PACIFIC CLIMATE IMPACTS CONSORTIUM, JUNE 2014

PCIC SCIENCE BRIEF: CROP YIELD UNDER CLIMATE CHANGE AND ADAPTATION

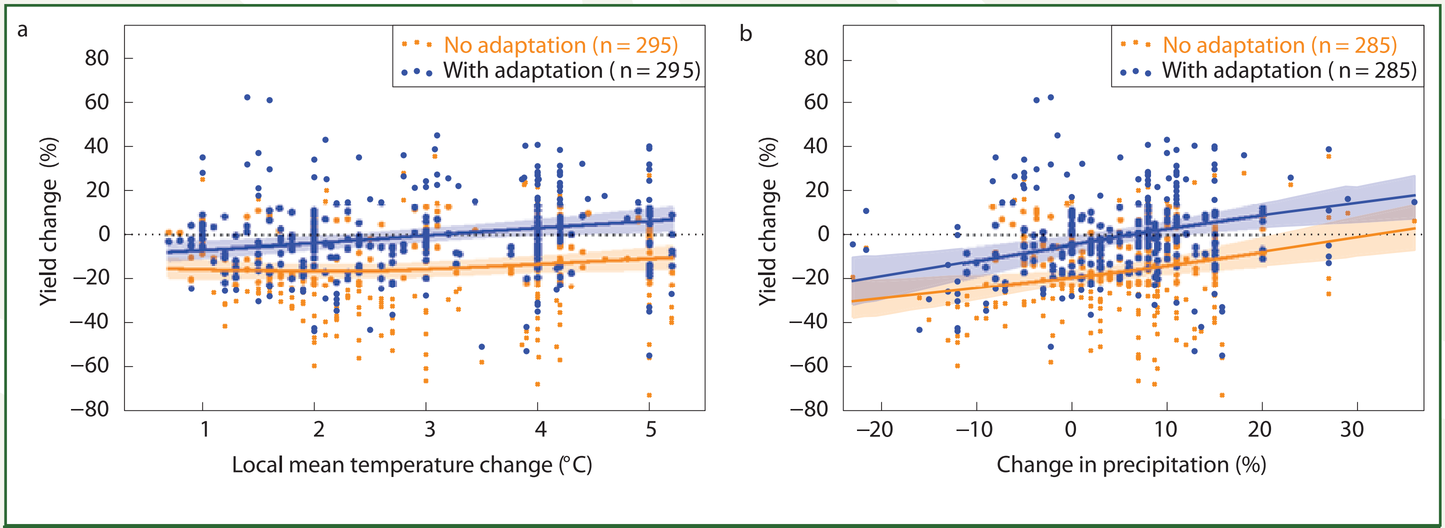

Figure 1: Quantification of the benefits of adaptation, from Challinor et al. (2014).
The above figure shows the percent change in yield as a function of (a) temperature and (b) precipitation. The dots represent the results from individual simulations, the solid curves[1] represent averages and shading indicates 95 % confidence intervals[2] (i.e. there is a 95% chance that the shaded interval includes the true average response to temperature or precipitation change). Orange dots, lines and shading are used for the no adaptation simulations, whereas blue is used for simulations that assume adaptation. The figure indicates that adaptation may be effective at offsetting yield losses across a variety of precipitation changes and temperature increases. However, note that each panel of the figure is of the average tendency of three types of crops across two regions considered together and there is a large scatter in results. The effectiveness of adaptation varies by crop type and region.

A recent meta-analysis published in the journal Nature Climate Change, by Challinor et al. (2014) examines 1,722 crop model simulations, run using global climate model output under several emissions scenarios, to evaluate the potential effects of climate change and adaptation on crop yield. The authors find that, without adaptation, projected corn, rice and wheat production is reduced when areas experience 2.0 °C or more of local warming, with losses greater in the second half of the century due to larger changes in climate. Crop-level adaptations are projected to be able to increase yields by an average of 7-15% when compared to similar scenarios that do not utilize adaptation. Projections indicate that adaptation may be more successful for wheat and rice than for corn. Though less data is available on yield variability, Challinor et al. find that it is likely to increase.

The world's cereal grain harvest is primarily made up of three crops: corn, rice and wheat, with corn being the largest harvest, at over 900 million metric tons produced annually (compare with around 700 million metric tons for rice and wheat, just over 100 metric tons for barley, the next largest grain, and just under 300 million metric tons for soy). While rice and wheat are mostly grown for direct human consumption, most corn is grown for livestock feed and it is also used for ethanol production. Grain production can be affected by a variety of factors including climate, competition for both land and water from other uses, demand, disease, pests, soil quality, weather and weeds. As the Earth's climate changes, it is expected that

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1. The best fit curves were determined using locally weighted polynomial regression. For more on locally weighted polynomial regression, see: Wand, M. P. and M. C. Jones, 1995: *Kernel Smoothing*, CRC Press, 232 pp.

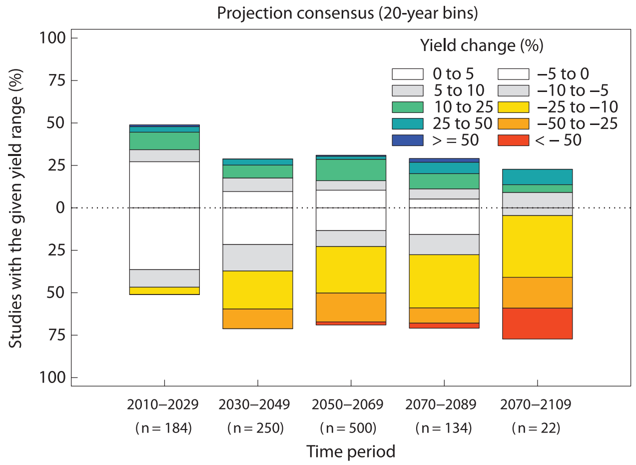

Figure 2: Projected changes in crop yield for all crops and regions, taken from Challinor et al. (2014).
The above figure shows the projected changes in crop yields for all crops and regions for the 21st century. The colours indicate the percent change in crop yield, and the horizontal axis is time, while the vertical axis shows the consensus among the studies, in terms of the total percent of studies that show each given change in yield. Each bar sums to 100% and the thickness of each coloured region within the bars shows the percent of studies that find a given change in crop yield.

there will be effects on crop productivity and there is some evidence that climate change has already affected corn and wheat production.

The authors of a recent paper in *Nature Climate Change* conducted a meta-analysis of 1,722 simulations of crop yield response to climate change from the peer-reviewed literature. These simulations come from crop models that vary in complexity from simple statistical models to process-based models that simulate some of the important biological and physical factors involved in crop growth. All of these models use the output from global climate models (in some cases this is downscaled first) that are run using assumptions about future greenhouse gas emissions (for the scenarios used, see Methods). The authors use the output from these models to understand how yields may be affected as the climate continues to change throughout the 21st century and what effect adaptation measures may have on crop production.

Challinor et al. work from the crop yield data set used in the IPCC's Fourth Assessment Report (AR4) and add to this studies that have been published since AR4, doubling the total number of studies used for the earlier assessment. The authors consider three questions: (1) what impacts would varying degrees of climate change be expected to have on the three main cereal crops, in temperate and tropical regions, (2) what effects might adaptation have, as a function of temperature and precipitation and (3) how is yield projected to change later this century. Challinor et al. distinguish between several adaptation strategies that involve making changes in planting date, fertilizer used, irrigation, plant breed or other aspects of crop management and the cultivation process.

The authors find that, without adaptation measures, all three crops in both temperate and tropical regions are projected to have reduced yields as temperatures increase. This is especially pronounced once local temperatures have increased by 2.0 °C or higher. However, adaptation methods are reasonably effective at increasing crop productivity across a wide range of temperature and precipitation changes (Figure 1). The projections indicate that with adaptation reduced yields for wheat and rice may be avoided. However, even with adaptation, declines in tropical wheat production are projected beyond 3.0 °C of local warming. The authors note that "there is little evidence for the potential to avoid yield loss" for corn. Also, the lack of studies that investigate projected corn yields in the tropics (particularly with adaptation) limit what can be inferred for corn in this region.

Challinor and colleagues find that, when the effect of increasing temperature is examined across all studies, the result is a statistically significant yield loss of 4.90% per degree of warming. They note that this is consistent with earlier research examining sensitivity to warming in historical crop yields. The authors also find statistically significant increases in yield of 0.53% for every percent increase in precipitation and 0.06% for every increased part per million of atmospheric carbon dioxide. Adaptation is also projected to have a statistically significant benefit overall, with yields 7.16% greater than scenarios in which adaptation is not implemented.

When all of the projections are analyzed over 20-year periods, most indicate reduced yields later in the 21st century and that yield reductions increase over time (Figure 2). Figure 2 includes both those simulations with agricultural adaptation and those with no adaptation. All of the simulations used are driven by one of six different IPCC SRES emissions scenarios[3]. Because both changes in mean yields over time and year-to-year yield variability determine whether demand for grain can be met, the authors examine the six available studies that investigate yield variability. They find that "increases in yield variability be-

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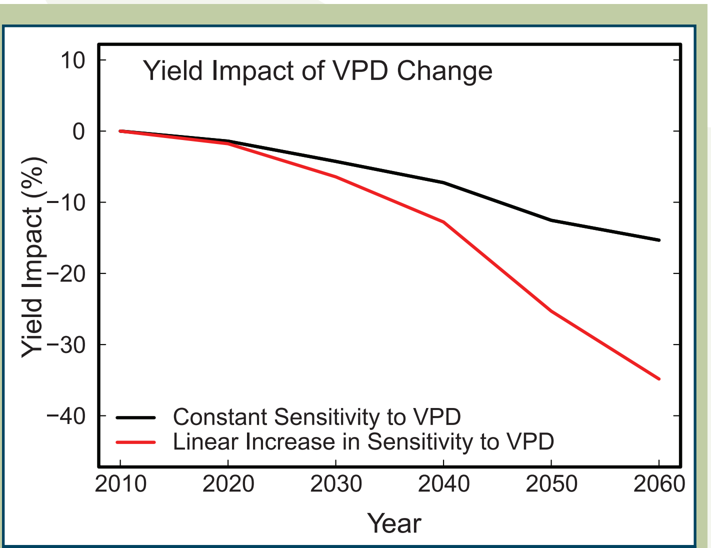
[2] Estimated confidence intervals were determined using a commonly used non-parametric inference method, known as the "bootstrap" technique. For more on the bootstrap technique, see: Efron, B. and R. J. Tibshirani, 1994: *An Introduction to the Bootstrap*, CRC, 456 pp.

IN DETAIL:

As mentioned, corn is the largest volume crop among the cereal grains. The United States produces about 40% of this harvest and one important question concerning continued productivity is the sensitivity of yields to drought stress. A recent study in *Science* by Lobell et al. (2014) examines this question using field-level data from the central US, covering the time period of 1995-2012 and simulations from the Agricultural Productions Systems Simulator (APSIM) model[6].

They find that, though corn yield has increased over the historical period, the sensitivity of the yields to drought stress has also increased. The authors also determine that the largest factor contributing to drought sensitivity are changes in vapour pressure deficit (VPD), a measure of the difference in humidity between the inside of the plants' leaves and the surrounding air. Terrestrial plants have evolved stomata, a pore of adjustable size formed of two cells, to expose photosynthetic cells in the plant's interior to carbon dioxide from the surrounding atmosphere, while allowing the escape of oxygen and minimizing water loss through transpiration. The transpiration rate increases with increasing VPD and this can contribute to plant water stress. Water stress, in turn can affect plant metabolism, growth patterns and photosynthesis.

It is important to note that VPD can increase even if the relative humidity of the surrounding air increases. The number of plants per acre has increased as a result of changing agricultural practices, which makes less water available to each plant and Lobell and colleagues note that simulations of higher density planting show greater sensitivity to VPD.



Estimated impact of mean vapour pressure deficit (VPD) projections on corn yield taken from Lobell et al. (2014). The figure above shows the estimated impact of changes in VPD on corn yields. VPD projections are derived from the output of 29 climate models. The black line indicates the impact assuming a constant sensitivity of -27% yield per kilopascal[7]and the red line indicates a linear increase in sensitivity that matches the historical rate (7% per kilopascal per decade).

The authors note that, if the sensitivity of yields remains constant at its current value, then corn yields may be reduced by 15% in 50 years as a result of this sensitivity to VPD. If sensitivity continues to increase at its current rate, then the impact to corn yields in 50 years may be as large as 30%. The projected impacts of VPD sensitivity on corn yields for the period of 2010 to 2060 are plotted above.

come increasingly likely as the century progresses."

The authors find that, among the adaptation methods they consider, adjusting the plant breed is the most effective in increasing crop yields and that irrigation also showed a benefit. However, the authors caution that the studies used are limited in that they do not simulate pests, weeds, diseases and changes to water availability in the future.

Methods

The authors work from an earlier database of 573 simulations of crop yield under changing climatic conditions from the 42 studies compiled for the IPCC's Fourth Assessment Report (AR4) and add 49 more studies, bringing the total number of simulations to 1,722. The simulations include crop yield changes under several IPCC emissions scenarios[3] (A1B, A1F1, A2, B1, B2 and IS92a).

The authors first gather their data set and implement a quality control procedure to remove data sets that are not representative of global production. They then examine and plotted yield data versus temperature from the simulations, dividing them up by crop type, region and whether or not adaptation methods are implemented in the simulation. For the plots, best fit curves are estimated using a local polynomial regression technique1 and confidence

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3. The Intergovernmental Panel on Climate Change published a set of emissions scenarios known as the Special Report on Emission Scenarios (SRES) in 2000, in order to provide input for evaluating the consequences of various trajectories of future greenhouse gas emissions. For more on the these emissions scenarios, see here: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=23
4. A linear regression model assumes a relationship between a dependent variable, such as crop yield, and one or more independent variables, such as temperature and precipitation. For more information on linear regression modeling, see: Rencher, A.C. and B. Schaalje, 2007: *Linear Models in Statistics, Second Edition*. John Wiley and Sons, 688 pp.

intervals are derived using a statistical bootstrap technique2. In addition to these, a linear regression model4 is fitted to the 882 entries that have information on yield, temperature, carbon dioxide and precipitation. The model includes variables for the presence of adaptation, region type (temperate or tropical) and crop metabolism5 (C3 or C4) as well as changes in temperature, carbon dioxide and precipitation. From this, the effects of warming, changes to precipitation, increased atmospheric carbon dioxide and adaptation were determined. The authors also examined several adaptation strategies (planting date, fertilizer, irrigation, plant type or other agronomic) individually, in order to determine the effectiveness of each. A second statistical model that fits both the main variables and the first-order interaction effects between them is also used. Challinor et al. also conduct a number of sensitivity analyses to ensure the robustness of their conclusions.

Challinor, A.J., J. Watson, D. B. Lobell, S. M. Howden, D. R. Smith, and N. ChhetriA, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4**, 287–291, doi:10.1038/nclimate2153.

Lobell, D.B., M.J. Roberts, W. Schlenker, N. Braun4, B.B. Little, R.M. Rejesus, G.L. Hammer, 2014: Greater sensitivity to drought accompanies maize yield increase in the U.S. midwest. *Science*, **344**, 6183, 516-519, doi: 10.1126/science.1251423.

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5. The terms C3 and C4 refer to two different types of plant metabolism. Due to their differing metabolisms, C3 plants do not do well in hot and dry conditions, whereas C4 plants tend to do better under such conditions.
6. The Agricultural Productions Systems Simulator (APSIM) is developed by the APSIM Initiative, a joint venture of the Commonwealth Scientific and Industrial Research Organisation, the University of Queensland and the State of Queensland's Department of Agriculture, Fisheries and Forestry. It is a modular modelling framework that simulates the biophysical and physical processes of crops and soil, as well as management characteristics for several different crop types. For more information on APSIM, see: http://www.apsim.info/AboutUs/APSIMModel.aspx.
7. Kilopascals are a unit of pressure. Water vapour in the air exerts a certain amount of pressure on its surroundings, as do the other gases that make up the atmosphere. The pressure exerted by the water vapour on its surroundings at a given temperature is used as a measure of the amount of water vapour in the air. Because the vapour pressure deficit (VPD) is the difference between the amount of water vapour inside the leaf and the amount of water vapour in the surrounding air, the VPD is measured in units of pressure, such as kilopascals. A kilopascal is equivalent to the pressure from an object of about 102 kilograms in mass, over a square metre, on the Earth's surface (for reference, the mass of an average adult human is between roughly 60 to 80 kg).