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Swarms of grasshoppers and locusts have troubled scientists for hundreds of years, and the problem may be about to get even worse.

CROP PESTS

Under attack

The threat of insects to agriculture is set to increase as the planet warms. What action can we take to safeguard our crops?

BY AMY MAXMEN

John Stulp shakes his head as he surveys the fields of his farm in Lamar, Colorado, which have been ravaged by the worst drought the United States has seen for over 80 years. He says he'll be lucky to harvest a third of the 2,000 hectares of wheat he planted last year, and he has either sold or killed all but 3 of his 200 cattle because the grass they feed on never greened. "I've been through dry weather," Stulp says, "but nothing this severe."

This year's wheat crop was planted in mid-2012, but by spring 2013, Stulp's water-stressed plants were spindly and covered with brown wheat mites. These tiny arachnids use their syringe-like mouthparts to suck the sap from the stems and leaves, leaving gaping wounds through which more fluids evaporate. "I don't know if it was the heat, water loss or mites that killed the wheat," he says, "but the crop could not survive the combined stress."

Dry fields infested with pests are the stuff of nightmares for farmers, but they also trouble the minds of scientists. In 1665, the first issue of one of the world's oldest scientific journals, *Philosophical Transactions of the Royal Society*, contained a report on swarms of locusts devouring fields of corn. The anonymous author wrote that once the swarm's eggs hatch, they "produce again such a number of locusts that then they do far more mischief than afore, unless rains do fall, which kill both eggs and the insects themselves."

Despite centuries of enquiry, the science behind drought-driven infestations lacks both breadth and hard numbers. This information is increasingly important because climate models predict that by the end of this century, the hottest seasons on record today will be the norm in many areas[1] and droughts may be routine. Farmers urgently need to know whether dry, insect-ridden crops reflect unusual situations or expected outcomes.

What's more, in order to feed the projected 9 billion people who will inhabit the Earth by 2050, farmers must increase their cereal yields by at least 40%. An average of 15% of crops worldwide are currently lost to insects, so controlling pests is crucial to achieving that goal. "When we think about what the major impediments are to increasing crop yield, I don't think we spend enough time considering pests," says Joshua Tewksbury, director of the WWF's Luc Hoffmann Institute in Gland, Switzerland. We need to know which insects

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ICARDA

ICARDA entomologist Mustapha El-Bouhssini looks for pests on wheat crops in Morocco.

will be the most damaging under drought conditions, and where droughts will occur more often.

PEST PERFORMANCE

Droughts tend to be hot and insects generally thrive in warmer weather. As the temperature rises they eat more, mate more and produce more young. Freezing winter temperatures can kill insect eggs laid the previous autumn, and can act as a latitudinal barrier to geographical spread.

Although anecdotes such as Stulp's are powerful, they mask the nuances present in every agricultural ecosystem, including the biology of different herbivorous insects, the natural resilience of certain crops, and the community of predators and pathogens that kill crop pests. There may be several reasons why the brown wheat mites on Stulp's farm flourished, for example. Maybe the warm winter allowed more mite eggs to hatch. Maybe the dried-out plants left the wheat more vulnerable than usual to predation. Or perhaps one of the mite's predators had not survived the drought, leaving its prey free to roam. By figuring out which factors contribute most to a crop's demise, agroecologists hope to identify strategies to mitigate pest damage.

"Our goal is to inform farmers so they can make decisions based on what is right for them."

Droughts also make plants more nutritious to pests, as the lack of water concentrates the amino acids. Studies dating back to the 1970s suggest that some herbivorous insects specifically target water-stressed plants. The mountain pine beetle, for example, killed about 750,000 hectares of trees in 2010–11 in the western United States in an infestation thought to be fuelled in part by droughts[2]. Pines normally produce a sticky resin, which suffocates beetles that burrow beneath the bark, but water-stressed trees are unable to secrete enough sap. Beetles finding such trees emit chemical signals called pheromones that attract other beetles. The resulting mass predation weakens the tree further and the beetle population multiplies.

However, the relationship between insect populations and drought is not consistent. "Sometimes there are more insects and sometimes less," says Claudio Gratton, an entomologist at the University of Wisconsin-Madison. One explanation for this variation, Gratton says, is that although insects can respond positively to dry conditions for a while, eventually they suffer as the plants they feed on deteriorate. For example, aphids can flourish during short droughts as plant nutrients become more concentrated, but these benefits cease during prolonged droughts because of a drop in fluid pressure within the phloem of water-stressed plants[3].

Predators of pests are also affected by drought. Some, such as fungi, require humidity to survive and so are less effective during droughts, whereas others fare better in dry conditions. Sanford Eigenbrode, an entomologist at the University of Idaho in Moscow, is studying parasitic wasps that attack the cereal leaf beetle, a pest of wheat throughout the northwestern United States. The wasp lays its eggs in the beetle's pupa, a life-cycle stage between the larva and the adult. The wasp larvae that hatch from these eggs eat the pupa's non-vital tissues and finally kill it while emerging from its body. Beetle pupae normally cover themselves in feces, and Eigenbrode suspects that this faecal shield acts as a barrier to keep the wasp at bay. But producing faeces requires water, and Eigenbrode thinks that in extremely dry conditions, beetle larvae are unable to deploy their shields quickly enough to prevent predation. The US Department of Agriculture has funded Eigenbrode's project to test this hypothesis — part of a US$20 million grant to address the effects of climate change on US wheat production.

A GROWING THREAT

Farmers in the tropics lose up to 50% of their crops to pests — including insects and plant pathogens — compared with just 25–30% in Europe and the United States[4]. Part of the problem is that pests are a year-round problem in the tropics, and farmers are often poorer and rarely have access to safe and effective pesticides, robust varieties of plants and adequate irrigation.

Recent droughts in tropical areas are causing concern that an already dire situation could worsen. In 2011 and 2012, the Horn of Africa experienced its worst drought for 60 years. Crop failures contributed to the deaths of nearly 260,000 Somalis, and millions of people across the region were malnourished.

Climatologists expect droughts to become more frequent in other arid regions too. The International Panel on Climate Change predicts that over the next 90 years, rainfall in some parts of North Africa and western Asia will decline by 30% and the average temperature will increase by 4 °C.

The effects of climate change are already being seen. Mustapha El-Bouhssini, an entomologist at the International Center for Agricultural Research in the Dry Areas (ICARDA), says that some pests once found at low levels have recently become more frequent and have extended their ranges. In the unusually hot and dry year of 2010, for example, a previously rare pest, the barley stem gall midge, besieged Syrian farms. "Ten thousand farmers abandoned their fields because of these pests," says El-Bouhssini. The cereal leaf miner, which was once restricted to Syria, can now be found throughout neighbouring Jordan and Iraq, he says. And the hessian fly, a pest of wheat, has crossed the Mediterranean from North Africa into Spain, Portugal and southern France. "In my opinion," El-Bouhssini says, "these migrations are the effects of climate change."

Jürgen Kroschel, an agroecologist at the International Potato Center in Lima, Peru, says that outbreaks of potato tuber moth are more severe in years that are hotter and drier than usual. There is less rain to wash the moths off the leaves and stems of the potato plant, and the dry conditions mean the larvae can crawl down through cracks in the soil to

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burrow into the tuber. Potatoes grown in the Peruvian mountains, about 3,800 metres above sea level, have escaped these outbreaks because of the cold evening temperatures. But as the planet warms, the moth may move to higher elevations. Kroschel's team predicts that over the next 40 years, a further 90,000 hectares of potato crops will be at risk of infestation as the moth spreads to mountainous regions in Bolivia, Ecuador and Peru[5].

As global temperatures rise, pests that are now confined to the tropics may spread to cooler parts of the world. Farms at mid-latitudes may face a doubling of crop loss due to pests by the end of this century, according to a preliminary model developed by Tewksbury, David Battisti, an atmospheric scientist at the University of Washington in Seattle, and Curtis Deutsch, an atmospheric scientist at the University of California, Los Angeles. The model projects global pest damage to wheat, maize and rice, and is based on the relationship between insect population growth and temperature, and incorporates projections about climate change over the century. If the predictions are accurate, solutions are desperately needed for agriculture in temperate zones. "Today, insect pests reduce the yield of maize in the United States by about 8% annually, which amounts to about US$800 million," says Battisti. "A doubling of pest damage would roughly double that amount."

Battisti says that models will be refined as more data become available. For example, the current model (which has not yet been peer-reviewed) does not consider how insect predators, such as parasitic wasps, will limit pest populations. "When I think about the response of pests to climate change," he says, "the detailed ecology is so complicated it will require a lot of work to understand it."

An adult cereal leaf beetle and a larva deploying its faecal shield (top). A turnip cutworm (*Agrotis segetum*) in a potato tuber (bottom).

AFFORDABLE FIXES

Once the models incorporate enough information to make detailed predictions, scientists can recommend strategies to control insects that are specific to each farmer's particular crop, region and finances. For example, subsistence farmers in Africa may not be able to afford genetically modified plant varieties that are resistant to pests, or highly specific pesticides that reliably kill crop-eating insects while leaving the rest of the ecosystem intact.

The Food and Agriculture Organization of the United Nations (FAO) is aware of these limitations to farmers' abilities to respond. In some cases, says Mark Davis, an agroecologist at the FAO, providing access to technology might be the best plan to combat crop loss. In other cases, farmers will benefit more from education on sustainable agricultural practices, such as intercropping (introducing plants among the main crop that are either more attractive to pests to act as bait, or that are unpleasant enough to pests to repel them). "Our goal is to inform farmers about their options so they can make decisions based on what is right for them," Davis says.

An arsenal of tools and techniques to protect crops from droughts and ravenous insects is now being assembled. Plant varieties that are selectively bred or genetically engineered to resist insect pests or withstand water stress will be one line of defence (see 'Discovery in a dry spell', page S7). This year, the agriculture company Monsanto, based in St Louis, Missouri, sold the first genetically modified drought-tolerant plant, a variety of maize, to farmers across the western United States. The idea is that these more robust plants will be able to withstand pest attack even under drought conditions. Ideally, these varieties would be combined with other means of defeating insects, such as pesticides and biological controls — for example, deploying ladybirds to eat sap-sucking aphids. "There's a misconception that people will just rely on biotechnology, and that's not the case," says Troy Coziahr, an agroecologist at Monsanto. "We cannot rely on one or two tools to make land more productive. It's a huge undertaking."

Other strategies involve changing traditional practices. For example, Scott Merrill, an agroecologist at the University of Vermont in Burlington, encourages farmers to change the way they monitor pests. Typically, he says, US farmers check for insects on a specific day of the year and decide whether to use pesticides. A smarter approach, Merrill says, is to use a 'degree day' model and check their fields when the temperature reaches a predetermined level. That way, farmers will be prepared for the early hatching of insects that generally follows a spell of higher-than-normal temperatures.

If such strategies fail to reach farms, crop loss will not be the only dire consequence. Another danger is that farmers may become so desperate to defeat crop-eating bugs that they increase their use of chemical pesticides. Pesticide companies predict that markets in countries with emerging economies, such as India and China, will grow rapidly as farmers are able to spend more money spraying their crops. The pesticide market in India, China and Japan was worth US$11.7 billion in 2011 and is expected to reach $16.2 billion by 2016. Many of the pesticides used today in the United States and Europe — so-called third-generation compounds — are much less poisonous than the ones used 50 years ago. But most farmers in the developing world can't afford the expensive new pesticides and are more likely to turn to older, more toxic versions that are still quite dangerous to health and the environment. If regulations regarding the use of these harsh chemicals are not enforced, their use will escalate, putting the environment and human and animal health at risk.

We are faced with a hungry planet and rising temperatures, and pests will be an increasingly important part of the story. Once the scientific details are understood we can adopt policies that will enhance sustainable agriculture and hopefully mitigate problems in the long run. But in the garden of possibilities, the one certainty is that there is no time to waste. As El-Bouhssini warns: "Climate change is with us." ■

Amy Maxmen *is a freelance science writer based in New York City.*

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