in the upper Midwest (e.g., Iowa and Wisconsin) and New England (e.g., Maine). In contrast, yield increases of 10–25 percentage points are projected for Appalachia and other isolated areas of the country. Yield effects under RCP 8.5 suggest sharp contrasts between the eastern and western United States , with yield declines of 10–25 percentage points throughout much of the eastern states and yield increases across much of the western states, particularly by 2070 (fig. 13.6).

Although the climate projections suggest there is potential for significant increases in relative yields for CRP mixes across the West, these percentage increases occur in areas with low absolute baseline yields. Therefore, the projected declines in relative yields in the eastern United States are potentially more significant, as these areas have higher absolute yields. In many instances, the yield reductions are less than 10 percentage points; however, larger reductions are projected for some areas, particularly under RCP 8.5. It should also be noted that as CRP vegetative cover comprises a broad mix of species, there may be significant opportunities for adapting the mix of species used in a particular region to reduce adverse consequences and enhance potential benefits of climate change to yields.

Figure 13.6 | Relative yields for a CRP mix of grasses under baseline climate conditions, as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



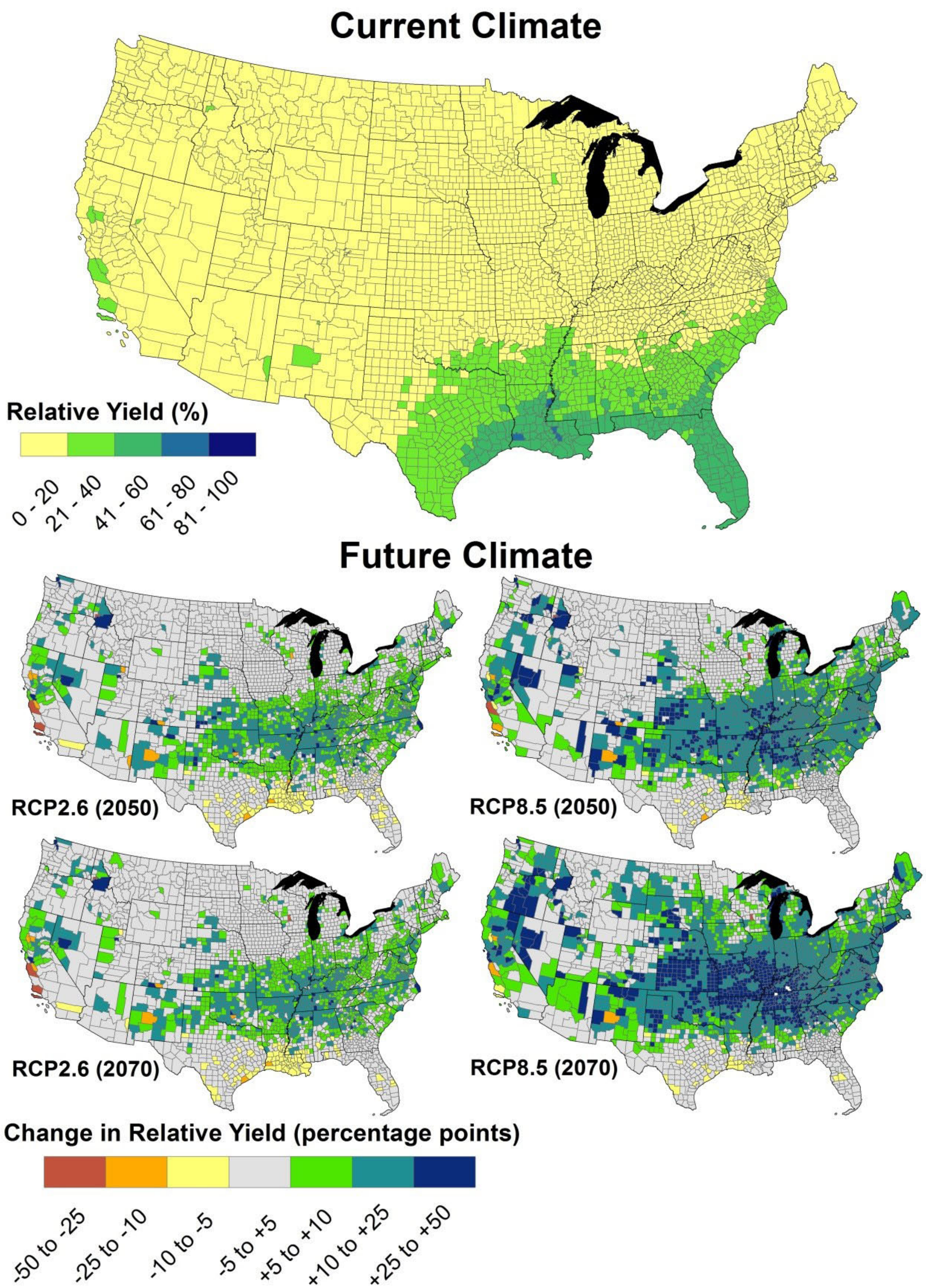
13.3.2.2 Energy Cane

The perennial grass energy cane is a variety of sugar cane selected for high fiber content that enhances biomass yield, making it suitable for use as an energy crop (Matsuoka et al. 2014). Due to poor frost resistance (Sandhu and Gilbert 2014), potential land areas suitable for energy cane production are currently found exclusively in the deep, sub-tropical South (fig. 13.7). The implications of climate change for energy cane yields are most significant for the Southeast. The current high-yield zone along the Gulf Coast remains largely unchanged at ±5 percentage points of baseline values, regardless of the time horizon or RCP considered (fig. 13.7). This result, however, may be an artifact of the modeling. The climate projected for the Southeast by 2050 is unprecedented in the context of other regions of the United States, and thus, there are limited analogues for training the model. However, the physiology of energy cane is known to have temperature thresholds beyond which germination success and photosynthesis plateau or decline. Therefore, higher temperatures across the southern United States may not necessarily drive continual increases in energy cane yields, particularly given the potential for rainfall reductions.

Model results indicate that the current range of energy cane may expand northward significantly under the climate change scenarios. Much of the southern United States, Midwest, and Mid-Atlantic regions are projected to experience an increase in energy cane yields of 5–25 percentage points under RCP 2.6 (2050 and 2070) (fig. 13.7). Such yield increases would likely expand the land area that is viable for cultivation of energy cane as an energy crop. Under RCP 8.5, the yield increases by 2050 are more substantial and widespread—increasing on the order of 10–25 percentage points. By 2070, relative yields increase 25–50 percentage points from northern Georgia, Alabama, and Mississippi, westward to southern Illinois, Kansas, and Oklahoma (fig. 13.7). Although climate change is projected to enhance the suitability of other U.S. regions for energy cane production, for most regions, the increases in relative yields would be less than 5 percentage points. Given that relative yields for much of the rest of the United States are effectively zero, this level of increase is relatively insignificant in the context of cost-effective biomass production.

The limited frost tolerance of energy cane is a significant barrier to the expansion of this high-yielding energy crop into other areas; therefore, a key research challenge is to pursue selective breeding and hybridization to enhance energy cane's frost tolerance (de Siqueira Ferreira et al. 2013; Sandhu and Gilbert 2014). For example, miscane is a hybrid of sugarcane and miscanthus with greater frost tolerance and disease resistance (de Siqueira Ferreira et al. 2013). The projected changes in energy cane yields suggest that climate change will also enhance the ability to expand the range of commercially viable energy cane production in future decades.

Figure 13.7 | Relative yields for energy cane under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



13.3.2.3 Miscanthus

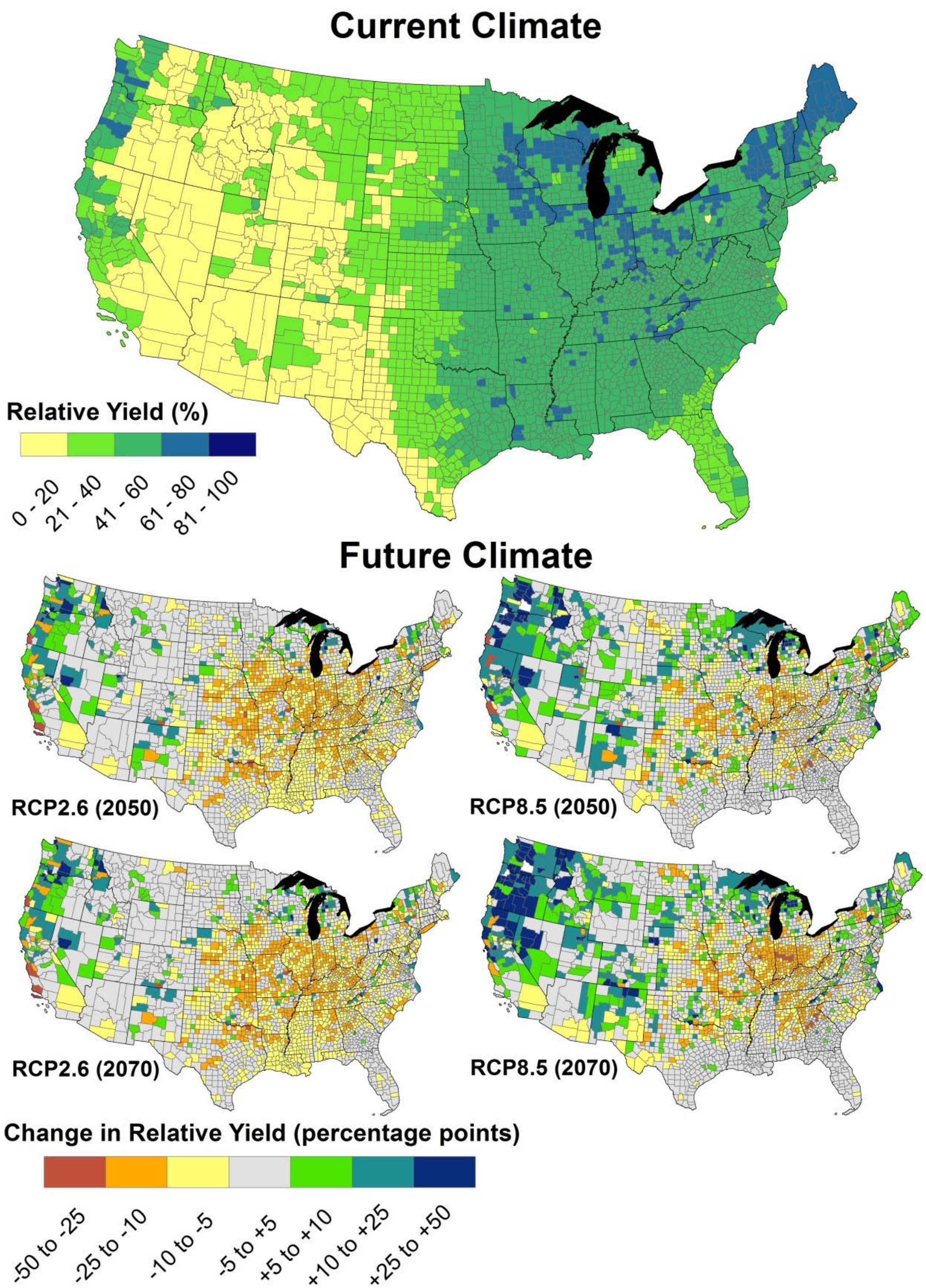
Miscanthus is a large, high-yield perennial grass that is increasingly being developed as a bioenergy resource in the United States for direct combustion as well as for conversion to ethanol (Khanna, Dhungana, and Clifton-Brown 2008; Heaton et al. 2004). Miscanthus is being explored as a biomass energy crop in field trials in various locations around the United States. Modeling suggests that relative yields in excess of 40% can be realized throughout much of the eastern United States under baseline climate conditions (fig. 13.8). Higher relative yields in excess of 60% may be achievable in parts of the Midwest and Northeast.

Modeling of the effects of future climate change on miscanthus yields in U.S. counties suggests that effects of climate change may be modest and transient. Yield changes for much of the continental United States are projected to be within ±10 percentage points of baseline values in both 2050 and 2070 (fig. 13.8). More counties experience positive yield changes under RCP 8.5 compared to RCP 2.6. However, reductions in relative yields of 10–25 percentage points are projected in parts of the Midwest and isolated counties across the South in 2050 and 2070. A number of counties along the West Coast—northern California, Oregon, and Washington—are projected to experience large increases in relative yields.

These increases are larger under RCP 8.5, particularly in 2070. Many of these counties have the potential for modest potential yields in the current climate (fig. 13.8), and thus, could represent new zones for viable production of miscanthus as an energy crop in future decades.

Miscanthus is considered to be an energy crop with moderate tolerance to a range of climatic stressors (Quinn et al. 2015), which explains its potential for widespread cultivation across the eastern United States (fig. 13.8). Selective breeding and hybridization of miscanthus can help address potential problems with survival through the winter during the first year of growth (Quinn et al. 2015; Clifton-Brown and Lewandowski 2000), while also expanding heat tolerance. Projections of changes in miscanthus relative yields in response to climate change suggest that higher temperatures may enhance winter survival, particularly in northern latitudes. However, higher temperatures may also contribute to greater heat stress during summer.

Figure 13.8 | Relative yields for miscanthus under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



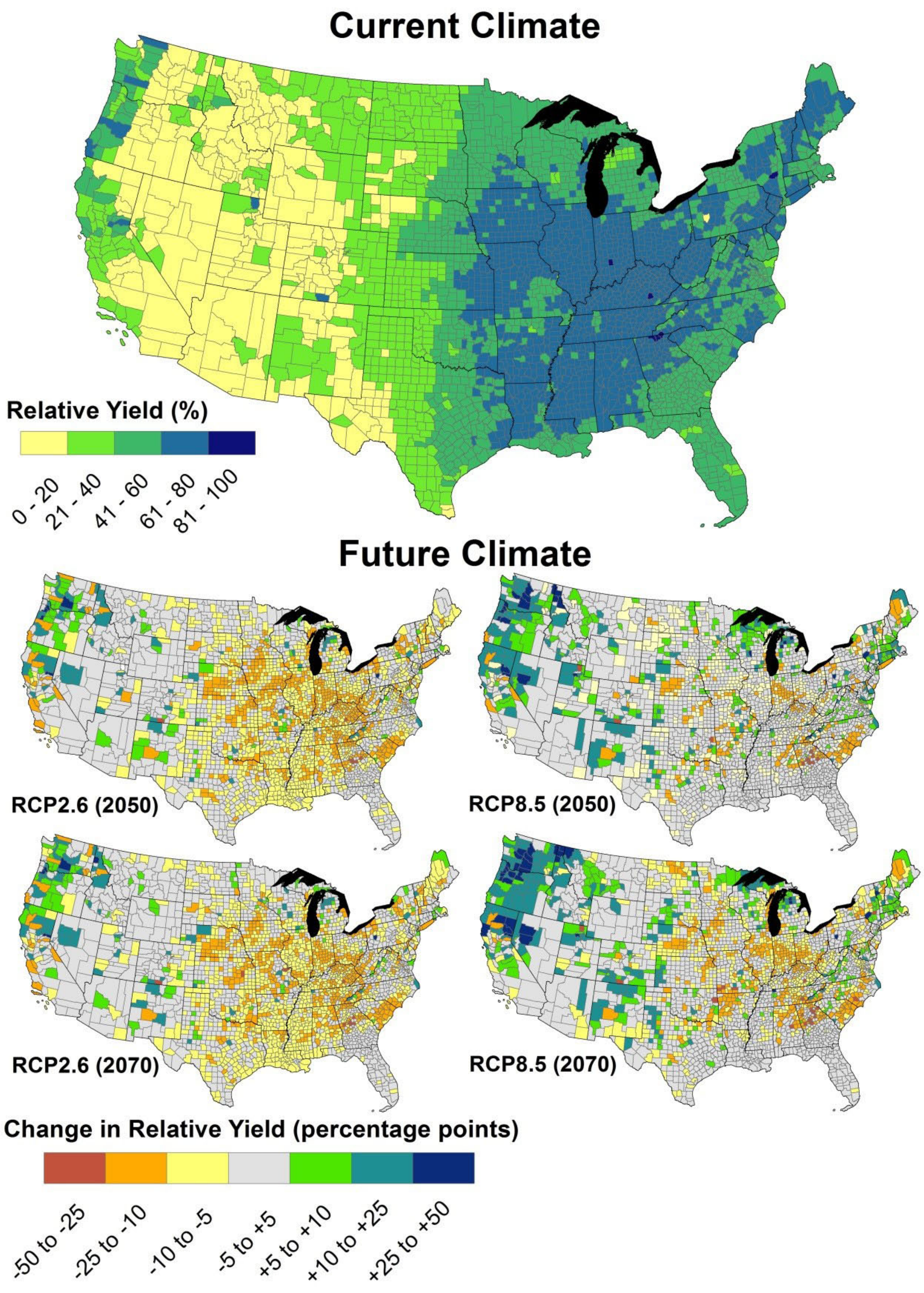
13.3.2.4 Poplar

Poplar (including hybrids of various types) is one of the fastest-growing tree types in the temperate United States. Their rapid growth, ability to grow under a range of site conditions, ability to resprout after harvest, and low requirements for chemical inputs has made them a popular species for commercial forestry (Smith et al. 2009). However, these same qualities also make poplar suitable as a source of woody biomass for bioenergy. Modeling of the distribution of poplar relative yields under the current climate indicates high yields are possible throughout the eastern United States, from Louisiana to Maine (fig. 13.9). In addition, conditions are suitable for relatively high poplar yields along the West Coast.

Projections of changes in relative yields for poplar in response to climate change vary significantly when different assumptions are used regarding future atmospheric GHG concentrations. For example, under RCP 2.6, changes in yields are within ±10 percentage points of baseline values throughout much of the continental United States (fig. 13.9). Generally, changes in the Southeast and Midwest tend to be more negative, while changes in the West tend to be more positive. However, a number of counties in the Southeast and Midwest are projected to experience more substantial declines on the order of 10–25 percentage points. In contrast, increases of 10–25 percentage points are projected for parts of Appalachia and some counties in the Pacific Northwest. Differences between 2050 and 2070 under RCP 2.6 are negligible. For the higher GHG concentrations associated with RCP 8.5, yield effects are spatially heterogeneous. By 2050, yield declines of 10–25 percentage points appear in isolated areas of the Midwest, Southeast, and New England. Yet, yield increases of 10–25 percentage points are projected as well. By 2070, adverse yield effects persist, but overall, yields are more positive across the United States and, in particular, the Pacific Northwest.

The genus *Populus* comprises species that are generally tolerant of a range of environmental conditions (e.g., Wang et al. 2012), creating opportunities for the selection of particular species of *Populus* to suit specific sites. Nevertheless, model results (fig. 13.9) suggest that future productivity of poplar is sensitive to changes in rainfall, as well as rising temperatures that could increase the risk of prolonged heat stress. However, model results also suggest there may be trade-offs in yields over different time scales, spatial gradients, and trajectories of future GHG concentrations.

Figure 13.9 | Relative yields for poplar under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



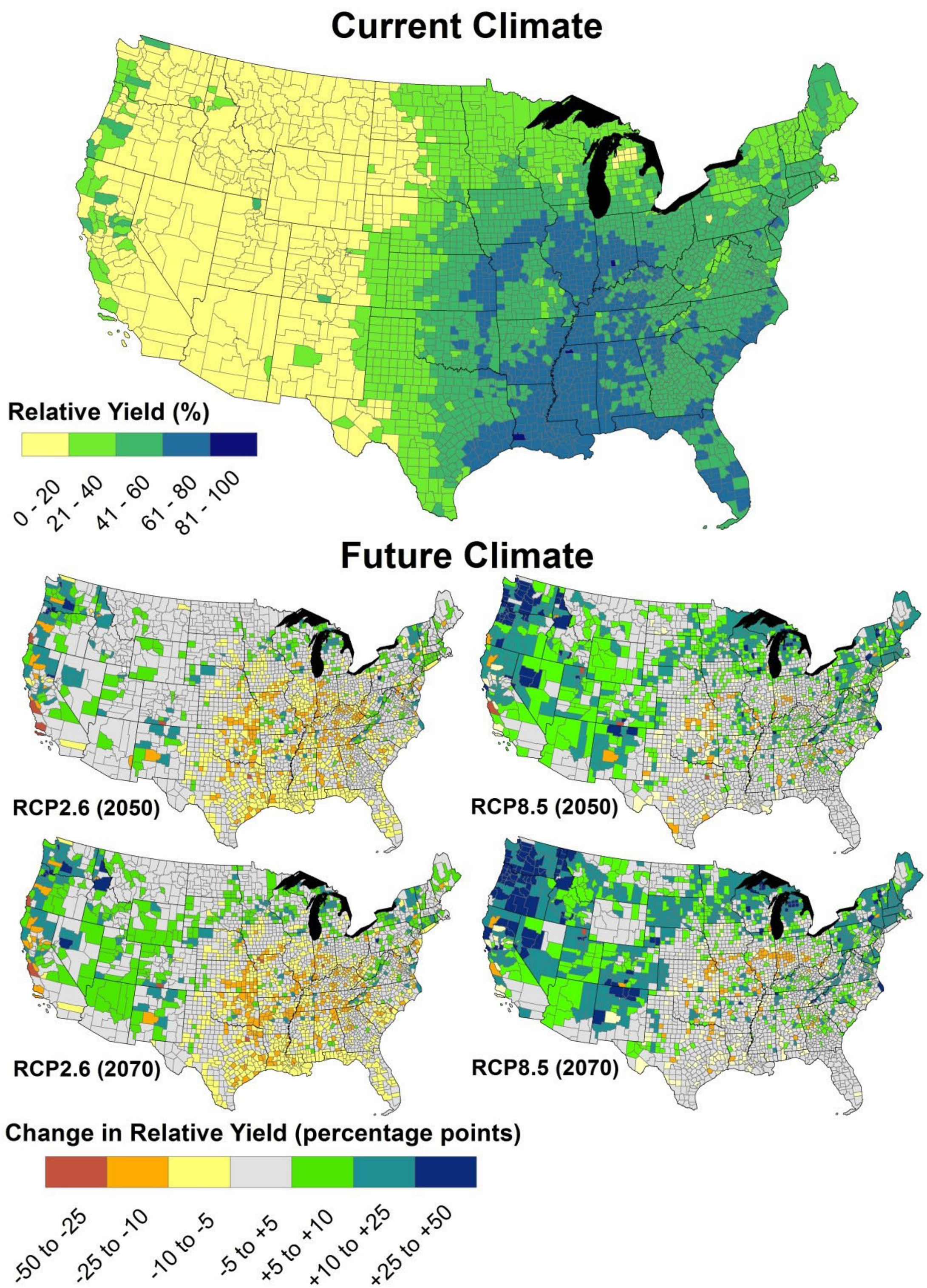
13.3.2.5 Sorghum

Sorghum is an annual, C4 grass with high photosynthetic efficiency. Sorghum is currently produced for livestock feed and table syrups, with an estimated 8.8 million acres of U.S. land allocated for its production in 2015 (NASS 2015; Braun, Karlen, and Johnson 2007). Almost 90% of this area is allocated toward grain sorghum in the arid plains states, from Kansas southward into Texas (USDA 2009; NASS 2015). However, several characteristics make biomass sorghum a useful energy crop for conventional agricultural systems, as well as underutilized agricultural and rural lands. Biomass sorghum tolerates a range of soil conditions, uses nutrients efficiently, and is relatively drought-tolerant due to a deep root system (Regassa and Wortmann 2014; Shoemaker and Bransby 2010).

At present, much of the eastern half of the continental United States has climatic conditions suitable for the growth of biomass (i.e., forage) sorghum (fig. 13.10). The highest yields are associated with the Midwest, lower Mississippi River Valley, coastal Gulf of Mexico, and the coastal Carolinas (fig. 13.10). This distribution is indicative of a preference for mild to warm conditions with plentiful rainfall. Under RCP 2.6, projected relative yields of sorghum change little (i.e., ±10 percentage points) from current baseline values in both 2050 and 2070. However, declines in relative yields of 10–25 percentage points are simulated among some central plains counties in Kansas, Oklahoma, Missouri, and Arkansas, which are currently a center for sorghum production (USDA 2009). Meanwhile, increases of 10–25 percentage points in relative yields of sorghum are projected for a number of counties along the West Coast. This general pattern of response to climate change is also reflected in model results for RCP 8.5. However, relative yields tend to be higher for RCP 8.5 across the United States relative to RCP 2.6, particularly in New England, Appalachia, the northern Plains States, and the West, where increases are frequently in excess of 25 percentage points. Hence, some of the areas that are projected to experience reductions in relative yields with RCP 2.6 are projected to experience increases with RCP 8.5 (for both 2050 and 2070).

The suitability of biomass sorghum for a broad range of climatic conditions increases the resilience of the crop as the climate changes. This is evidenced by the projected modest effects of climate change on relative yields of biomass sorghum, even assuming high atmospheric concentrations of GHGs and relatively long (i.e., 2070) time horizons. However, it is interesting to note that some counties where sorghum yields are projected to decline the most (i.e., Kansas and neighboring vicinities) also comprise the region currently associated with the highest concentration of grain sorghum production. Furthermore, those areas that are identified as having the greatest yield potential for biomass sorghum in the baseline climate (fig. 13.10) are not necessarily those where production is currently concentrated. While sorghum performs well relative to alternative crops in the more arid West, other crops may be more economically viable in areas of the eastern United States that receive more rainfall. However, when sorghum is grown for forage on underutilized agricultural land rather than for grain in conventional agricultural production, such competition is alleviated.

Figure 13.10 | Relative yields for sorghum under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



13.3.2.6 Switchgrass (Lowland and Upland)

Switchgrass, a perennial herbaceous plant, has been described by the U.S. Department of Energy as a "model" high-potential energy crop (Patt et al. 2010). Productivity of switchgrass is dependent upon the selected cultivar and the environmental conditions under which cultivars are grown. Lowland cultivars tend to have higher yields but reduced cold tolerance, relative to upland cultivars, which limits the northern geographic limit of viability for the former cultivars. Upland cultivars also have a higher drought tolerance (Stroup et al. 2003). As a consequence, lowland cultivars are anticipated to be most productive in the Southeast and, in particular, the Gulf Coast States of Louisiana, Mississippi, and Alabama (fig. 13.11). Meanwhile, the most productive regions for upland cultivars are concentrated in the Midwest. However, high productivity is also anticipated farther south and in parts of New England (fig. 13.12).

Because relative yield, rather than absolute yield, was modeled, this assessment does not make direct comparisons of yields between lowland and upland cultivars in different regions of the United States. However, it is possible to compare the relative changes in yields between these two sets of cultivars for different U.S. regions (fig. 13.11 and fig. 13.12). This exercise shows that projected effects are consistent with the differential temperature limits of the two cultivars. Relative yields of lowland switchgrass remain largely unchanged in the South under RCP 2.6 (fig. 13.11). However, significant yield increases are projected for the northern U.S., from Minnesota to New England, because of increasingly mild conditions. For RCP 8.5, larger increases in relative yields on the order of 25–50 percentage points are projected for many counties in the North by 2050. In addition, the West is projected to experience significant increases in relative yields. These changes become more pronounced by 2070.

For upland cultivars, higher temperatures associated with a changing climate increase thermal stress, particularly in the Midwest and Southeast, which reduces yields for RCP 2.6 in both 2050 and 2070 (fig. 13.12), whereas the western U.S. is projected to experience modest increases in yields. For RCP 8.5, similar yield reductions are projected for the Midwest and Southeast, but larger increases on the order of 10–25 percentage points are projected for other U.S. regions by 2050, particularly on the West Coast. By 2070, relative yields increase by 25–50 percentage points above baseline values for all RCPs, and increases are more widespread throughout the West.

The clear differences in yield responses to alternative climate change scenarios between lowland and upland cultivars of switchgrass emphasize the importance of cultivar selection to the yields that are realized on landscapes. Cultivar selection is therefore a valuable tool for adapting the cultivation of biomass to a changing climate. Consideration for the performance of different cultivars in a changing climate may also help guide the prioritization of characteristics that are enhanced or suppressed through selective breeding and hybridization. For example, while higher temperatures in the North would be beneficial for lowland cultivars (fig. 13.11), they could enhance thermal stress and drought risk in the South. Hence, enhancing lowland cultivars' tolerance to drought and thermal stress may enable them to continue to be productive in the South, as well as become increasingly suitable in the North.

Figure 13.11 | Relative yields for lowland switchgrass under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).

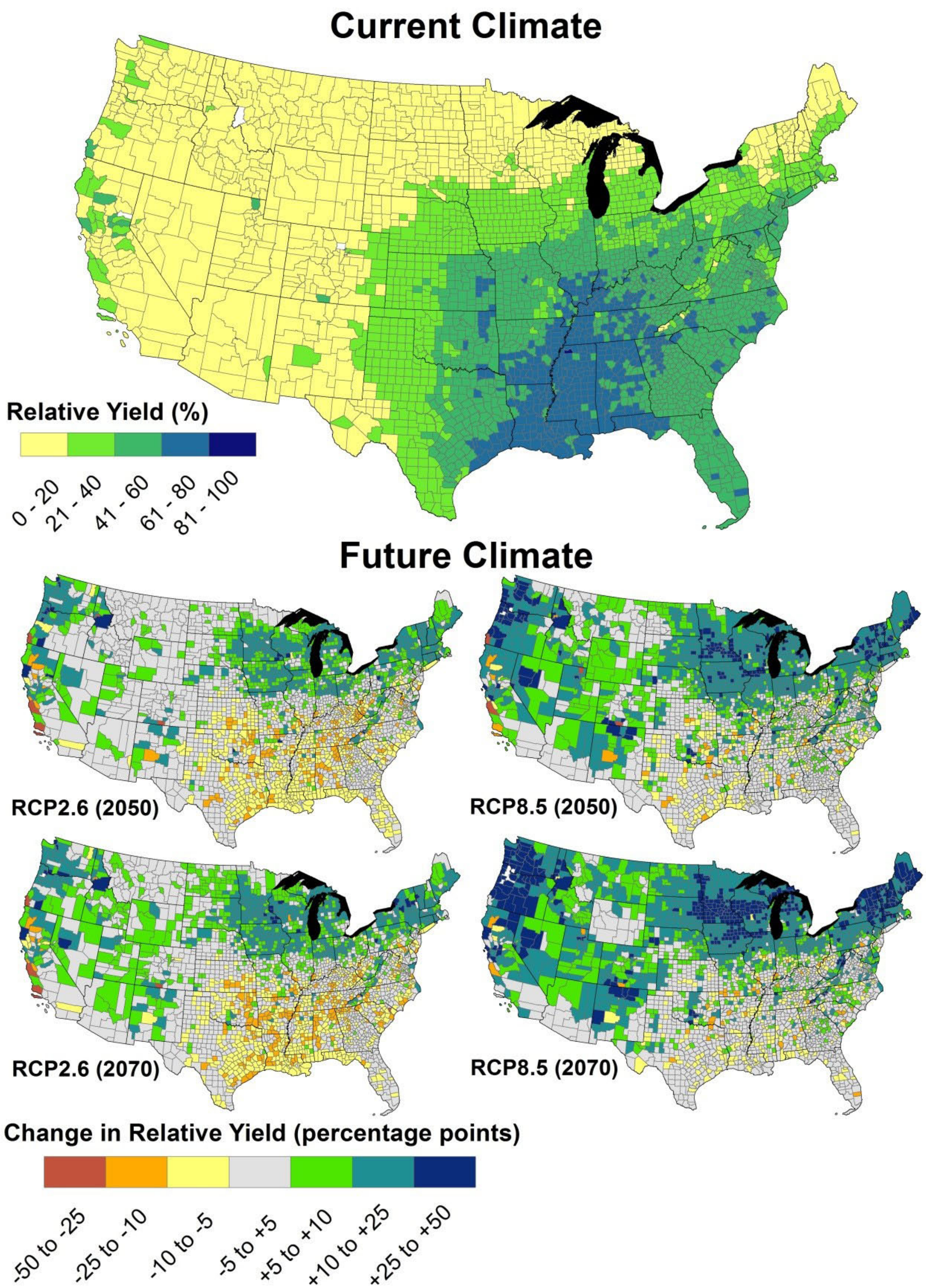
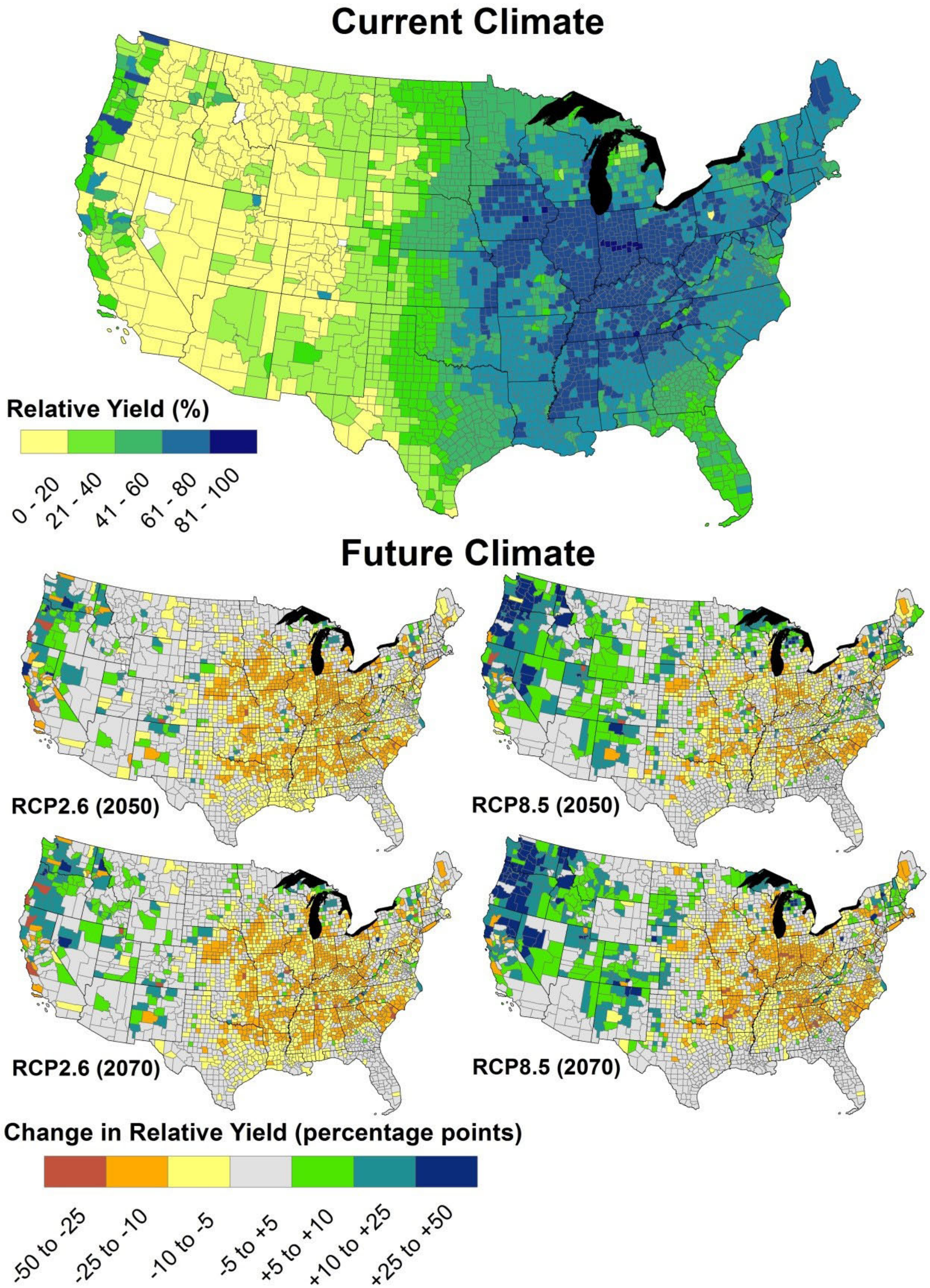


Figure 13.12 | Relative yields for upland switchgrass under baseline climate conditions as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



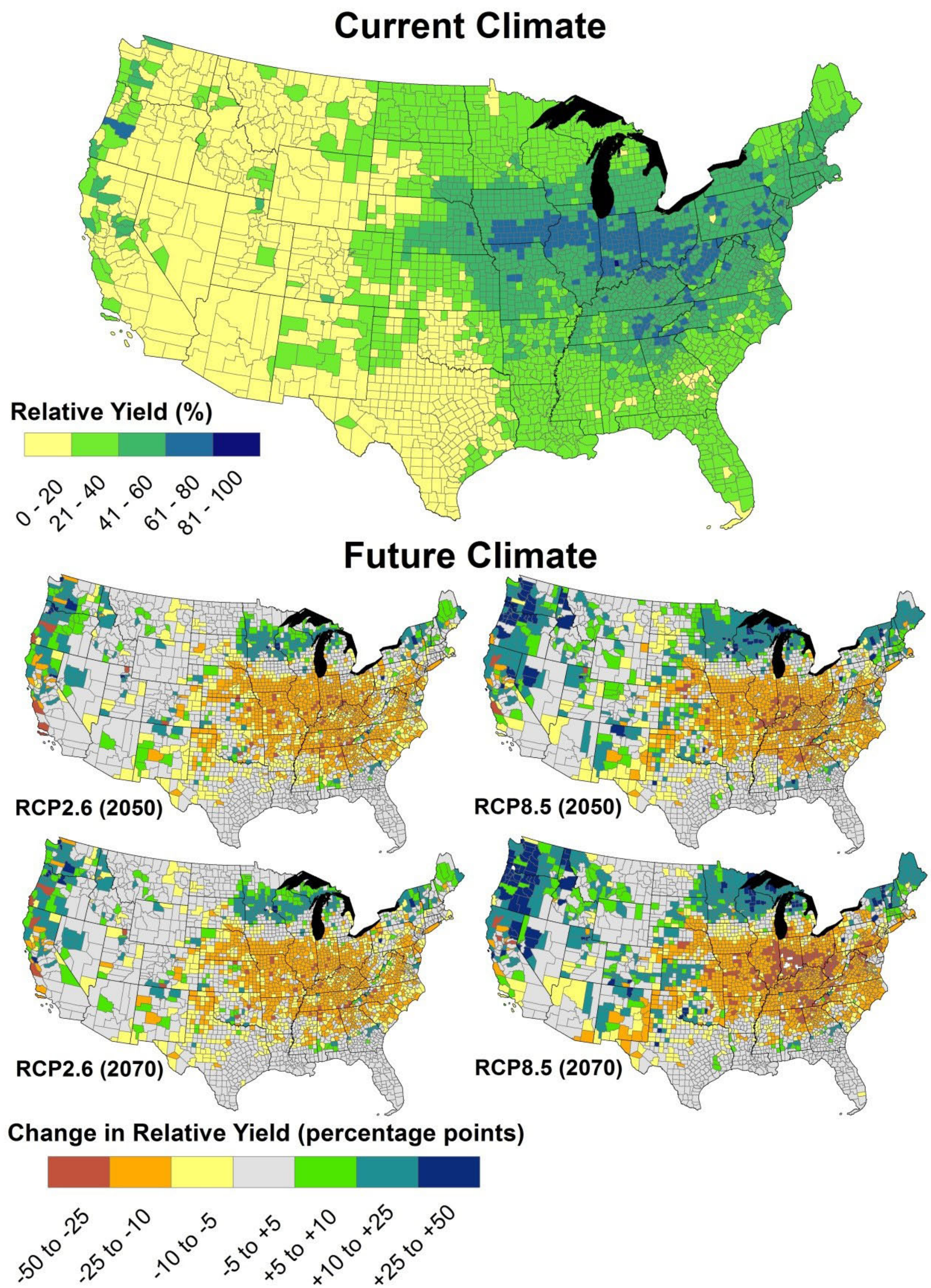
13.3.2.7 Willow

Shrub willow is a perennial hardwood that is considered to be particularly useful for biomass production on underutilized agricultural lands, including those with relatively poor drainage and nutrient content compared to conventional agricultural lands. Like poplar, willow resprouts after coppicing, allowing it to be harvested for 20 years. Under current climate conditions, willow is best-suited to the Midwest, Mid-Atlantic, and New England regions of the United States (fig. 13.13). However, favorable climatic conditions can also be found in northern California and parts of the Pacific Northwest.

The geographic restriction of high-yield willow cultivation to relatively cool climates suggests that willow may be adversely affected by climate change and, in particular, higher temperatures. By 2050, model results project that relative yields of willow could experience declines on the order of 10–25 percentage points in the Midwest and Mid-Atlantic under both RCP 2.6 and RCP 8.5, although the effects are greater under RCP 8.5. Meanwhile, significant increases of 10–25 percentage points or more are projected for the upper Midwest and northern New England. This same pattern arises under RCP 8.5, but is more pronounced. In addition, by 2070, significant increases in yields of 25–50 percentage points are projected for a number of coastal counties in the Pacific Northwest.

The response of willow to climate change indicates that a significant shift in the geographic distribution of willow could transpire over the 21st century. While some regions are projected to become significantly more productive and potentially open up new areas for significant cultivation of willow as a biomass resource, substantial declines in yields are projected over much of willow's current range of climatic suitability. Therefore, ongoing genetic improvements in shrub willow to enhance productivity, improve disease resistance, and reduce production costs (Smart et al. 2005; Smart and Cameron 2008) could be accompanied by efforts to enhance thermal stress and drought tolerance. This could contribute to extending the range of climatic and environmental conditions in which willow can generate high yields.

Figure 13.13 | Relative yields for willow under baseline climate conditions, as well as projected changes (percentage points) in relative yields for different time periods (2050 and 2070) and RCPs (2.6 and 8.5).



13.4 Uncertainties and Limitations

While the modeling results presented here provide some first-order insights into how different energy crops may respond to changes in temperature and precipitation, a number of relevant factors were not incorporated. The development of a more process-based understanding of energy crop responses to changing climatic conditions would assist in reducing uncertainties associated with purely empirical methods. For example, the methods here do not capture the physiological processes of energy crop growth and how climate interacts with each stage of development. Furthermore, the methods here reflect yields as a function of changes in long-term, average climate conditions for a selected group of ESMs. Different ESMs, and therefore ESM ensemble projections, produce different estimates of changes in temperature and, especially, rainfall. Although downscaling methods can help address uncertainties caused by topography, such as mountain ranges, they can also introduce additional uncertainties and biases into model projections (Lo, Yang, and Pielke 2008; Salathe, Mote, and Wiley 2007; Chen, Brissette, and Leconte 2011; Teutschbein, Wetterhall, and Seibert 2011).

Langholtz et al. (2014) argue that extremes of weather and climate are important factors that influence the effects of climate change on biomass. Significant uncertainties remain with respect to projections of changes in the frequency, intensity, or duration of climate extremes, and agricultural models often remain poorly equipped to assess their effects. Yet, capturing the effects of such extremes is an important aspect of understanding the implications of climate change for biomass. Similarly, the results do not account for the effects of changes in atmospheric CO_2 concentration on energy crop physiology and growth, which could have important implications for net energy crop responses to future changes in the climate (McGrath and Lobell 2013). This is particularly important for C3 plants such as poplar and willow (Bishop, Leakey, and Ainsworth 2014; Gielen et al. 2005).

In addition to the direct effects of climate variability and change in energy crop yields, indirect effects can also be important over different time scales. Like conventional crops, energy crops are susceptible to pests and disease, which are also likely to respond to a changing climate. These disturbances could have positive or negative effects on biomass, and those impacts may be region- and cultivar-specific. However, such indirect effects are not captured in the current assessment, and they are often poorly represented in agricultural modeling in general.

Finally, as a managed resource, biomass production systems can be improved and modified in response to new knowledge , innovation, and changing environmental conditions. Such adaptation can arise both autonomously and through strategic planning on behalf of the bioenergy industry and supporting institutions. However, the effects of potential management responses to a changing climate, on behalf of individual agricultural enterprises or the bioenergy industry, more broadly are often neglected in modeling the potential of bioenergy. The results presented here are no exception, as they reflect models of the biophysical response of energy crops but not technological, social, economic, or institutional responses. In particular, future decisions regarding water management for biomass production will have a significant influence on biomass productivity. As land managers gain experience with biomass-production systems, more information will become available regarding how energy crop yields respond to different management regimes or technological innovations.

13.5 Discussion

The modeling of energy crop responses to alternative climate change scenarios indicates that, much like conventional crops or other forms of vegetation, energy crops are sensitive to climatic conditions. The U.S. climate is projected to change significantly in coming decades, particularly for regions such as the Midwest and Southeast that are considered productive landscapes for the development of biomass resources (Walsh et al. 2014). Therefore, in considering the future potential of bioenergy as a significant energy resource for the United States, attention should be given to long-term changes in regional climatic conditions, particularly for energy crops with multidecadal lifespans.

Model projections of climate change effects on different energy crops indicate that climate change could alter yields and shift the geographic distribution of commercially important energy crops. However, responses to climate change among different crops are highly variable. This variability is a function not only of geographic variability in current climate and future climate change, but also variability in the inherent sensitivity of different energy crops and cultivars.

Based on changes in climate variables alone, both significant increases and decreases in energy crop yields are projected to occur in future decades given the current genetic composition of crops and levels of technology associated with crop production and the biomass supply chain. These changes may have greater significance at the regional level than the national level. As a managed resource, biomass-production systems can be improved and modified in response to new knowledge, innovation, and changing environmental conditions. Hence, there are significant opportunities for adaptation to maintain or even enhance the supply of biomass for energy. However, this can be aided by greater focus on the implications of climate change on the long-term strategic selection and deployment of energy crops across the U.S. landscape.

13.6 Summary and Future Research

Climate change is likely to drive changes in the geographic distribution of energy crops. However, there are significant opportunities for adaptation to maintain or even enhance the supply of biomass. This process can be aided by greater focus on the implications of climate change on the long-term strategic selection and production of energy crops across the U.S. landscape. For example, agricultural crop models and/or other physiologically and process-based models for projecting the responses of energy crops to climate change could be coupled with ESM projections of future climate change (Langholtz et al. 2014). However, this integration may require more focused efforts to incorporate knowledge generated by field trials associated with different energy crops and cultivars into agricultural modeling frameworks (Surendran Nair et al. 2012). Furthermore, more rigorous application of ESM projections could enable analysis of the transient response of energy crop yields over different time scales and in response to short-term climatic variability, as well as long-term average climate conditions and atmospheric CO_2 concentrations.

In addition to improving the modeling of energy crop responses to climate variability and change, there are also significant opportunities for adapting energy crops to a changing climate. These include the following (Langholtz et al. 2014):

- Continued investments in the genetic improvement of energy crops in general, as well as specifically for climate-related stress
- Improved management practices to reflect climate change implications for plant establishment, maturation, and harvesting
- Strategic planning for the deployment of different energy crops and cultivars to maintain biomass yields as the climate changes
- Evaluation of the implications of shifting energy crop yields and economic competitiveness for the biomass supply chain, including transportation and refining.

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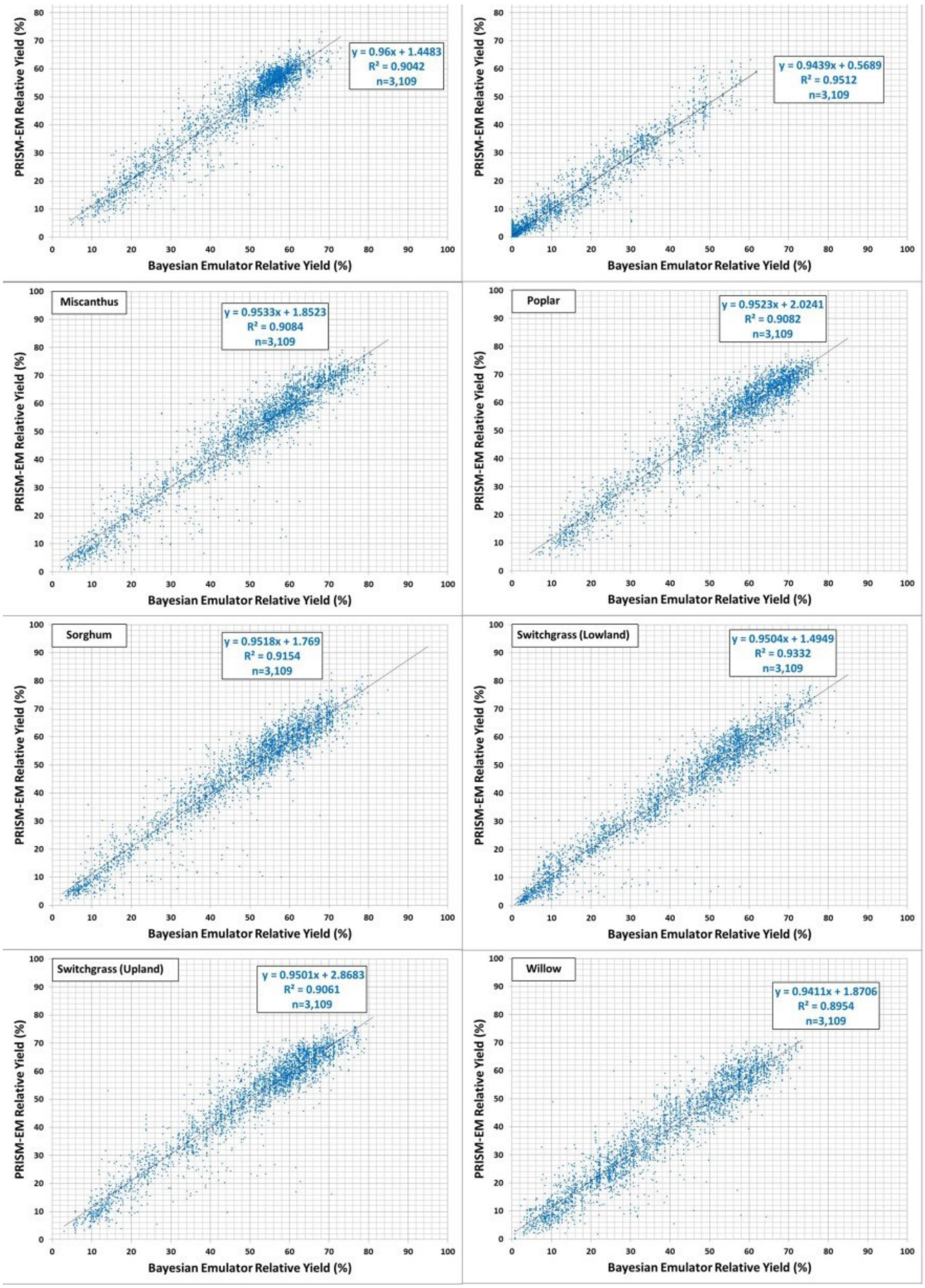
Appendix to Chapter 13: Additional Details on Model Validation

13A.1. Validation Statistics for Bayesian Models

In order to validate the performance of the Bayesian models, model results under the baseline climate (30-year averaged T_{min}, T_{max}, and total rainfall from PRISM) for annual relative yields for all counties considered in the analysis (3,109) were compared against estimates from the Bayesian models (fig. 13A.1). Bayesian models explained over 90% of the observed variance in relative yields for all energy crops (R^2 ranging from 0.90 to 0.95), and the slopes of the regression lines were close to 1 (ranging from 0.94 to 0.96).

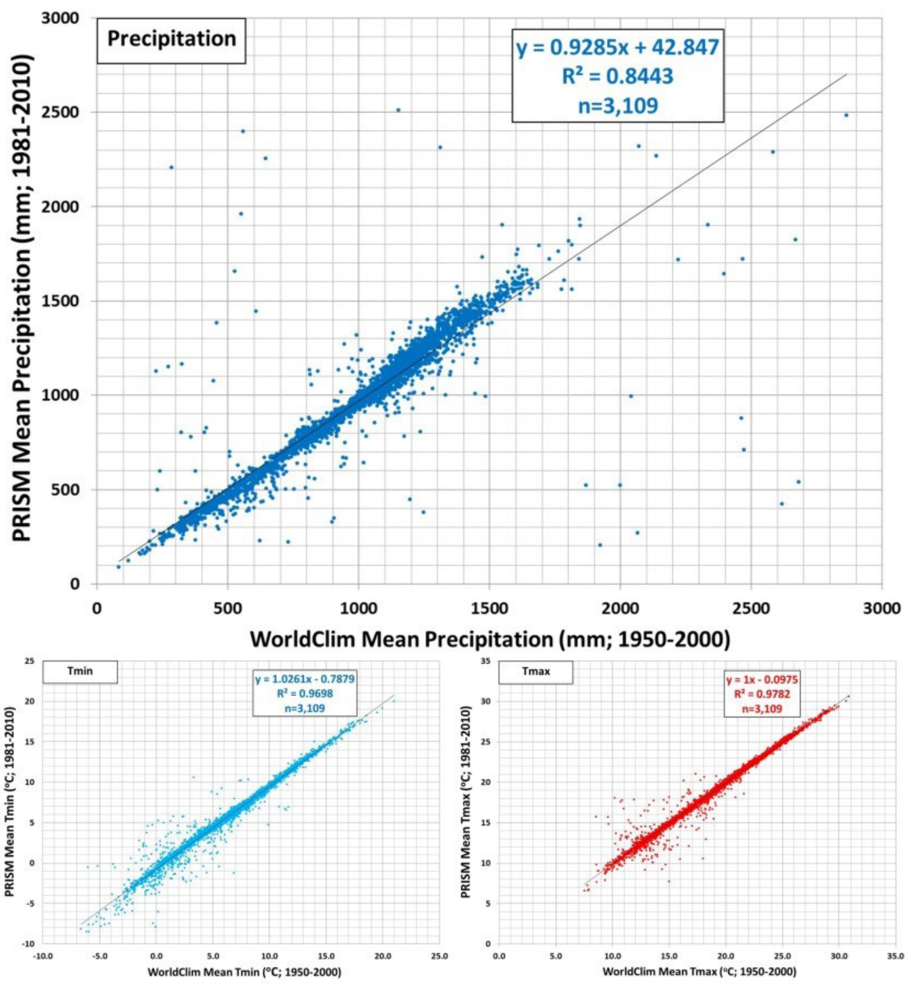
Figure 13 A.1 | Validation plots for Bayesian models of county feedstock relative yields. For each feedstock considered in this assessment, the figures plot the relative yield for PRISM-EM averaged over 30 years (1980–2013) against the yields predicted by the Bayesian graphical models using the PRISM historical climatology.



13A.2. Comparison of Worldclim and PRISM Historical Climatologies

The Bayesian models were trained with historical PRISM temperature and precipitation data, and relative yield data from PRISM-EM. However, projections of future climate conditions and yields were based on the WorldClim dataset, and projected yields were evaluated against those associated with the baseline WorldClim climate conditions. Because the baseline climate for WorldClim was developed using different methods, data, and time horizon than PRISM, it was necessary to test for homogeneity between the PRISM and WorldClim baseline climate conditions for T_{min}, T_{max}, and annual total precipitation. Significant discrepancies between the two data sets would raise questions as to whether the responses generated by the Bayesian models using WorldClim data are reasonable representations of the relationships between climate and yields within PRISM-EM. Comparison of T_{min}, T_{max}, and total annual precipitation between PRISM and WorldClim baseline data using least-squares linear regression indicates close agreement (R^2 = 0.97 for T_{min} and T_{max}, and 0.89 for total annual precipitation) (fig. 13A.2). However, significant discrepancies for precipitation were observed between the two data sets for a small number of counties, which likely explain outliers in Bayesian model yield projections observed in the validation of the Bayesian models (see section 13A.1).

Figure 13A.2 | Comparison of the distribution of T_{min}, T_{max}, and precipitation between the PRISM historical climatologies and the WorldClim historical climatologies.



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