NATURE | OUTLOOK

Modelling: Predictive yield

Neil Savage

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Farmers would benefit from better long-range weather forecasts. What else can science provide to help them decide what to plant?

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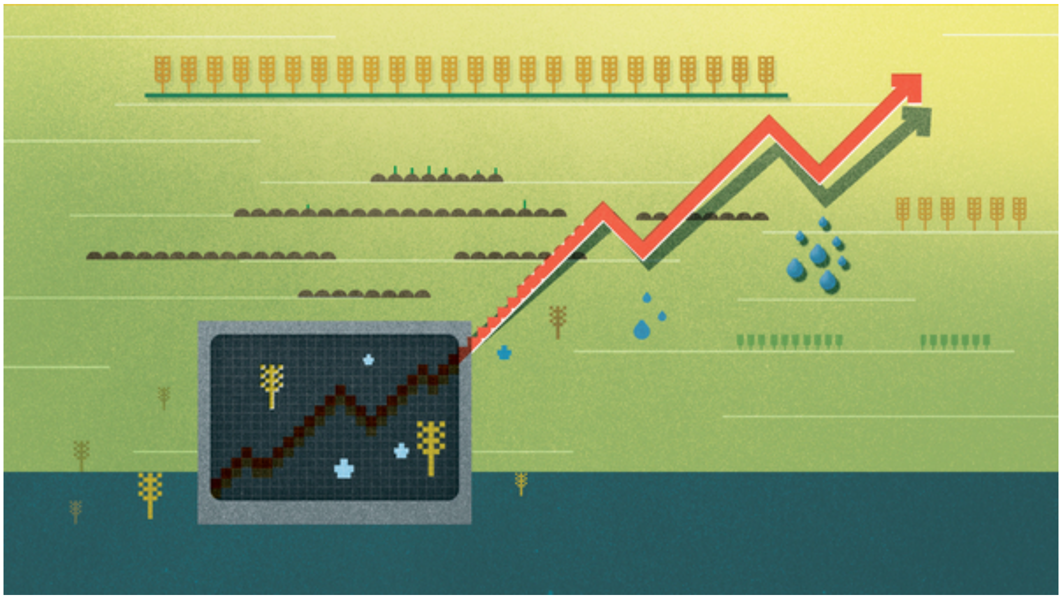
No one saw the drought coming. “Everyone thought it was going to be a record year,” says Joshua Elliott, a computational scientist at the University of Chicago. In the United States, the winter of 2011–12 was warm and dry, followed by a mild spring that allowed farmers to start planting earlier. “People didn't start talking about drought until well into June,” he says. By July, maize stalks were only half as tall as they should have been and their leaves were wilting. “That's when people realized it was going to be a really severe drought.” It turned out to be a record year all right, but for a different reason.



GAVIN POTENZA

According to the US Department of Agriculture (USDA), maize harvests in 2012 were down by 13% from the year before; hay was down 9%; alfalfa was down 20%; and millet production fell by a whopping 66%. The total yield of US crops dropped by about 22%, according to Elliott, who models the effect of drought on crops for NASA's Goddard Institute for Space Studies in New York. And because the country is a major supplier of the world's food, the shortage drove up prices across the globe.

If farmers could have advance warning of what the next year, or even the next planting season, will be like, they could prepare for it by planting different strains or altering irrigation plans, for example. “They may shift their ratio of, say, soybeans to corn [maize], or early planting to late planting,” says James W. Jones, an agricultural engineer at the University of Florida and director of the Florida Climate Institute in Gainesville. It is possible to model crop growth to predict yields, but these models need to be fed accurate forecasts of when and where drought will strike for truly powerful prediction.

Looking for clues

Climate drivers such as the El Niño Southern Oscillation (ENSO) offer some predictive power. During an El Niño, which might last 6–18 months, average surface temperatures in the Pacific Ocean off the coast of South America are higher than normal. The warmer water affects the temperature and moisture content of the air above it, altering rainfall patterns on land. In the southwestern United States, where the 2012 drought hit hardest, El Niño reduces average rainfall. Other parts of the world get wetter. During La Niña, which is the counterpoint to El Niño and occurs when sea surface temperatures in the same area are below normal, the effects on rainfall are reversed.

By monitoring sea surface temperatures, scientists can anticipate the course of an El Niño. But that knowledge helps forecast drought only in certain areas and at certain times; farther away, for example in Europe, the effect of ENSO is too small to be useful. Even in the southwestern United States, the ability to predict anything useful beyond the 5 to 10 days of a weather forecast is pretty much limited to the winter, says Richard Seager, a climate modeller at Columbia University's Lamont-Doherty Earth Observatory in New York, as other factors become more important in summer. “What we really want to predict are those severe droughts that depend on a lot of weather variability,” Seager says.

Another climate driver, the Pacific Decadal Oscillation, occurs more slowly, with water temperatures fluctuating over a period of 20 years. The latest warm phase began in 1998, Seager says, allowing forecasters to say that conditions are likely to be drier for the next five years, but they cannot be more specific than that. “That's pretty much arm-waving,” says Seager.

The problem is that scientists don't really understand the mechanisms underlying ENSO or any of the other long-term natural variations that affect the world's weather patterns. “We can do some sort of statistical extrapolation based on past oscillations, but that's not a perfect method,” says Aiguo Dai, an atmospheric scientist at the State University of New York, Albany. Mechanistic models that simulate the physical processes leading to drought might be better, but only if the mechanisms can be precisely described. “We don't know if the models capture all the physics,” Dai says.

Efforts are underway to do better. The US National Oceanic and Atmospheric Administration (NOAA) is part-way through its three-year Modeling, Analysis, Predictions and Projections (MAPP) programme, which aims to increase scientific understanding of natural climate variation and its relationship to drought. Annarita Mariotti, a climate scientist at NOAA who is acting director of the MAPP programme, says the team still needs to work out which processes can be forecast. “There is a lot of research trying to dissect what is predictable from what is not predictable.”

The scientists need to understand processes such as how air temperature and precipitation interact with soil moisture — for instance, whether a dry spring makes a summer drought more likely — and how snow and vegetation cover affect atmospheric conditions. Getting such interactions right should lead to better outcomes. “Predictability is really in the chain of processes,” Mariotti says. “Each element, and the coupling of these elements, is important.”

Modelling crop growth

Every day, NOAA's models produce forecasts for up to 9 months. Accuracy over the

> **“Basically it's just a huge**

longest time frames is poor, however, and the lack of regional detail renders them worthless for farmers. Elliott says that running these models 100 times as often might produce more useful results, but that's hard to do with the existing computing resources. “Basically it's just a huge computation and data challenge at this point,” he says.

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Even with an accurate forecast, there is another part of the equation: predicting how crops will respond to drought. This depends on when in the growing season the drought occurs, how severe it is, and where in the world it is happening. Agricultural scientists have plenty of models — tailored to specific crops — that can simulate how plants react to variations in temperature, rainfall or about 40 other parameters that describe the characteristics of soil (see 'Soil science comes to life', page S18). These models work well, says Elliott, but they need better weather predictions to feed in.

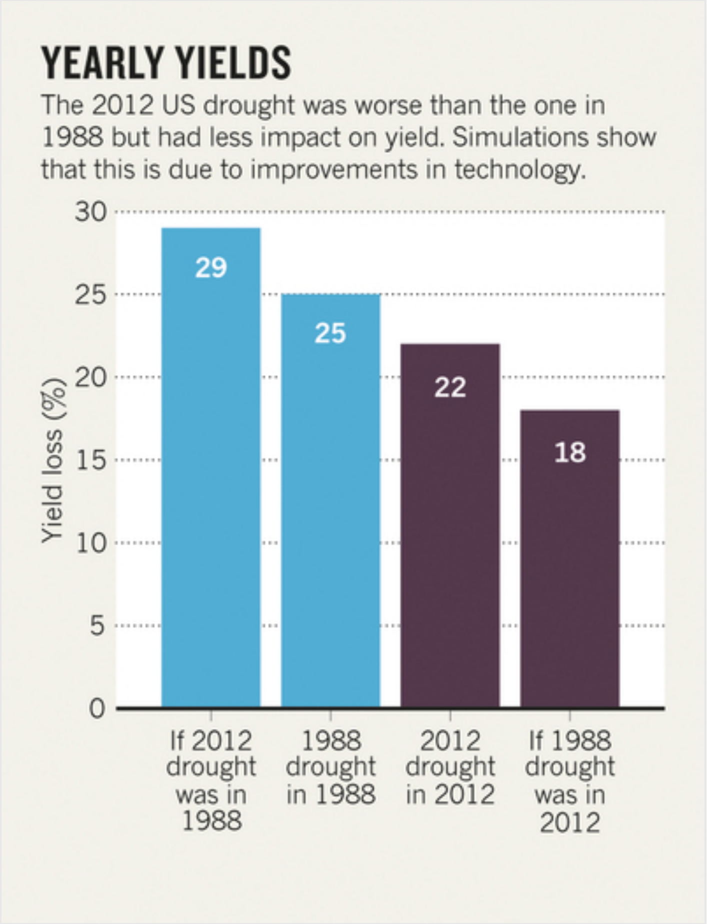
The crop models do have some limitations, however, often due to a dearth of measurements or the lack of a good description of a physical process, says Jones. Current models go wrong if there is an excess of water, for instance, owing to a lack of drainage data. And although they simulate nitrogen uptake very well, they are less proficient at describing the effects of other nutrients, such as phosphorus and potassium. This shortcoming is trivial in US agriculture, where there is plenty of both. But the models are less useful in Africa and Asia, where the soil is often poor in such nutrients, Jones says.

Jones is involved in the Agricultural Model Intercomparison and Improvement Project (AgMIP), which combines models based on different parameters and methods. The idea is that any systematic errors in a given model will be compensated for by others. In a recent paper in *Nature Climate Change*, the team combined 27 different wheat models and measured how well they dealt with rising temperature and carbon dioxide level, and calculated how many different models would have to run together to cancel out the errors. For temperature rises of 3 °C and carbon dioxide increases of 540 parts per million, the team found that it would take at least five different wheat models, averaged out, to come up with a reliable prediction[1]. The MAPP project is doing much the same with climate projection models. Such comparisons help scientists understand where the uncertainties lie in their models, Jones says.

Testing strategies

Models have another purpose as well as prediction: they allow scientists to study crop management practices. “I'm interested in the US corn [maize] industry as an important use case for production systems in the rest of the world,” says Elliott. “What can it teach us about how to make Africa less drought sensitive?” For instance, the models could simulate possible outcomes if African farmers were to adopt US practices, such as tilling agricultural waste back into the soil to increase its ability to retain moisture.

US crop management has changed considerably in the 25 years since the previous severe drought. Planting now takes place on average about 30 days earlier than it did in the 1970s, mostly because improvements in tractor technology allow more rows to be planted at once. And knowing how to angle the leaves to get the right amount of sun lets farmers plant fields about 50% more densely.



Elliott used the models to compare agricultural practices during the two droughts (see 'Yearly yields'). The loss of yield in 1988 was about 25%, slightly worse than the 22% loss in 2012, even though the 2012 drought was more severe. But when he ran the simulations with the drought conditions swapped, the results were remarkable. Simulating the 1988 drought with 2012 technology produced a loss of only 18%, but if farmers had used 1988 technology during the 2012 drought, the losses would have exceeded 29%.

Modelling can also help farmers cope with climate change by making suggestions based on expected future conditions. This is more challenging, says Jones, because of a lack of real-world data to feed into the models. For instance, increased atmospheric carbon dioxide should benefit plant growth, but field experiments — where extra carbon dioxide is piped around certain plants — are limited. Scientists also need to consider how such increased growth correlates with higher air temperature, which will also stimulate evaporation and reduce moisture.

As more environmental data are collected, physical processes become better understood, computer power grows, and the models are refined, scientists' ability to project droughts — and to suggest how farmers can deal with them — should improve. But there will be an upper boundary. “We should accept that there's some level of activity that is always going to be unpredictable,” Seager says. “There seems to be some fundamental limit to predictability. We may not have reached that limit, but it's there.”

References

1. Asseng, S. *et al*. *Nature Clim. Change* **3**, 827–832 (2013).