Farms Under Threat 2040

Projected Climate Impacts on the Growing Conditions for Rainfed Agriculture in the Contiguous United States

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Projected Climate Impacts on the Growing Conditions for Rainfed Agriculture in the Contiguous United States

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AMERICAN FARMLAND TRUST

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AGRICULTURAL PRODUCTION IS ESPECIALLY VULNERABLE TO CHANGES IN THE CLIMATE. Over 80% of croplands in the contiguous United States depend on timely and predictable rainfall to stay in production. With rising temperatures and shifting rainfall patterns, the crops and businesses supported by these rainfed croplands are increasingly at risk. This report showcases potential changes in rainfed growing conditions between 2016 and 2040 for selected crops (corn, winter wheat, and apples) and for croplands in general, under two potential futures: one where we continue to release high amounts of greenhouse gases into the atmosphere or a future where we act immediately to significantly reduce emissions. The resulting maps show how the emissions-related decisions we make in the next few years change the likelihood that present day crop varieties and production practices will remain viable in a given area by 2040.

We're already experiencing the early effects of climate change. However, if society can reduce greenhouse gas emissions, we will avoid the worst impacts of climate change. The maps shared in this report reinforce the pressing need for society to drastically and quickly reduce emissions to stop climate change from getting worse. This includes widespread action to help farmers implement practices that reduce their emissions and make the necessary changes to better adapt to changing climate conditions. By 2040, the likelihood of growing current crop varieties in certain rainfed areas is much less, indicating the scale of changes ahead. In addition to adjusting to changes in temperature and rainfall, extreme weather events and pests are expected to cause even more crop damage as climate change worsens. By acting now, we will limit the extent of adjustments and expenses farmers will face to adapt to climate change in their area and help thousands of farmers keep more of their rainfed agricultural land in production.

Introduction

In 2022, citrus growers along Florida's Gulf Coast lost 50–90% of their oranges to high winds and rain, drought reduced the winter wheat harvest in the Plains and Midwest by 25% and caused growers to abandon 43% of upland acres planted to cotton, and record rainfall disrupted the green chili harvest in New Mexico. These extreme events are becoming more likely due to the rise in global temperatures caused by climate change. Warming temperatures are also altering the day-to-day weather conditions that producers face. Growing seasons have become more unpredictable, rains are spotty and sometimes come all at once, and more consecutive dry days and hotter nights put plants and livestock under increasing stress.[1] These climate disruptions are becoming a new normal, making it even harder for farmers and ranchers to do what they do best—steward the land and keep the rest of us clothed and fed.

Crops and livestock are highly sensitive to weather and climate.[2] Over the past half century, farmers and ranchers were able to gradually adapt to changing climate conditions by implementing more practices or technologies to lower the risks they experienced from the weather. They developed strategies that, for the most part, could handle the historic fluctuations in temperature and rainfall they were seeing in their states. But now temperatures and rainfall in many states are deviating from these ranges, resulting in new and unexpected climatic shocks that can result in either an increased use of inputs or a drop in production.[3]

Moderate warming has been shown to benefit some crop yields in the short term. For example, between 1980 and 2020, yields of corn and rice increased by 13–14% in the southeastern U.S.[4] But the rising temperatures accompanied by more erratic precipitation will lead to significant yield losses in the long term. Many crops are stressed at temperatures above 90 to 95 degrees Fahrenheit (F), depending on water availability. As days above 93 F increase in frequency, even areas where sufficient moisture is available become less suitable for rainfed agriculture.[5] In relatively cool dryland areas (e.g., areas of the inland Pacific Northwest), periods of high temperatures can also damage crops.

> Unless society intervenes, food security will increasingly be at risk.

Unless society intervenes, food security will increasingly be at risk. The United Nations projects that food production will need to increase by 70% by 2050 (compared with 2009) to meet increasing food demand by a growing population.[6] But by the end of the century, yield losses could be as high as 11–28%. Even in the best-case scenario, where society reduces GHG emissions by 30–45% by 2030 (RCP 2.6),* yields of the world's most important crops could still drop by 2–9% by the end of the century.[7] While all sectors have a role to play in solving the climate crisis, agriculture is a sector that can play a critical dual role by reducing its own GHG emissions and by drawing existing carbon dioxide (CO_2) out of the atmosphere to slow climate change.

* The climate modeling community developed four Representative Concentration Pathways (RCPs) to quantify the impacts of future greenhouse gas concentrations on global warming ranging from very low future emissions (RCP 2.6) to very high emissions (RCP 8.5). See Appendix for a more in-depth explanation.

Projected changes in the land's ability to support cultivation and current crops due to warming temperatures and shifting rainfall patterns may lead farmers to switch to different crops to avoid yield losses or abandon cropland altogether.[8] This could cause disruptions for farmers, food supplies, and ecosystem functioning. For example, if society stays on a high-emissions trajectory (RCP 8.5), farmers who have not switched crops to minimize yield losses may see their profits drop by almost 30% by 2070.[9] Even if the farmers change crops, their profits could still drop by 16%. Crop changes under this high-emissions scenario are projected for 57% of U.S. counties and the infrastructure supporting current crop production (including farm equipment, storage facilities, markets, and transportation systems) will need to adjust to support agricultural producers in these counties. Any broad geographic changes in cultivation could also impact ecological processes and ecosystem services at a range of spatial scales.[10]

Having advanced notice of where these changes are projected to occur may help farmers and ranchers minimize—or avert—these potential impacts. To better understand the challenges ahead for agricultural lands, American Farmland Trust joined with Conservation Science Partners and the Center for Sustainability and the Global Environment at University of Wisconsin-Madison to model changes in fundamental agricultural land use by 2040. The models project the change in likelihood of using present day crop varieties and production practices in a given area by 2040 if 1) we continue on our current high-emission trajectory or 2) if we take steps now to significantly limit GHGs by 2030. The resulting maps reinforce the need for extensive and immediate GHG emissions reductions writ large, and for support of farmer-led strategies that both decrease emissions to limit future climate change (mitigation) and protect against the changing climate (adaptation) in order to keep rainfed croplands in production. The best window to change the trajectory of the changing climate is NOW[11] and with the right tools and support, agricultural producers can adapt to and help reverse these trend.

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What we mapped

The mega-drought in the southwestern U.S. has drawn attention to the increasing challenges for irrigated cropland as water supplies decline and demands from a multitude of users increase (see text box: *Why some rainfed croplands and other essential croplands are not included in our maps*). However, the remaining 86% of croplands in the contiguous United States that depend on timely and predictable rainfall are also at risk. This report showcases the short-term changes in rainfed growing conditions between 2016 and 2040 for selected crops (corn, winter wheat, and apples) and for croplands in general under two climate scenarios—a future where we continue on a high-emissions trajectory or one where we immediately take immediate climate action to reduce GHG emissions. Due to modeling limitations, our modeling does not account for future adaptive strategies[12] (e.g., improving soil health) that might reduce some of the risks. AFT also modeled where severe erosion hotspots may increase due to changes in land cover (report in progress).

Why some rainfed croplands and other essential croplands are not included in our maps[†]

This analysis focuses on how future climatic conditions could impact rainfed cropland, not irrigated cropland. Due to difficulties in separating irrigated acres from rainfed acres, counties where over 50% of the cropland is irrigated were removed from the analysis although rainfed cropland may be present in these counties as well. These counties are shown in dark grey on our maps. Although not included in our analysis—or in our maps—irrigated agriculture is an essential part of the American food system. Only 14% of U.S. croplands are irrigated but they account for more than 54% of the total value of U.S. crop sales, including over 70% of vegetables and 80% of fruits and nuts. States with a high proportion of irrigated cropland include California (73%), Nevada (61%), Wyoming (55%), Idaho (51%), Utah (48%), Nebraska (46%), and Arizona (45%). Warmer temperatures and shifting rainfall patterns will affect the availability of both surface and groundwater used for irrigation. By 2040, nearly half of the water basins in the U.S. could experience high or extremely high water stress due to declining supply and increasing demands. Rainfed cropland may also feel the effects of dwindling surface and groundwater supplies. The use of supplemental irrigation on rainfed croplands helps increase available soil moisture in some areas and provides a critical buffer during periodic droughts.

As temperatures rise and rainfall patterns shift[13] across different soils and terrain, AFT's modeling shows how likely it is that present day crop varieties and production practices will continue to remain viable in a given area by 2040. In addition to the challenges presented by changes in growing conditions (as mapped here), farmers will also likely lose crops to extreme weather events and pests (not mapped). Projected changes in temperature, moisture and winds also create the right conditions for severe weather to occur more frequently.[14] This means that growers will face more destructive

† For references, see box on page 29.

JOSHUA VEAL /U.S. FOREST SERVICE

winds, hail and/or tornados, prolonged droughts, extended heat waves, and torrential downpours. In addition, research is now showing that both heat and aerosols from increased wildfire events can enhance the severity of storms. From 2009 to 2018, wildfires in the western U.S. increased the occurrences of heavy precipitation rates by 38% and severe hail events (greater than 2 inches) by 34% in the central U.S.[15]

The severity of crop damage due to pests is also expected to increase as the temperatures warm. These biotic stressors already cause 10–40% of the world's crop production losses.[16] Where and when extreme weather events and significant crop damages due to biotic stressors will happen cannot be projected accurately at this time and are not included in our modeling.

How we did the mapping

We used the 2016 USDA National Agricultural Statistics Service Cropland Data Layer to define specific crop production areas for grain corn, winter wheat, and apples and the *Farms Under Threat: State of the States* cropland layer to define existing cropland.[17] These locations reflect not only favorable soil and climate conditions, but also the presence of markets and other factors that support production and any climate-related adaptations that are being used. From these areas, we extracted information on climate from the 2013–2017 National Aeronautics and Space Administration's Earth Exchange Downscaled Climate Projections (NEX-DCP30), on soils from the gridded National Soil Survey Geographic Database, and on terrain from the National Elevation Database to establish baseline conditions for every 30 by 30-meter pixel. We used this information to train machine learning algorithms on current conditions suitable for growing these crops.

The resulting 2016 baseline is a close but imperfect approximation of where a crop can be grown, since even though a certain location may be suitable for growing a particular crop, farmers may choose to plant different crops there because that is more profitable. Conversely, technological developments, along with innovations in crop genetics, pesticides and fertilizer, the use of drainage tiles, precision agriculture, farm policies (particularly crop insurance) and other new production practices, have pushed some crops into areas that are less biophysically suitable for production.[18] Because of this, we define suitability as the "probability of a given land use type being present" or the "likelihood of cultivation." It is not an indication of expected yield or productivity.

The algorithms then extracted the functionally important climate metrics from NEX-DCP-30 for the two representative climate trajectories we modeled. One extends the high-emissions climate trajectory we're currently on into the future (the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway 8.5 (RCP 8.5)). The other projects a low-emissions trajectory (RCP 2.6) where society takes immediate climate action to reduce GHG emissions (i.e., reducing GHG emissions by 30–45% by 2030) to hold warming below 2 degrees Celsius (3.6 F).

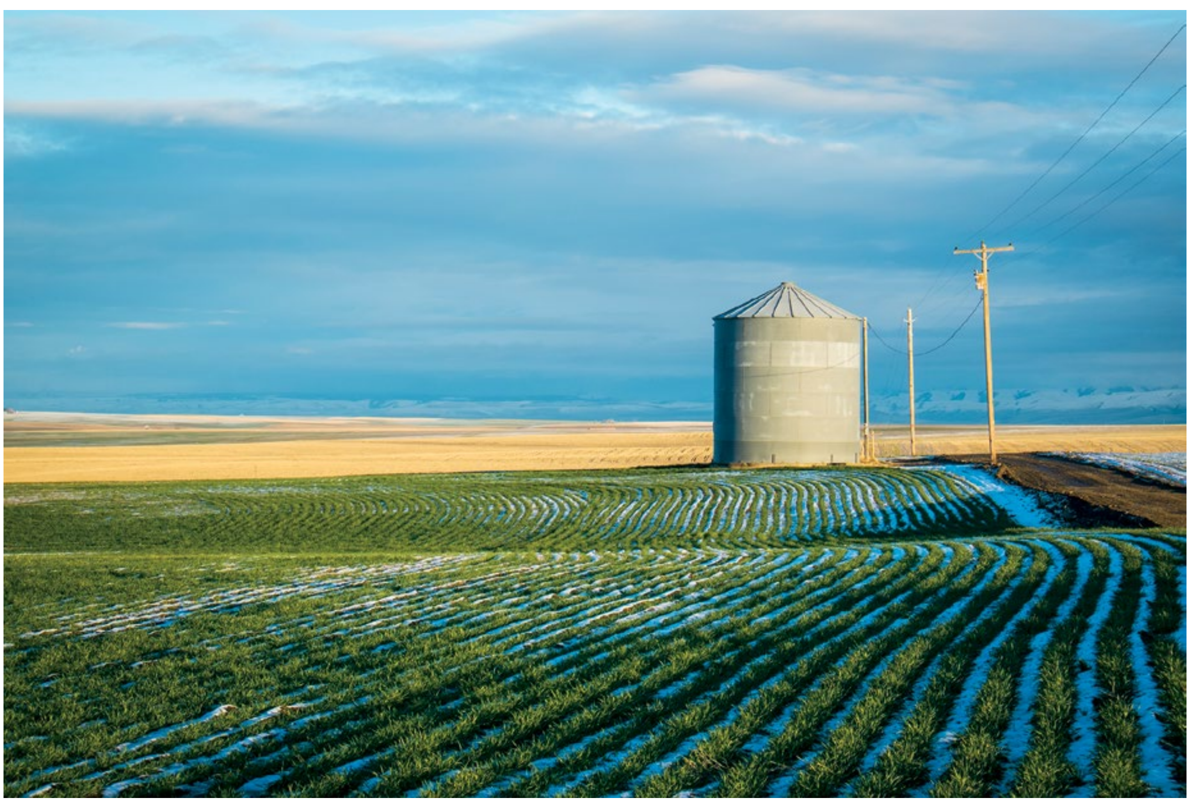
Finally, we measured deviations from 2016 growing conditions to project how much future climate conditions might affect the likelihood that farmers would still grow current crop varieties using present-day production practices. An increase or decrease in likelihood values could indicate an associated expansion or contraction of crop/cropland acreage. The degree of change in likelihood also provides an indication of the potential challenges farmers may face and the extent of adjustments that might be needed to adapt to climate change in their area.

If society remains on the high-emissions, worst-case RCP 8.5 trajectory, we are at greater risk of irreversible changes to the climate.[19] And while most researchers think emissions of the magnitude in RCP 8.5 are quite unlikely in the long-term, they are by no means impossible[20] (see Appendix for a more in-depth explanation).

Accuracy of projections and factors driving the models

According to our accuracy assessment, users of our maps can reasonably expect rainfed corn and winter wheat and apples will occur where our maps say they will occur in the future. The crops we assessed may still be grown outside of the areas we assumed to be biophysically optimal due to social and/or economic factors[21] that we were not able to include in our models. In general, the most important variables driving our projected future crop geographies were elevation, slope and variables related to summer moisture. All three of the crops we modeled were largely constrained by moisture dynamics and therefore the resulting projections primarily reflect an expected response to changing moisture regimes.

For the modeling that projected future changes in the likelihood of cultivation for cropland in general, the primary driving factors were less clear. This broad land use model pitted croplands, rangelands, pasturelands, and other land uses against one another in a competition for the same finite space with a moderate classification accuracy of 54%. Slope, soil properties, evapotranspiration and, to a lesser degree, temperature were important drivers.



ROBERT CRUM/ISTOCKPHOTO

Wheat field in winter.

What we found and why it matters

As temperatures rise and rainfall becomes less reliable, many rainfed areas will become less suitable for growing crops, leading to reduced yields and a potential shift in production to other areas. Our modeling focuses on the short-term consequences of global warming and suggests that, by 2040, there will be far more areas facing increasing threat due to climate change than increasing opportunity—especially under the high-emissions trajectory (see Table 1 and Figure 1). As weather conditions suitable to support an individual crop change, climate mitigation and adaptation measures will be critically important to keep these areas productive for their current cropping systems. While some areas, particularly to the north in the contiguous U.S., may become more suitable for some crop systems, shifting croplands to new areas presents its own problems. Significant environmental impacts can result from expansion of cropland.[22]

Our modeling focuses on the short-term consequences of global warming and suggests that, by 2040, there will be far more areas facing increasing threat due to climate change than increasing opportunity—especially under the high-emissions trajectory.

It is notable that our models project climate-driven changes to rainfed agriculture for both climate trajectories by 2040. Farmers and ranchers face adaptation challenges regardless of actions taken to reduce GHG emissions farther in the future. The differences between continuing the status quo and taking immediate climate action today become clearer after 2050. By then, there will be stark differences between the two climate trajectories.[23] For example, the climatic shifts that led to drought conditions over most of the contiguous U.S. in 2012 are representative of what to expect more frequently by 2050–2070 if we continue on a high-emissions trajectory.[24] The resulting increase in intensity and frequency of extreme weather events (heat waves, heavy downpours, floods, major hurricanes) will take a huge toll on agricultural lands.[25] This reinforces the need for extensive and immediate implementation of climate mitigation policies, as well as adaptation strategies, like adopting soil health practices, that simultaneously pull carbon dioxide out of the air while making agricultural lands more resilient.

Farmers and ranchers face adaptation challenges regardless of actions taken to reduce GHG emissions farther in the future.

Visualizing projected changes

The map projections shown here and in our companion web application illustrate the shifts in rainfed growing conditions as indicated by changes in the likelihood of cultivation between 2016 and 2040. Because our focus was on rainfed agriculture, AFT excluded counties where over 50% of the cropland is irrigated, using a combination of annual irrigation maps and data from the 2017 USDA Census of Agriculture to identify these counties (shown in dark grey).

Corn and wheat, along with soybeans, are the most expansive rainfed crops produced today in the U.S. Apples are long-lived woody perennials and are heavily irrigated in some critical production areas like Washington state, but less so in the eastern U.S. For rainfed corn and winter wheat, we removed from our data crop areas that were irrigated, so the resulting maps focus on rainfed production. In contrast, non-irrigated apple orchards could not be separated from irrigated orchards due to a lack of data. As a result, the maps of projected likelihood of cultivation for future commercial apple production presuppose the use of irrigation where necessary.

To visualize potential effects of changes in future growing conditions, we used the difference between the projected likelihood of cultivation in 2040 and the 2016 baseline. For areas with below average likelihood of cultivation in 2040, using present day crop varieties and production practices may become increasingly difficult. The resulting maps show where likelihood values improve as values rise above the 2016 average *(increased opportunity)*, where likelihood values remain above the 2016 average (even if values decline) (*remain above average*), where likelihood values stay below the 2016 average (even if values rise) (*remain below average*), and where likelihood values drop below the 2016 average (*increased threat*).

Limitations

While our visualization approach highlights hotspots of change nationally, it may not work as well in parts of the country where a given focal crop's acreage may be entirely on lands that are below the 2016 national average of the likelihood of cultivation as defined by our modeling (e.g., parts of the Northeast). Although shifts in likelihood values may still occur in these areas, they happen below the national mean and are not easily detected by our visualization approach. This potential shortcoming is the result of our need for a visualization approach that works well to simplify the complex results of our modeling at a broad, national level. It does not mean that climate impacts will not be felt in these areas. What you see here is only one way to interpret the changes in projected likelihood of cultivation. Both the raw projected likelihood layers and summary statistics are available for cropland and our three focal crops and can paint a more detailed picture of projected change. Contact AFT at maps@farmland.org to discuss custom approaches to visualize this data in your state or region of interest.

> Both the raw projected likelihood layers and summary statistics are available from AFT and can paint a more detailed picture of projected change.

Projections for crops and cropland

Because individual crops tend to have a narrow range of tolerable temperatures, moisture requirements, and terrain, the impacts of climate on the future likelihood of growing individual crops like corn, winter wheat, and apples show up more readily than they do for the much broader cropland category which encompasses all crops and their associated tolerances.

In Table 1, we show the percent change in acreage of projected growing conditions in 2040 for rainfed cropland, corn, and winter wheat, and for apples. The projections assume that irrigated acres remain constant.

Table 1. Change in growing conditions as percent of the acreage in 2040 compared to 2016 baseline.

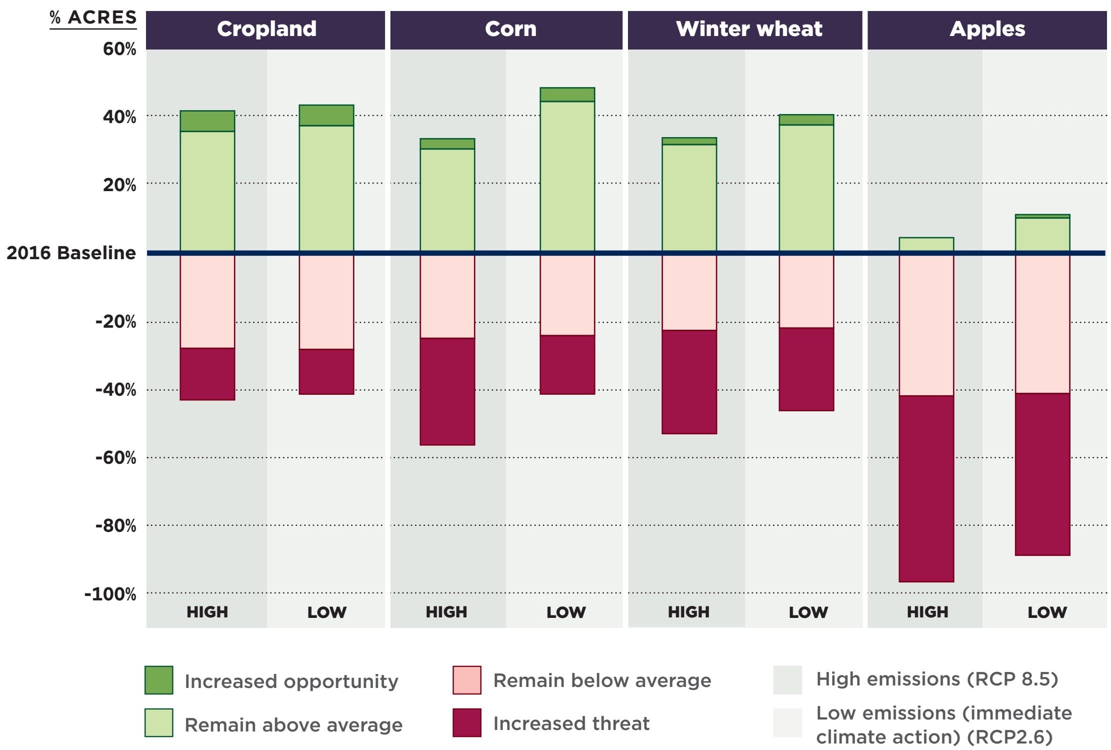
	Percent of crop/cropland cover acreage in 2040							
	Cropland*		Corn		Winter wheat		Apples	
Change in Rainfed Growing Conditions, 2040**	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6
Increased opportunity	6%	6%	3%	4%	2%	3%	0%	1%
Remain above average	35%	37%	30%	44%	31%	37%	4%	10%
Remain below average	28%	28%	25%	24%	23%	22%	42%	41%
Increased threat	15%	13%	31%	17%	30%	24%	54%	47%
Irrigated acres (held constant), not mapped	17%	17%	11%	11%	14%	14%	NA	NA

* Changes in cropland likelihood values between high emissions (RCP 8.5) and immediate climate action (RCP 2.6) are similar when summarized at the national level but mask subtle, yet highly impactful, changes occurring at regional, state and county levels.

** A previous *Farms Under Threat* report[26] cited findings that 86% of cropland nationwide was rainfed.[27] Here we exclude all cropland within counties where irrigated cropland represents greater than 50% of total cropland acreage, which results in a slightly lower percentage of rainfed cropland (83%) for the U.S. In addition, the two efforts assessed cropland area in different time periods and are thus not directly comparable.

To help visualize what these percent changes in likelihood mean, Figure 1 shows the amount of rainfed agricultural land remaining above or below the 2016 average by 2040 under the two contrasting climate trajectories. By 2040, the shift downwards in acres above the 2016 average (in shades of green) to acres below the 2016 average (in shades of red) is evident as more and more acres become less suitable for production and the likelihood of cultivation diminishes. Although some acres rise above the 2016 average (increased opportunity in dark green), more acres drop below the 2016 average (increased threat in dark red), especially with apples.

Figure 1. Changes in rainfed growing conditions by 2040. This figure shows how the likelihood of cultivation will change by 2040 relative to the 2016 average. Below this baseline, the use of present-day varieties and production practices will be much more difficult. The acres where likelihood of cultivation remains above the 2016 average in 2040 are shown in light green while acres that remain below the 2016 average in 2040 are shown in light red. A small percentage of acres move above the 2016 baseline (dark green) in 2040, denoting increased opportunity for cultivation, while a significant percentage of acres move below this baseline (dark red) indicating increased threat. Irrigated acres were not mapped and are not shown.

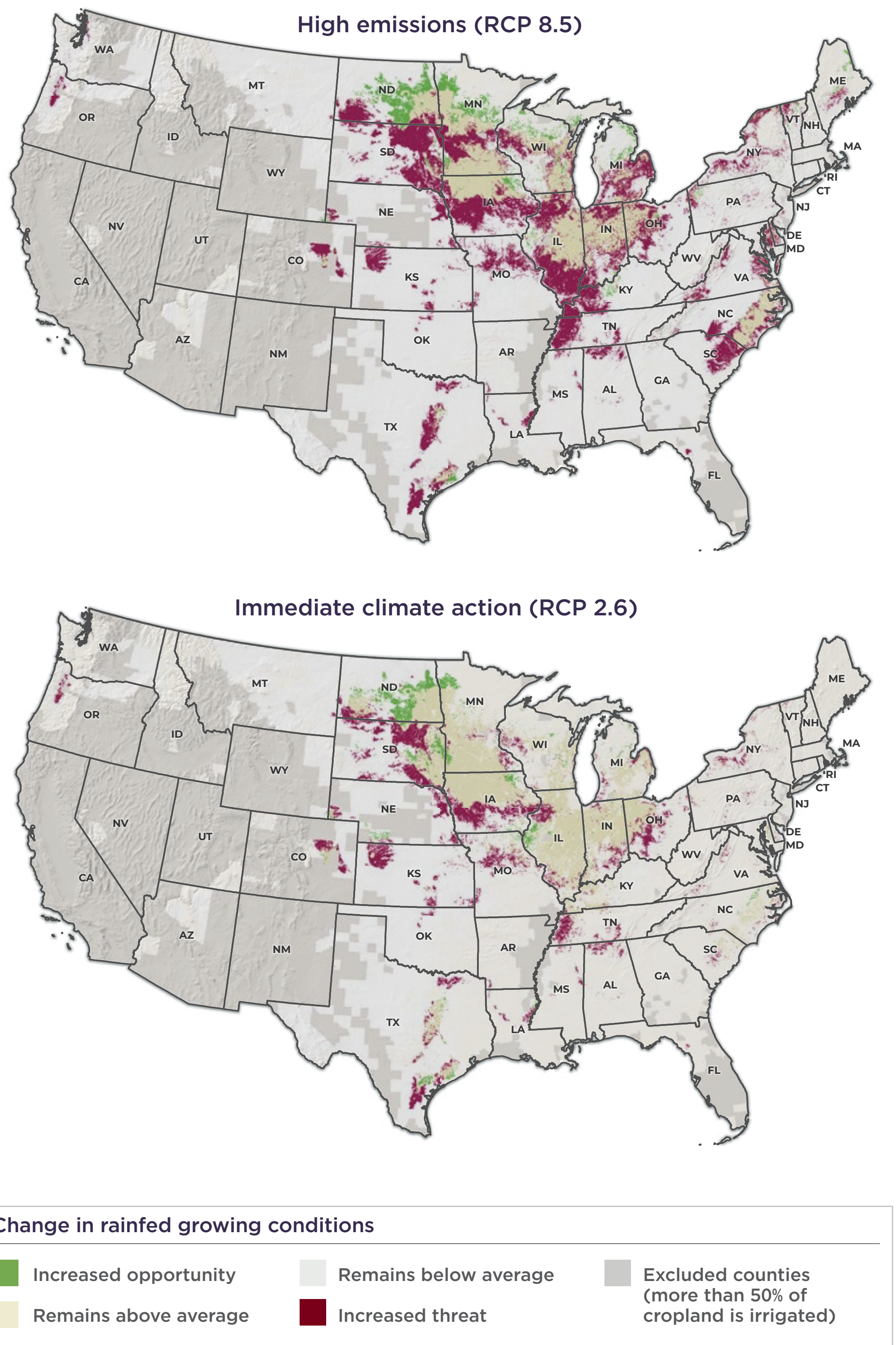


Rainfed corn

Corn can grow almost anywhere in the country and is especially well-suited to the Midwest. It is uniquely sensitive to hotter temperatures and water stress, especially if they occur during the pollination and grain-filling stages. High temperatures and drought stress can limit corn growth at any stage by reducing photosynthesis, increasing oxidative stress, and increasing nighttime respiration rates.[28] These conditions occurred in 2012 during one of the worst droughts on record in the U.S. Roughly 77% of the contiguous U.S. was abnormally dry or under exceptional drought. Among row crops, losses were most substantial for U.S. grain corn, with more than a quarter of the corn lost.[29] Although continual improvements in corn hybrids and other agricultural technologies have been able to maintain a steady increase in U.S. corn yields, yields will most likely be progressively reduced in the future due to warmer and drier climates.[30] Higher air temperatures speed up evaporation from soils and plants and not only encourage drought conditions to build but also intensify. Warming also diminishes snowfall and reduces snowpacks that can play a crucial role in moderating the impacts of drought by storing water in the winter and releasing it when it's needed in the warmer, drier months. In other words, because of hotter temperatures, it is now easier to get into, and harder to get out of, drought.

We highlight potential climate threats and opportunities for rainfed corn production by 2040 in Figure 2.

Figure 2. Climate threat and opportunity for rainfed corn by 2040



Our models suggest that the changes in temperature and rainfall will likely make it much more challenging to grow corn in many areas under the high-emissions trajectory. By 2040, only 33% of the acres are likely to remain highly productive with the current corn varieties (Table 1). This is because 31% of the acres may experience increased climate threats that make them less likely to support the corn varieties and management strategies currently in use, while only 3% of acres under corn production in 2016 may rise above the average likelihood of cultivation (increased opportunity). In contrast, immediate climate action could maintain almost 50% of the corn acreage in the above-average category by 2040 and also limit the percent of acres that may experience a deterioration in growing conditions (increased threat) from 31% to just 17%.

Rainfed winter wheat

Wheat is the world's primary rainfed crop in terms of harvested area, is a leading source of dietary protein,[31] and provides approximately 20% of all calories consumed by humans.[32]

Winter wheat represents 70–80% of the wheat grown in the U.S. and is primarily rainfed.[33] It is a long-duration crop and typically stays in the ground 7–8 months. It is usually planted in the fall, goes into dormancy over winter, and begins growing in the spring. It is then harvested in the summer or early fall. It can withstand freezing temperatures for extended periods of time in early stages after planting and needs freezing or near-freezing temperatures to break dormancy and initiate seed production. At the same time, winter wheat is very susceptible to heat stress.

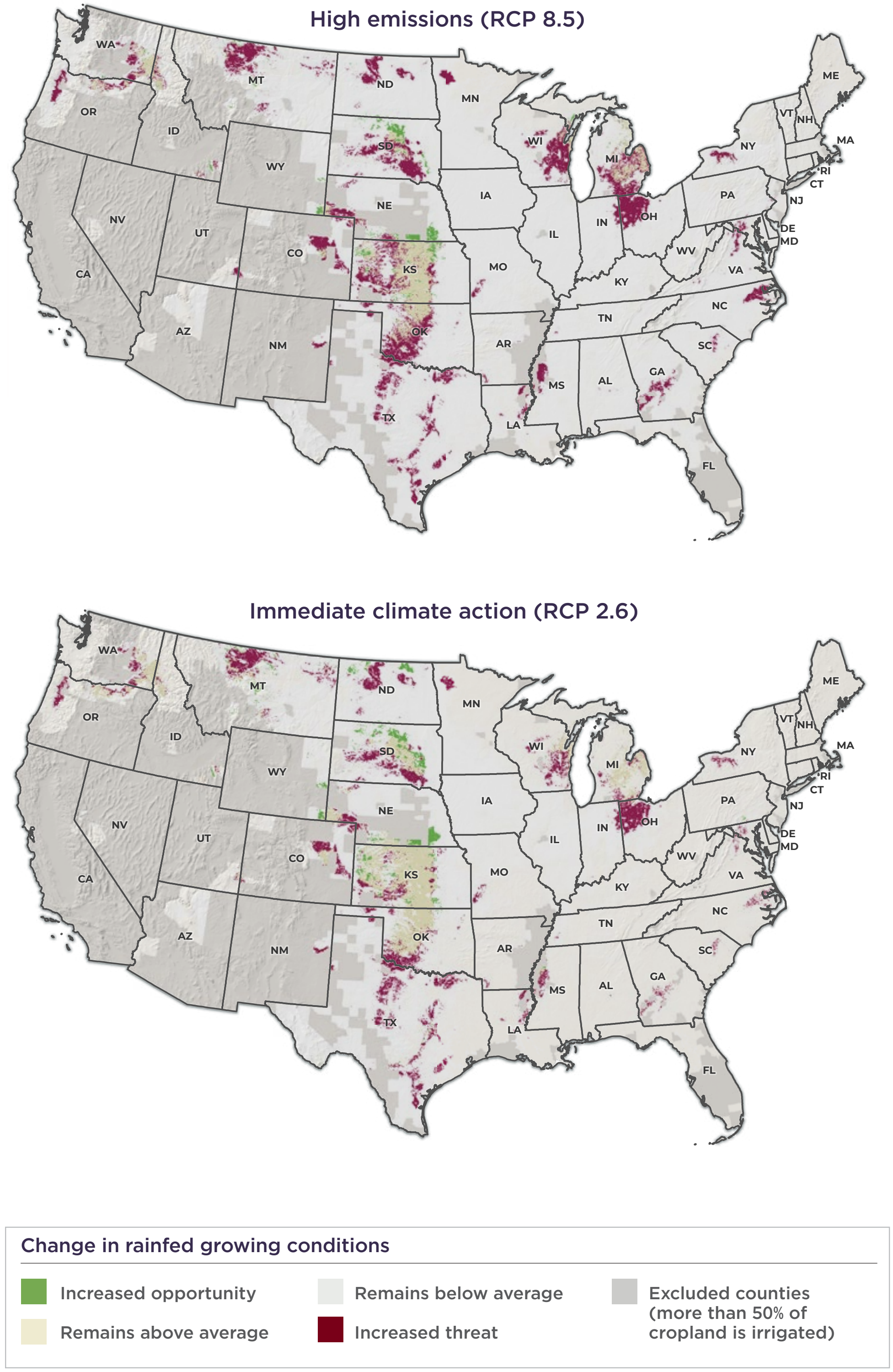
The climate threat and opportunity for rainfed winter wheat by 2040 is shown in Figure 3.

Our models suggest that if society stays on a high-emissions climate trajectory (RCP 8.5) instead of rapidly reducing GHG emissions, 30% of the winter wheat acres will drop below average and be much less likely to support the winter wheat varieties currently grown (Table 1). The acres under increased threat in the high-emissions climate trajectory join the 23% of acres that were already below the 2016 average where cultivation was less likely.

Conversely, only 2% of winter wheat acres nationwide rise above average, indicating that conditions may now favor winter wheat over other crops and lead to an increased opportunity for cultivation. For the immediate climate action trajectory, our models suggest that fewer acres will be below average in 2040 (44%) while slightly more acres (37%) may experience conditions that lead to a higher likelihood of winter wheat cultivation when compared to the high-emissions trajectory. Modeling by other researchers shows that the primary driver of production loss for this cropping system will be heat stress, so yield losses may be mitigated by developing heat tolerant winter wheat varieties and by shifting planting timing to avoid exposure to high heat.[34]

Warming temperatures and short-season varieties may also encourage farmers to double crop winter wheat with corn or soybeans more often in the northern tier of the Corn Belt. However, the increased moisture requirements of crops may make the timing of rainfall more critical. Double cropping may increase the economic returns for farmers, reduce the risks from extreme weather events during critical periods such as pollination, and help limit soil erosion since the ground has cover for the entire year, not just a portion of the growing season. But these benefits are not projected to be large enough to make up for the yield losses that are projected for corn and soybeans.[35]

Figure 3. Climate threat and opportunity for rainfed winter wheat by 2040



Apples

Apples are uniquely vulnerable to climate change since weather plays a key role in pollination and fruit set and the fruit is susceptible to heat, sun, and frost damage.[36] Winter chill accumulation is also needed to keep orchards productive and profitable.[37] Apples are grown commercially in 32 states on over 320,000 acres and are heavily irrigated in some critical production zones (e.g., Washington state). The estimated costs of planting a commercial orchard can be quite high (e.g., $7,000–$19,000/acre in Kentucky).[38] Commercial orchards are expected to produce for at least 20 years and decisions on cultivars to plant up until now have largely depended on how the fruit will be marketed.[39] Most apple trees will start to produce fruit in their third or fourth year, but this can vary greatly. Some varieties are slower to fruit. Apple varieties are grafted onto rootstock and the rootstock influence can cause the same variety to start fruiting in a range of about two to seven years.

Under the high-emissions climate trajectory, our models estimate that, by 2040, the conditions on all but 4% of the commercial apple production acreage in the contiguous U.S. will be much less likely to support the apple varieties we currently grow. Modeling shows that 54% of the acres will drop below average likelihood of cultivation while 42% remain below it (Table 1). By taking immediate climate action, we keep more acres above average (11%), which means they may still support the current apple varieties. However, even with immediate climate action many areas currently under commercial apple production in the U.S. may face increased challenges due to changing climate conditions in 2040 (see red areas on maps).

The top apple producing states are Washington, New York, Michigan, Pennsylvania, and California. In the top apple producing state, Washington apple growers may see production shift to the east and north, though viability across the region will depend on irrigation-water availability (Figure 4). And in New York, growers may need to increase adaptation measures (e.g., switching cultivars, adding more drainage lines to handle excessive rainfall, using shade-cloth netting to reduce heat stress, etc.)[40] (Figure 5). Modeling shows similar outcomes in Michigan and Pennsylvania, with the likelihood of cultivation in top apple producing counties dropping irrespective of the climate trajectory, particularly in Pennsylvania's southeastern region (e.g., Adams County). **Immediate climate action, however, may help limit the extent to which growers need to adapt.**

Although apple production in the Northeast may benefit from longer growing seasons, researchers warn that cold season varieties (e.g., McIntosh and Empire) may be negatively affected by warmer temperatures and reduced winter chill periods due to a changing climate, and farmers may need to transition to new apple varieties over time.[41] Taking immediate climate action can help retain the long period of winter chill apples need, perhaps until late in the century, giving farmers more time to plan for the future and breeders more time to develop new apple varieties.[42]

Figure 4. Climate threat and opportunity for Washington State commercial apple production by 2040

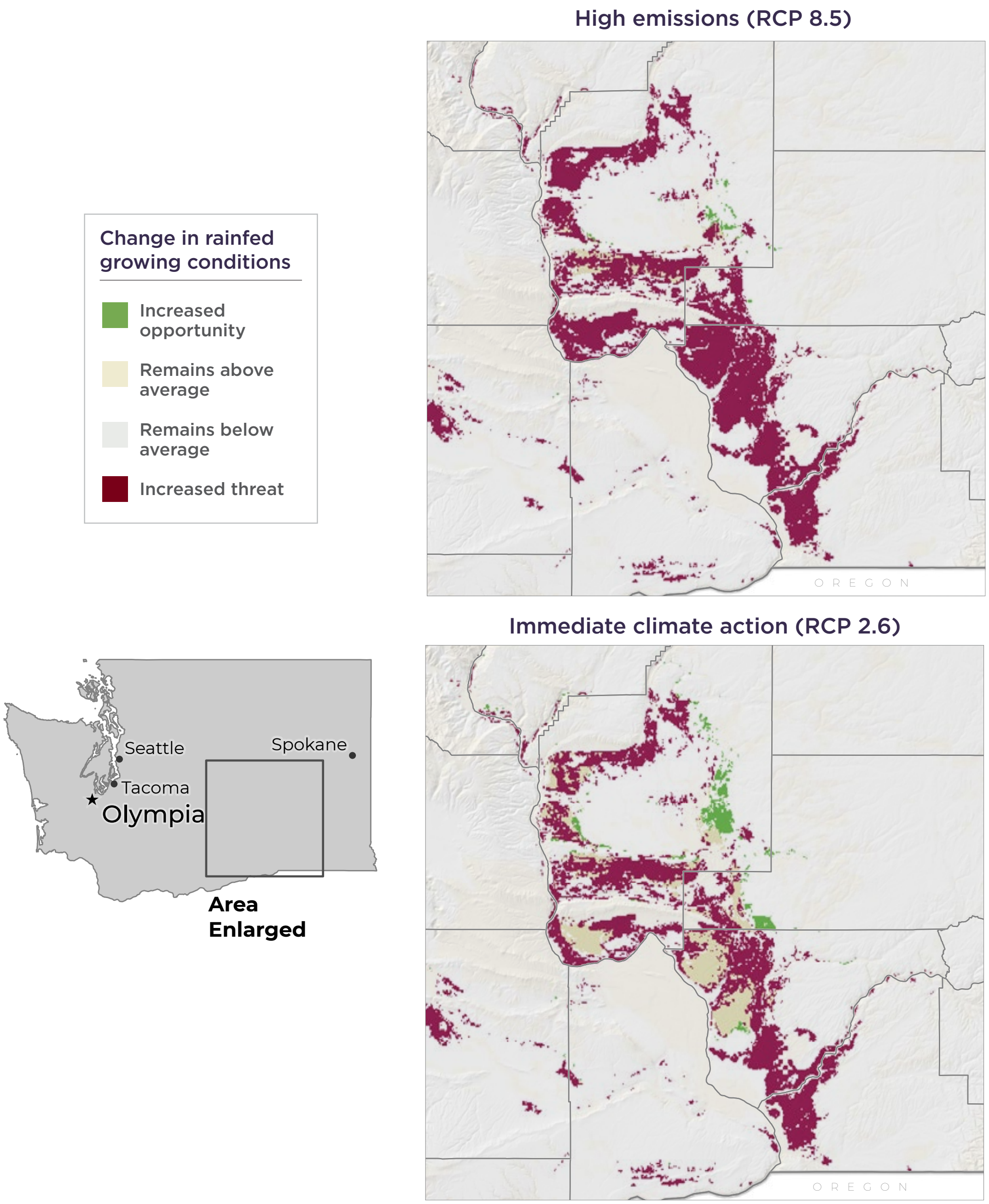
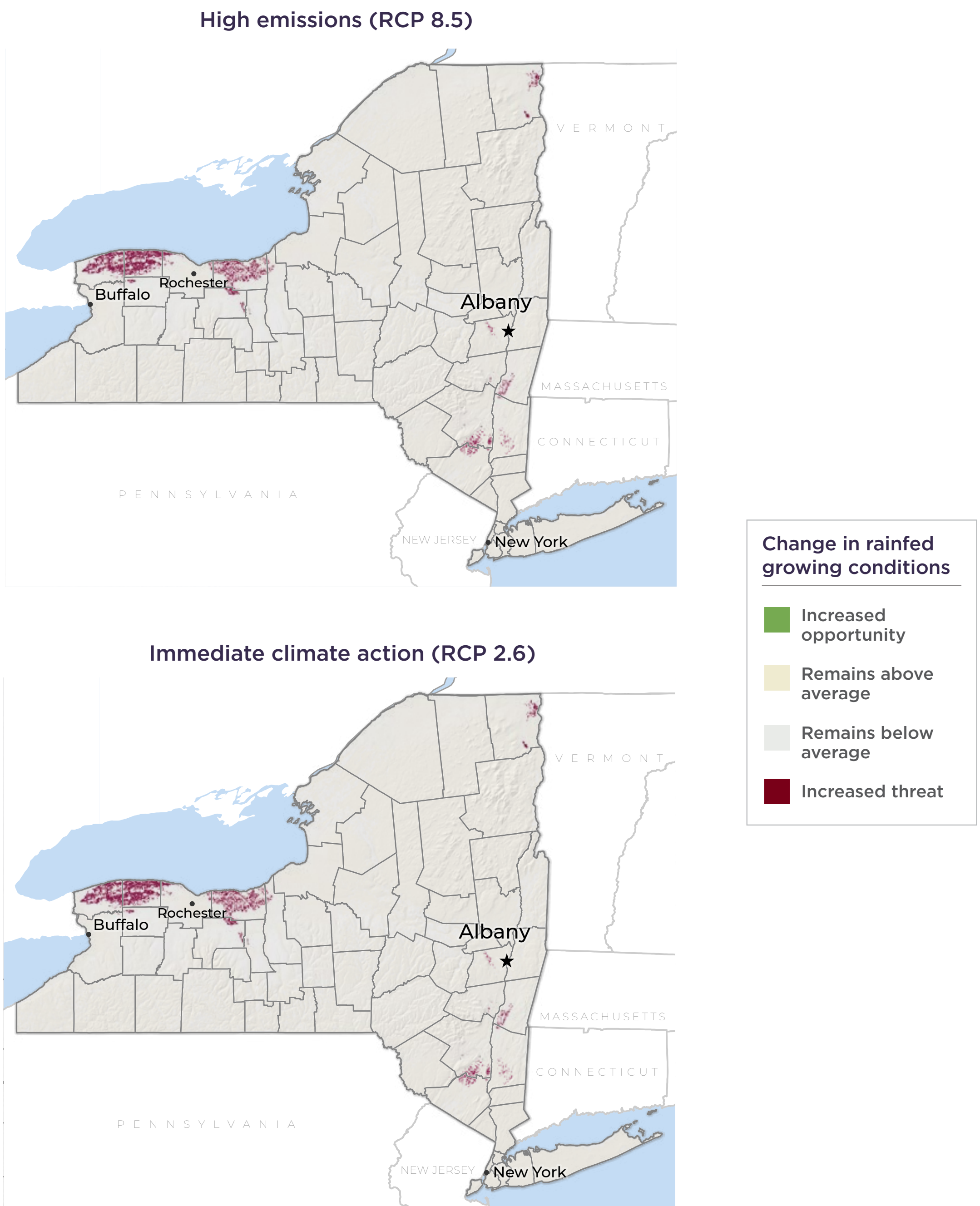


Figure 5. Climate threat and opportunity for New York State commercial apple production by 2040



Rainfed cropland

Although land-use decisions are influenced by prices and market demands, climatic conditions govern where and what crops can be grown, how much management and inputs will be needed, and how much will be harvested (i.e., crop yields). Climate, along with soil conditions and terrain, determines whether agricultural lands are best used as cropland or pastureland or managed as rangeland.[43] As mentioned previously, improvements in technologies and crop genetics, along with other factors, have made it possible for farmers to grow crops in areas that are already less than optimal for crop production.[44] Now, however, increasingly erratic temperatures and rainfall threaten to further reduce the biophysical suitability of more and more rainfed cropland acres. Our projections show that acres that were already marginal for production could become even more biophysically unsuitable and acres that were previously optimal for production could become far less optimal(Figure 6).

> Now, however, increasingly erratic temperatures and rainfall threaten to further reduce the biophysical suitability of more and more rainfed cropland acres.

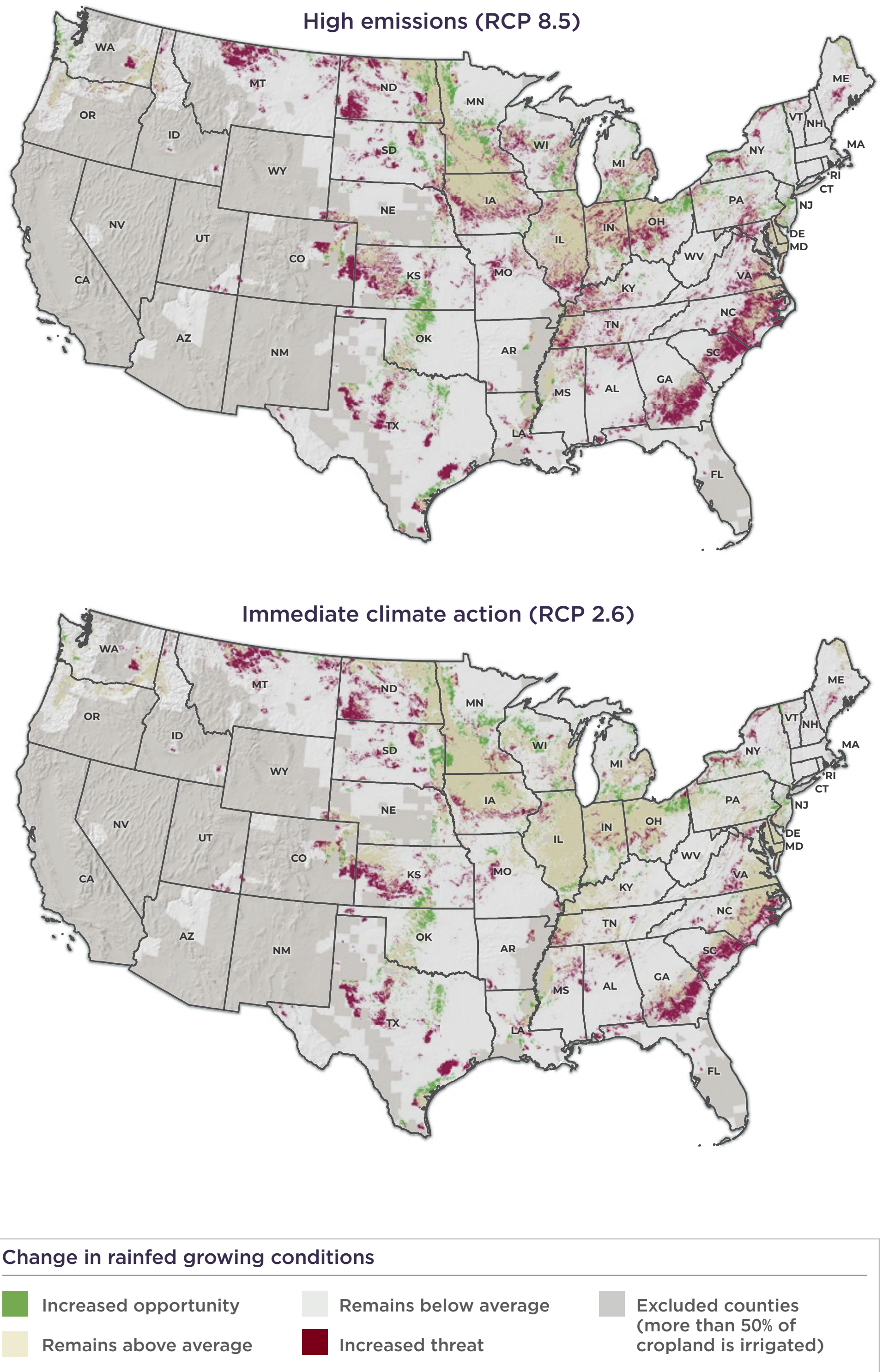
If society stays on its current high-emissions climate trajectory (RCP 8.5), the model suggests that 15% of rainfed cropland acres will drop below average likelihood of cultivation (increased threat) and join the 28% of the cropland acres that remain below average (Table 1). This means that 43% of cropland acres may face increased challenges for crop production and are less likely to support the crop varieties and production practices currently in use. Thirty-five percent of the cropland acres remain above average and 6% show increased opportunity so 41% of cropland acres are above the mean likelihood for cultivation. Compared to the high-emissions trajectory (RCP 8.5), immediate climate action (RCP 2.6) results in slightly more cropland acres above the 2016 average (43%) by 2040, and 2% fewer cropland acres that may face increased climate threats. Rising likelihood of cultivation values identify increased opportunities on a small percent of existing cropland and here, farmers may be able to intensify their cropping, while in other areas they may choose to convert the existing grassland or forestland into cropland, which means significant negative environmental impacts on carbon storage, water quality, and biodiversity.

> 43% of cropland acres may face increased challenges for crop production.

At first glance, the differences in likelihood of cultivation values for the two future climate trajectories assessed on rainfed cropland appear minimal when we compare immediate climate action to staying on a high-emissions pathway in the short term. When aggregated to the national level, the projected changes in the likelihood of cultivation between the two climate trajectories are not dramatic, perhaps because cropland is a broad land use category that can support a wide array of agricultural systems and practices, or because farmers can switch from one crop to another to maintain land in crop production. Any significant changes occurring at the county level even out when aggregated to the national level. However, at local scales, the projected declines in the likelihood of cultivation could have a profound effect on local

> At local scales, the projected declines in the likelihood of cultivation could have a profound effect on local communities, particularly where agriculture is an important local economic driver.

Figure 6. Climate threat and opportunity for rainfed cropland by 2040



communities, particularly where agriculture is an important local economic driver. If farmers can no longer support crop production on even a small percentage of lands where crops are currently planted, it may cause economic ripple effects in diverse industries and affect agribusinesses, jobs, and any locally sourced, value-added food processing. This may also lead to losses in tax revenues. Indeed, climatic changes have already influenced which crops farmers can grow and where they can grow them. Between 1970 and 2010, the changes in temperature and rainfall were partly responsible for moving cotton, hay, spring wheat, and corn westward (buffered by irrigation), winter wheat, soybeans, corn, and hay northward and some hay, soybeans, spring wheat, and corn to higher elevations.[45]

Projections by other researchers show significant changes in rainfed cropland by the end of the century without immediate climate action. This is particularly a threat in the central and southeastern U.S. where cropland may be replaced by pasture, leading to a 6% decrease in cropland and a 33% increase in pastureland.[46]

Although farmers have always adapted their cropping systems to adverse environmental conditions, **the speed and complexity of climate change pose problems on an unprecedented scale.**[47] Advances in precision irrigation, drought-resistant crops, and targeted fertilizer treatments will help farmers and ranchers cope with increasingly erratic weather in the short term. But even at the present pace of agricultural innovation, the impacts of a warming climate on American farms and ranches will likely outpace technological fixes within decades.[48]

The realization that agriculture will not be able to keep pace with changes to the climate has amplified the need for society to rapidly decarbonize, and to help farmers transition to farming practices that reduce on-farm GHG emissions, sequester carbon, improve soil health, and conserve water. A consortium of 12 of the largest food and farming businesses is now urging food companies and governments to come together immediately to change the world's agricultural practices or risk "destroying the planet." They conclude that "regenerative farming practices,"[‡] which cover 15% of the world's croplands, must triple by 2030 to keep the climate within safe limits.[49]

‡ Depending on crop and farming operation, these regenerative farming practices (as defined) include reducing or eliminating tillage, crop rotations, inter-cropping, Integrated Pest Management, fertilizer optimization, drainage water management, irrigation efficiency, crop diversification, cover cropping, and livestock integration.

A grim warning but there is hope

At no other point in history has agriculture been faced with such an array of familiar and unfamiliar risks, interacting in a hyperconnected world and a precipitously changing landscape. The growing frequency and intensity of disasters, along with the systemic nature of risk, are jeopardizing our entire food system.

—FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS[50]

Unless society quickly makes deep cuts (of 45%) in GHG emissions by 2030, statistically-based projections show a 90% chance that global temperatures will increase this century by 2.0 to 4.9 C (or between 3.6 to 8.8 F).[51] Even if water is still available for supplemental irrigation on rainfed cropland, and new cultivars selected to maintain the original growing period under warming can balance the effects of moderate warming (3.6 F), these two crop management options may not fully compensate for the impacts that greater levels of warming beyond 3.6 F will have on food production.[52]

Immediate action to reduce GHG emissions will help limit some of the adverse effects of future warming, but today's farmers and ranchers still face the consequences of GHG emissions already in the atmosphere. Our agricultural systems and the infrastructure that supports them will need to match the new climatic conditions and growing pressures on land and water resources. Despite these increasing challenges, society will continue to rely on farmers and ranchers to manage their agricultural lands as part of a larger ecosystem, delivering not only food but also renewable energy and ecosystem services like clean water and wildlife habitat.[53]

To keep their operations viable, farmers and ranchers are already transitioning, and will continue to transition to a suite of soil health and other climate-smart practices that can improve the fundamental functions of soil and water, reduce stressors on crops and livestock, and build resilience to warmer and drier conditions as well as heavier rains. Croplands managed for soil health (i.e., using practices like no till, cover crops, and diversified crop rotations) have a greater resilience to the changing climate. Their soils are less vulnerable to erosion, have increased water-holding capacity during drought, support crop yield stability, and in most cases also sequester carbon. Improving soil health is also among the least costly and most immediate actions that can help reduce GHG emissions on a meaningful scale. This can serve as an important bridge as new climate-friendly energy and transportation technologies are developed and implemented. Soil health practices rely on current technology and knowledge and robust programs for implementation. However, it can take 3–5 years to start seeing the benefits and 10–50 years to fully restore soil health, depending on the land use history, region, soil type and climatic conditions.[54] Many of these actions may need outside funding and/or will likely require additional, innovative financial and technical assistance to implement.[55] Luckily, systems of service providers and programs at the local, state, and federal level are already poised to be reinvigorated to meet these and other environmental, economic, and food security goals.

In 2022, USDA invested $2.8 billion in the Partnerships for Climate-Smart Commodities to kick-start the implementation of climate-smart systems on farms and ranches with practices that improve soil health, sequester carbon, reduce GHG emissions, and increase the economic and ecological resiliency of diverse farm operations. At the same time, Congress passed the Inflation Reduction Act, legislation meant to help set the nation on a net-zero emissions path by mid-century to avoid the consequences of the worst-case high-emission trajectory. This included a nearly $20 billion investment to support voluntary adoption of on-farm practices that will reduce GHG emissions and sequester carbon.

However, the 2040 climatic impacts spotlighted in AFT's maps make it clear how important it will be for farm bill programs to provide enough technical and financial assistance to achieve the scale of landscape resiliency needed. Even after years of aggressive outreach, farmers on 95% of U.S. croplands still do not plant cover crops.[56] AFT recently completed a series of listening sessions across the country with farmers, ranchers, agricultural service providers, and others on how the 2023 Farm Bill can build on the Conservation Title (Title II) Programs to support more farmers and ranchers in adopting climate adaptive and mitigating practices. The participants discussed the challenges they face from the changing climate, the barriers they experience in adopting conservation practices, and what they think the next farm bill should do to make our agricultural lands more resilient and keep their operations profitable.[57] Their responses reinforce the need for immediate action and new approaches.

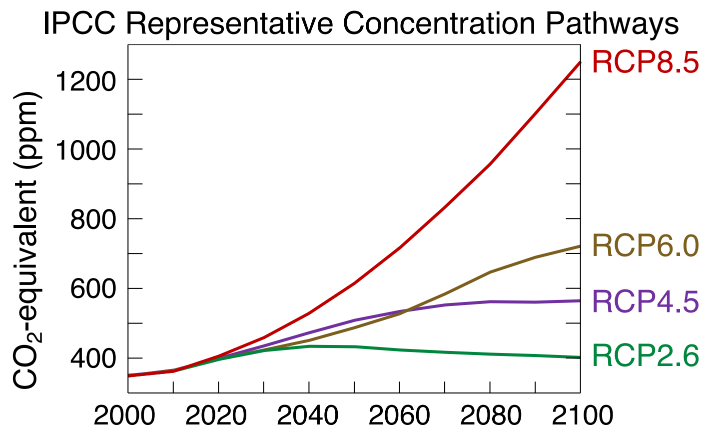
> The best window of opportunity to change the trajectory of the changing climate and avoid further compounding impacts is NOW and with the right tools and support, agricultural producers can adapt to and help reverse these trends.

The best window of opportunity to change the trajectory of the changing climate and avoid further compounding impacts is NOW[58] and, with the right tools and support, agricultural producers can adapt to and help reverse these trends. In its 2023 Farm Bill platform, AFT has laid out a series of policy recommendations designed to help farmers build on-farm resilience while mitigating and adapting to the current impacts of climate change. Actions include improvements to the Conservation Title (Title II) Programs and the Crop Insurance Title (Title XI) Program to build on-farm resilience and reduce risk (e.g., offering crop insurance discounts for risk-mitigating practices like cover crops), and the creation of a new federal match to bolster emerging innovative state soil health programs. State and local governments also have critical roles to play in taking actions to reduce GHG emissions and supporting farmers and ranchers in being a part of the climate solution. Implementing these recommendations will improve our chances of limiting warming, and in the process, make agricultural land and businesses more economically and environmentally resilient.

> Implementing these recommendations will improve our chances of limiting warming to tolerable limits, and in the process, make agricultural land and businesses more economically and environmentally resilient.

Appendix: Climate trajectories

Figure 7. The RCP climate trajectories[59]



The global climate change trajectories show different climate futures based on the amount of greenhouse gases (GHGs) we release into the air in the years to come.[60] Called Representative Concentration Pathways (RCPs), they are the result of extensive modeling. GHGs trap heat in the atmosphere and include carbon dioxide (CO_2) from burning fossil fuels, tilling soil, and clearing forests; methane (CH_4) from producing fossil fuels, from livestock, and from other agricultural practices; nitrous oxide (N_2O) from agricultural land use and industrial activities; and fluorinated gases emitted from a variety of industrial activities. Key factors driving changes in GHG emissions include technology, lifestyle and behavioral changes, economic and population growth, climate policy, and changes associated with energy use and land use. The climate trajectory we are currently on is in line with the higher-end emission scenarios and will push the world past tipping points that will make climate breakdown irreversible (between RCP 6.0 and RCP 8.5) by the end of this century.[61]

RCP 8.5: High-emissions climate trajectory: Assumes we fail to take immediate climate action and emissions continue to rise throughout this century, resulting in a global temperature rise of about 5–6 degrees C (9–10.8 degrees F). RCP 8.5 is the most aggressive scenario in assumed fossil fuel use for global climate models. While the rapid decline in the cost of renewable energy production makes it unlikely that the world will follow this trajectory to the end of the century, current global emissions are very similar to this trajectory. Unfortunately, this scenario continues to be in close agreement with the historical total cumulative CO_2 emissions. It may also be the best match out to 2050 under current and stated policies.[62] However, many experts now feel that the world is on track for global warming in the realm of about 3 C (5.4 F) by the end of the century, not 5–6 degrees C.[63] Climate scientists are now trying to improve the accuracy of their models.

RCP 2.6: Low-emissions, immediate climate action trajectory: Assumes CO_2 emissions start declining by 2020 and go to zero by 2100, CH_4 emissions go to approximately half of their 2020 levels and sulfur dioxide (SO_2 is an indirect GHG) emissions decline to about 10% of the 1980–1990 levels. To achieve these goals, we need to immediately reduce GHG emissions and remove more carbon dioxide from the air (2 Gigatons of CO_2 per year). Following the RCP 2.6 trajectory keeps global temperature rise below 2 C (3.6 F) by 2100 but still puts 30% of species at risk of extinction. Allowing temperatures to rise by more than 1.5 C (2.7 F) will vastly increase the risk of irreversible changes to the climate. The U.N. Emissions Gap Report 2022, released in October 2022, warns that governments are falling behind in their pledges and only an urgent system-wide transformation can avoid climate disaster.[64] The international community now needs to deliver enormous cuts to limit GHG emissions by 2030: 45% to get back on track to 1.5 C (the target of the Paris Agreement) and 30% for 2 C.

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