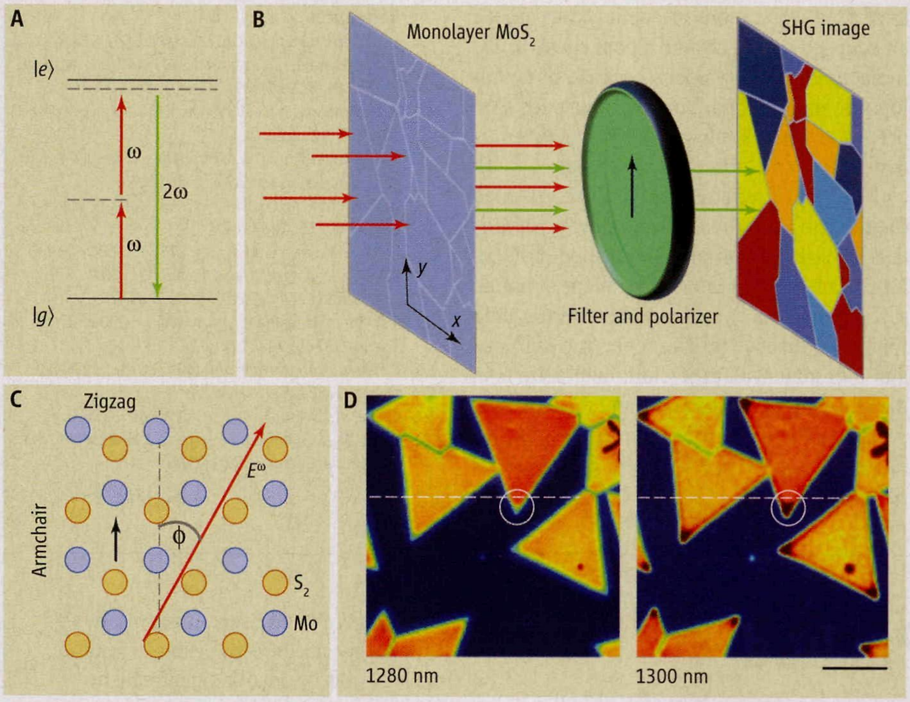

Edges do a frequency-doubled take. (**A**) In a second-harmonic generation (SHG) process, two photons of frequency ω (red arrows) absorbed by the ground state |*g*⟩ combine to form a high-frequency (2ω) photon (green arrow). The proximity of atomic states (or edge states |*e*⟩) to the energy 2ω of the output beam strongly enhances the generation of harmonics. (**B**) The SHG signal depends on the orientation of the MoS_2 flakes and the incident polarization of the excitation laser. The SHG image shows flakes of different brightness (encoded with different colors) for different crystal orientations. (**C**) Two-dimenstional crystal orientation and incident field polarization. (**D**) Yin *et al.* show that when the energy of the two pump photons is near the SHG frequency, the harmonic is strongly enhanced, as seen in the edge modes on the right circled in white; scale bar, 20 µm.

Although rough at the atomic scale, the edges of these monolayer islands are the more energetically favorable termination of MoS_2 zigzag edges, and they appear straight and sharp under the optical microscope. These zigzag edges have localized electronic states because they break translational symmetry. As Yin *et al.* show in proof-of-concept calculations, these edge modes have energies just below the band gap of an infinite MoS_2 monolayer. The localized electronic states enhanced in-plane nonlinear polarizability, and the resulting SHG enhancement allowed the direct optical imaging of the atomic edges.

Why were Yin *et al.* the first to optically observe such edge states? Other groups (*6–9*) used pump wavelengths of ~800 nm, but Yin *et al.* tuned their laser precisely at a two-photon resonance with the energy of the edge states, namely at ~1300 nm. They measured a well-pronounced maximum for the SHG from the edge states. Comparing the left and right images in panel D of the figure, even a detuning of 20 nm from the resonant input wavelength causes the signature of the edge states to completely disappear.

Edge states play an important role in electron dynamics for the quantum Hall effect and topological insulators, and the understanding of their physics is an important goal in realizing robust topological states in both solids and optics. Optical monitoring of the dynamics of such edge states could further clarify the mechanism of electrocatalytic hydrogen evolution (*11*). The direct mapping of edge states by optical methods developed by Yin *et al.* is an important step toward these goals. The nonlinear response reveals the structural and symmetry properties of 2D atomic monolayers, and it would allow the exploration of other types of 2D crystalline structures.

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BOTANY

Limits on Yields in the Corn Belt

Increasing vapor pressure deficit and drought sensitivity will limit future corn yields in the U.S. Midwest.

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In total global production, corn (maize, *Zea mays* L.) is the most important food and feed crop. Of the 967 million metric tons produced in 2013, 36.5% were produced in the United States, mostly in the Midwest Corn Belt. The United States is by far the world's largest corn exporter, accounting for 50% of corn exports globally (*1*, *2*). Until recently, breeding and management have allowed farmers to increase the number of plants per acre without loss of yield per plant. On page 516 of this issue, Lobell *et al.* (*3*) use a detailed data set for farms across the Corn Belt, to show that increasing yields have been accompanied by rising drought sensitivity, with important implications for future crop yields.

The data set contains yields, environmental variables, and management variables for Midwest corn fields in each year from 1995 to 2012. Lobell *et al.*'s analysis reveals that while corn yield has increased, drought sensitivity has also increased. This may be explained by the fact that with more plants per acre, less soil water is available to each plant. Yield was most sensitive to water vapor pressure deficit (VPD), a factor that has rarely been included in past analyses but that has major implications for yields as climate change progresses in the Corn Belt.

So what is the VPD, and why is it so important to crop production? To assimilate CO_2

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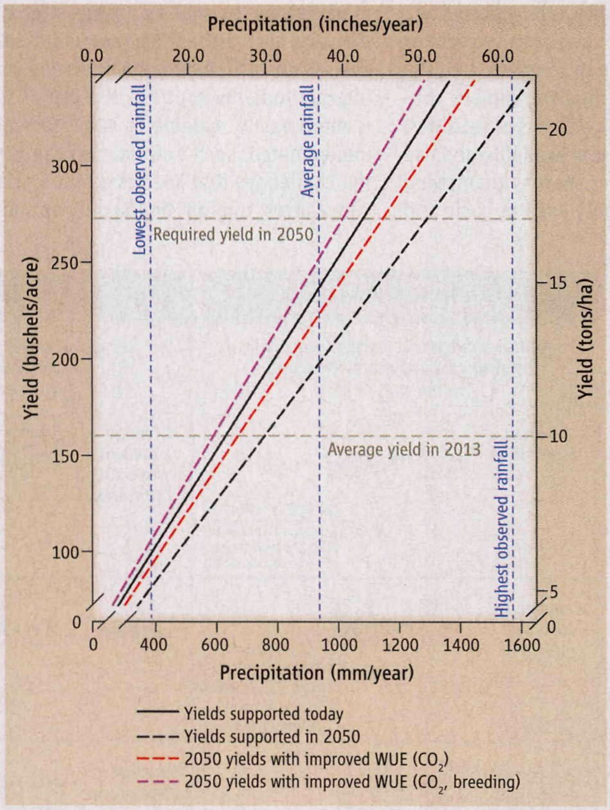
from the atmosphere, crop leaves must expose wet surfaces on the photosynthetic cells inside the leaf to the atmosphere. Pores (stomata) in the leaf surface open to allow CO_2 to diffuse to these wet surfaces; the same pores simultaneously allow water vapor to escape. This evaporation of water from the leaf, called transpiration, is an inescapable consequence of carbon assimilation by a crop. Through this process, 99% of the water absorbed by crop roots is lost to the atmosphere. The amount of carbon assimilated per unit of water lost is termed the water use efficiency of a crop (WUE). However, the rate of transpiration is proportional to the humidity gradient between the water vapor–saturated leaf interior and the drier bulk air; this gradient is the VPD. VPD can increase with rising temperature even if relative humidity (RH) rises. Although RH is most commonly reported, it is VPD and not RH that is directly proportional to water loss from crop leaves.

Lobell *et al*. show that VPD is expected to increase across their study area from 2.2 kPa today to 2.65 kPa by 2050. To understand the effect of this increase, consider that today, average precipitation across the study area is 37 inches (940 mm) per year. If we assume that 70% of this water is available to the crop, with the remaining 30% lost in drainage and runoff, then a VPD of 2.2 kPa would support a yield of 214 bushels per acre (see table S1). This is more than enough water to support the 2013 average yield of ~170 bushels per acre but would limit yield in areas receiving less than 25 inches of precipitation. If VPD rises to 2.65 kPa, an average rainfall of 37 inches would only support 192 bushels per acre (see the figure), making production far more vulnerable even to moderate droughts. However, if improved genetics and agronomy can achieve the 70% yield increase to 272 bushels per acre projected to be needed by 2050 (*4*, *5*), this would require 50 inches of precipitation per year (see the figure). Today, production across the study region is largely rainfed, but meeting these targets would require irrigation. Such a productivity increase is unlikely to be sustainable with respect to water resources. Are there any prospects that this demand could be mitigated?

A direct effect of rising atmospheric CO_2 concentrations is to increase WUE at the leaf level. This is because at higher atmospheric CO_2 concentrations, leaves can gain the CO_2 needed for photosynthesis with their stomata less open. Thus, less water is lost per CO_2 molecule assimilated. However, few studies have attempted to quantify this assumed benefit in a farm field. A study with soybean found that elevation of CO_2 to the anticipated 2050 level increased WUE by 12.5% on average across 4 years (*6*). A similar increase in WUE for corn would lower 2050 water demand to 44 inches, still well above current average regional precipitation.

An opportunity to further increase WUE was shown by a recent computational analysis that considered where within the crop canopy photosynthesis occurs (*7*). Normally, most photosynthesis occurs near the top of the canopy, where the humidity is closest to that of the bulk atmosphere and WUE is lowest. By making leaves more vertical or leaves at the top of the canopy less pigmented, light and thus photosynthesis could be distributed to deeper layers. This approach could increase WUE because humidity increases with depth into a crop canopy, allowing photosynthesis to occur at a lower VPD. A canopy bred to take full advantage of this principle could increase WUE by 13%, further lowering the 2050 water demand to 40 inches, but would still have substantial drought vulnerability.

These projections assume that the effect of VPD is mainly through photosynthetic productivity, as indicated by Lobell *et al.*'s study. However, the study raises a potentially grave concern beyond 2050, when yields are projected to decline at an accelerating rate with increasing VPD, perhaps because of other VPD-sensitive factors such as pollination. Beyond a VPD of about 2.8 kPa, yield decline with VPD becomes much sharper, with possible average yield losses of 40% as early as 2060. Thus, although rising CO_2 and crop redesign could provide some mitigation, the only real solution will be to avoid the CO_2 emissions that will otherwise cause rises in temperature (*8*) and, in turn, VPD.



Balancing corn yield and water needs. Across the three major Corn Belt states covered by Lobell *et al.*'s study, a given amount of precipitation will support average corn yields given by the black line. Lower yields would be supported under the higher VPD conditions projected for 2050 (dashed black line). If the anticipated rise in atmospheric CO_2 concentrations over this period leads to improved water use efficiency, this would raise yields somewhat (dashed red line). Breeding to optimize crop water use efficiency could lead to further improvements (dashed purple line). The central vertical blue line represents the mean rainfall for this area (calculated over a 36 year period to 2010), the left-hand vertical line the lowest annual rainfall during this period, and the right-hand vertical line the highest. The lower horizontal line gives the mean yield for 2013, and the upper horizontal line the yield projected to be needed to meet the growth in global demand for corn by 2050. Even in the most optimistic case, on average, there will only be sufficient rain to support about half of the increase in yield needed by 2050.

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Supplementary Materials

www.sciencemag.org/content/344/6183/484/suppl/DC1
Table S1

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