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The Impact of Climate Change on Grain Production: The Case of French Cereals

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Cereal yields have grown considerably over the past several decades in many regions of the world, but rising temperatures pose an emerging threat to this progress. Our analysis of over six decades of French weather and yield data sheds light on the potential impacts of climate change on cereal yields and contextualizes these impacts relative to expected future technological progress.

The impact of future changes in climate on agricultural yields is of interest to farmers, whose livelihood is directly affected, as well as policymakers, who may use projections of climate change impacts to better craft policies that mitigate the extent of warming, adapt institutions and industries to warming, or redistribute resources to compensate those most harmed by climate change. Indeed, there is mounting evidence that warming will harm grain yields in key producing regions. Two important crops that may be affected by climate change are wheat and barley. According to the United Nations Food and Agriculture Organization (FAO), wheat and barley represent the third and fourth most produced grains, with wheat being the second largest calorie source worldwide among all crops. France is a major producer of both crops, producing 5.4% of the world's wheat and 7.1% of the world's barley in 2013.

In France, wheat represents over half of total cereal acreage, while barley is grown on 18%. Both wheat and barley can be cultivated as either winter or spring crops, although winter wheat is far more prevalent than spring wheat. Winter crops are typically planted in mid- to late fall and harvested the following July or August. Meanwhile, spring crops are most commonly planted between late February and mid-March and harvested several weeks after winter crops.

Weather conditions may have varying effects on yield at each stage of plant growth. In the fall, excessively cold temperatures may be harmful to winter crops if they occur before the crop has acclimated to low temperatures, a concept known as cold-hardening. During the winter months, excessively warm temperatures may interfere with vernalization, an exposure to cool temperatures necessary to induce more rapid flowering in the spring. In the summer, high temperatures or a lack of rainfall can have adverse effects on photosynthesis and grain-filling, while excessive rainfall can result in flooding and foster mold growth.

Researchers seek to understand the relative importance of these various weather effects on crop yields under current and future climates using a variety of approaches. Process-based approaches typically rely on calibrating a deterministic biophysical model with experimental data. These highly parameterized models allow simulating plant growth and yield formation as temperature, moisture, or atmospheric variables fluctuate on a daily basis. In contrast, statistical approaches rely on large-scale relationships among observed variables, often aggregated over many farms. Our work adopts a statistical approach, using historical weather and yield data from France to obtain estimates of the effect of climate change on French wheat and barley yields.

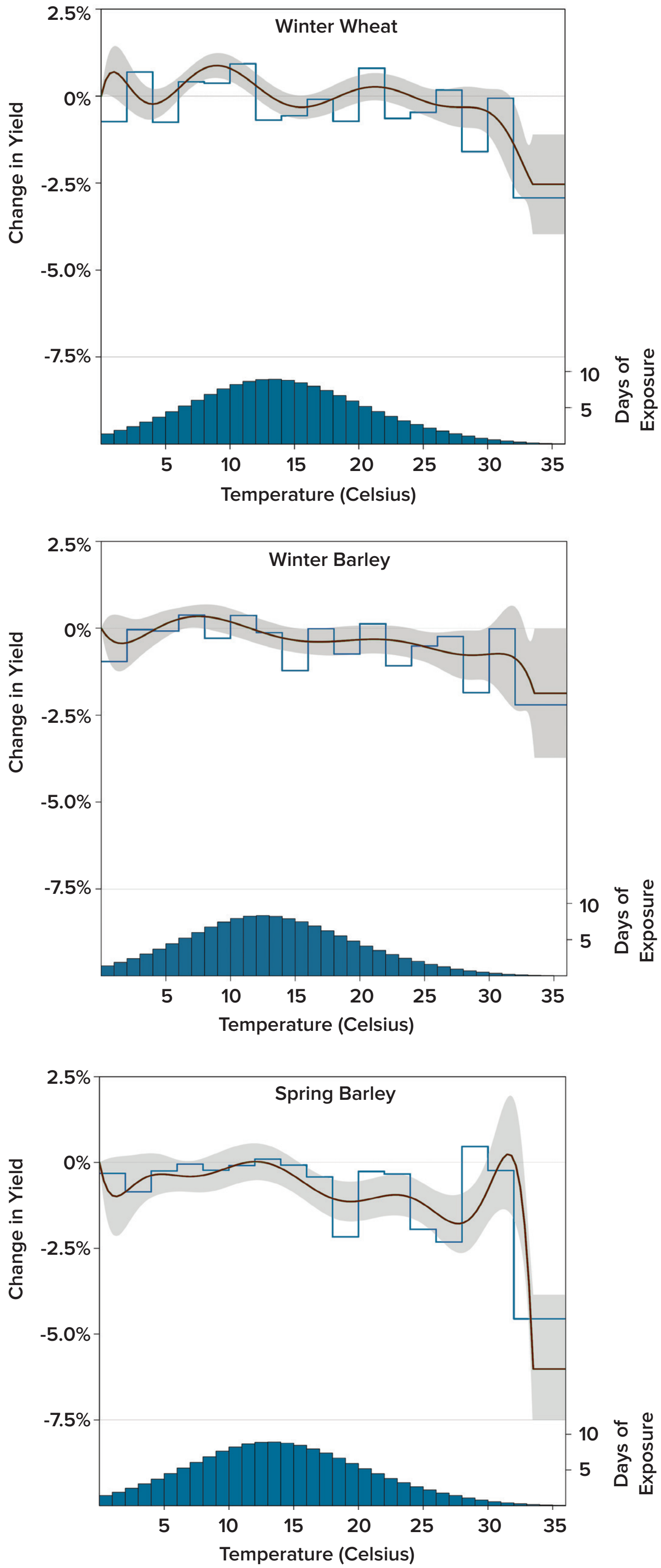

Figure 1. Temperature-Yield Relationship

Note: Graphs at the top of each frame represent percentage changes in yields if one day at 0 °C or below is replaced by one day at a given temperature, holding the total number of days in the season constant. The blue line indicates the step function specification and the red line indicates the polynomial specification. The 95% confidence interval for the polynomial regression is shown in gray. Histograms at the bottom of each frame show the average temperature exposure over the sample.

Effect of Temperature and Precipitation on Yields

Data on crop yields come from the French Ministry of Agriculture and include observations for 88 departments over mainland France from 1950 to 2016. Historical weather data for the same time period were obtained from a detailed gridded dataset for the European Union, which we aggregate to the department level based on the amount of agricultural area contained in each grid cell.

The level of exposure to specific temperatures within each day of the growing season has been shown to be important in predicting crop yields. We therefore compute exposure to various levels of temperature assuming that temperature follows a sine curve passing through the minimum and maximum temperature of each consecutive day. This procedure accounts for the day-night oscillation in temperature as we compute the exposure to every 1°C temperature interval for every day in the growing season.

We sum temperature exposure and precipitation over the spring-summer growing season and, in the case of winter crops, we separate fall and winter growing seasons. We define growing seasons based on a 2006 regional survey of French cultural practices.

Averaging temperature conceals the occurrence of temperature extremes, which may be important for yield determination. Therefore, it is important to account for the full range of exposure to temperatures in a flexible manner in a statistical model predicting the effect of temperature on yields.

To illustrate this, consider two days that both have an average temperature of 28°C. For the first, suppose it was 28°C for 24 hours, while for the second, suppose it was 22°C at night and 34°C during the day. The crop may respond very differently to these two days, despite the fact that they have the same average temperature. To ensure that our model is sufficiently flexible, we test two flexible functions of temperature: a step function and a polynomial. The step function allows the effect of each 2°C interval (0–2°C, 2–4°C, etc.) to be different, while the polynomial function allows each temperature to have a different effect, but imposes that the effect of two adjacent temperatures not be too different. In addition to a flexible function of temperature exposure and a quadratic function of total precipitation, we also control for time-invariant factors such as soils through the inclusion of department fixed effects and for technological progress, allowing time trends to be different in each of France's 21 regions.

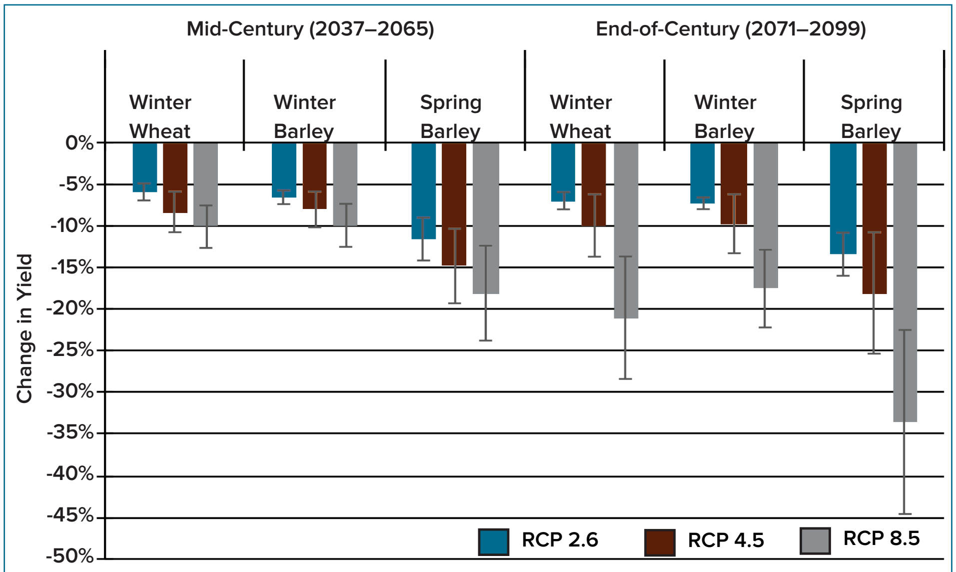

Figure 2. Mean Climate Change Impacts

Note: The average percentage impact across climate models for each Representative Carbon Pathway (RCP) are shown. Since these values are an average of five climate models, a +/- 1 standard deviation range is indicated by the error bars.

The effect of temperature on yields can be seen in Figure 1. The step function and polynomial response functions are quite similar qualitatively. Exposure to temperatures above 32°C are associated with yield declines for all three crops, although the extent of the damaging effects varies significantly across crops.

Spring barley, the crop most negatively affected by temperatures above 32°C, is also adversely affected by more moderate warm temperatures between 16–30°C. Both winter crops appear to benefit from cool temperatures between 7–11°C, although the effect is more pronounced for winter wheat. Graphs of the cold season temperature-yield relationship, not included here, suggest that exposure to temperatures below –6°C in the fall months is harmful, while the effects of winter temperatures are less important.

Climate Change Impacts

We project the impact that future climate change will have on wheat and barley yields relative to a world without climate change, based on the weather-yield relationships estimated on historical data. These impacts assume that land use and technology are held constant, with only the climate changing. The magnitude of the impacts naturally depends on the climate model or Global Circulation Model (GCM) and the assumed future trajectory of greenhouse gas emissions that we rely upon.

We project impacts under five GCMs and three possible trajectories of future atmospheric greenhouse gas concentrations outlined by the International Panel on Climate Change. These trajectories, called Representative Concentration Pathways (RCP), range from the mildest "RCP 2.6," which would require worldwide carbon emissions to begin decreasing immediately, to the most severe "RCP 8.5," representing a "business-as-usual" trajectory in which emissions continue to increase throughout the 21st century. We project climate change impacts for a mid-century period, 2037–2065, and an end-of-century period, 2071–2099. The impacts are relative to the baseline period of 1977–2005.

The average impact, across all climate models, for each crop and time period are presented in Figure 2 for RCP 2.6, 4.5, and 8.5. The error bars represent a range of plus and minus one standard deviation from the average. In the mid-century horizon, winter wheat and winter barley face declines of 6–10% depending on the RCP scenario. The impact on spring barley is predicted to be more severe, with yield declines ranging from 12–18%.

End-of-century impacts are roughly comparable to the mid-century projections in the low-emissions case, but far larger for mid- and high-emissions scenarios. For winter wheat, RCP 8.5 is associated with a yield decline of 21%, while winter barley yields are projected to fall 18% for the same scenario. Again, the impact on spring barley yields is much larger, with losses ranging from 13%–34% across RCP scenarios.

Comparison with Other Studies

Our results indicate that climate change will negatively affect French cereal yields, although the extent of the damage varies widely depending on the emissions scenario being

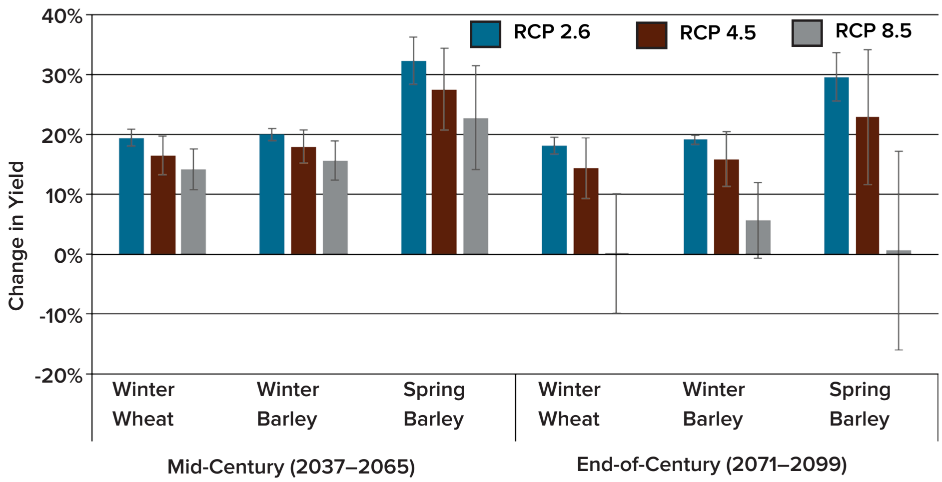

Figure 3. Net Impacts of Climate Change and Technological Progress

Note: The average net impact of climate change and technological progress across climate models for each Representative Carbon Pathway (RCP) are shown. Since these values are an average of five climate models, a +/- 1 standard deviation range is indicated by the error bars.

considered. The negative impact on wheat yields is consistent with the findings of many agronomic studies relying on process-based models. A 2015 statistical study on Kansas wheat yields by Tack et al also finds deleterious effects of climate change, although of very different magnitudes. We find that 5°C of warming would decrease French wheat yields by 24%, while Tack et al find that the same warming would decrease Kansas wheat yields by 50%.

This difference could possibly be due to differences in baseline climate, as the Kansas climate is substantially warmer than the French climate and thus the effect of additional exposure to high temperatures may be more detrimental in Kansas. Differences in the modelling approach may also explain the difference. The Kansas study uses a degree-day model that imposes slightly more structure on the weather-yield relationship than either the step function or polynomial specification used in our study. Finally, we are unable to rule out the possibility that data differences, including different levels of aggregation in the weather and yield data, contribute to the difference.

Technological Progress and Adaptation

Cereal yields in France have risen substantially over the past half-century. Since 2000, yields have averaged 6.1, 5.8, and 4.7 metric tons per hectare (MT/ha) for winter wheat, winter barley, and spring barley, respectively, compared to 1.9, 1.7, and 1.7 MT/ha during the 1950s. Even though the rate of growth has slowed over time, technological improvements will likely continue to increase yields in the near future, despite the counteracting effects of climate change. Our empirical results can be used to calculate the expected net impact of technological progress and climate change on yields.

The average net impact across climate models for each crop, RCP scenario, and time horizon are shown in Figure 3. Our results suggest that, relative to the 1977–2005 baseline, mid-century yields will be 14–32% higher depending on the crop and RCP scenario. For RCP 2.6 and 4.5, the end-of-century net impacts are quite similar to those in the mid-century case. The results for RCP 8.5 are more striking. Under these more severe climate changes, winter barley yields would be only 6% higher than in the baseline period while the negative effects of climate change would neutralize all of the expected technological progress for winter wheat and spring barley.

These estimates assume that farmers do not alter land use patterns in response to climate change. Although shifting production to cooler regions represents one potential adaptation mechanism, it is not without costs. New areas may have lower soil quality than current production regions and high fixed costs will prevent many farmers from easily shifting their operations onto new land. A second adaptation action consists in shifting to more resilient crops. Indeed, French farmers have been increasingly shifting from spring to winter barley since the 1960s, a trend that our results suggest may continue. Investment in the research and development of heat-tolerant crop varieties and improved farming practices, beyond the technological progress implied by our estimates, may also palliate the negative impacts of climate change on cereal agriculture.

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