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A young boy herds his goats in the Ghat District of Libya, which has been converted largely to desert in the last 100 years. TAHA JAWASHI/AFP/GETTY IMAGES

Redrawing the Map: How the World's Climate Zones Are Shifting

Rising global temperatures are altering climatic zones around the planet, with consequences for food and water security, local economies, and public health. Here's a stark look at some of the distinct features that are already on the move.

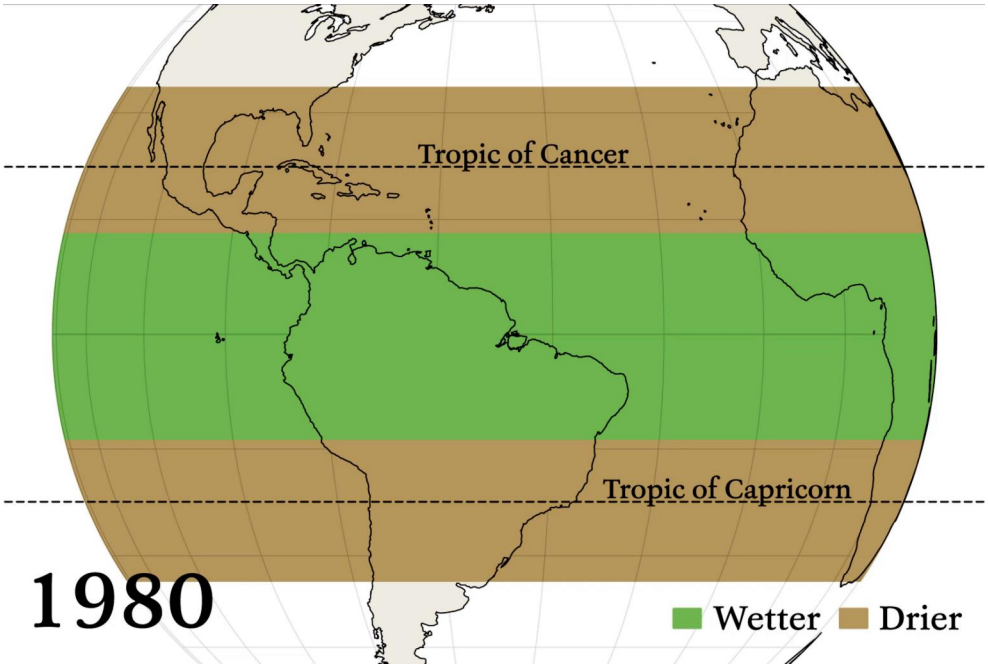
BY NICOLA JONES • OCTOBER 23, 2018

As human-caused emissions change the planet's atmosphere, and people reshape the landscape, things are changing fast. The receding line of Arctic ice has made headlines for years, as the white patch at the top of our planet shrinks dramatically. The ocean is rising, gobbling up coastlines. Plants, animals, and diseases are on the move as their patches of suitable climate move too.

Sometimes, the lines on the map can literally be redrawn: the line of where wheat will grow, or where tornadoes tend to form, where deserts end, where the frozen ground thaws, and even where the boundaries of the tropics lie.

Here we summarize some of the littler-known features that have shifted in the face of climate change and pulled the map out from under the people living on the edges. Everything about global warming is changing how people grow their food, access their drinking water, and live in places that are increasingly being flooded, dried out, or blasted with heat waves. Seeing these changes literally drawn on a map helps to hammer these impacts home.

THE TROPICS ARE GETTING BIGGER AT 30 MILES PER DECADE



The tropics are expanding by half a degree per decade. SOURCE: STATEN ET AL., NATURE CLIMATE CHANGE, 2018. GRAPHIC BY KATIE PEEK.

On an atlas, the boundary of the tropics is marked out by the Tropic of Cancer and the Tropic of Capricorn, at about 23 degrees north and south. These lines are determined by where the sun lies directly overhead on the December and June solstices. But from a climate perspective, most scientists draw the edges of the tropics instead at the nearby boundary of the Hadley cell – a large-scale circulation pattern where hot air rises at the equator, and falls back to earth, cooler and drier, somewhere around 30 degrees latitude north (the top of the Sahara desert and Mexico) and 30 degrees south (the bottom of the Kalahari Desert).

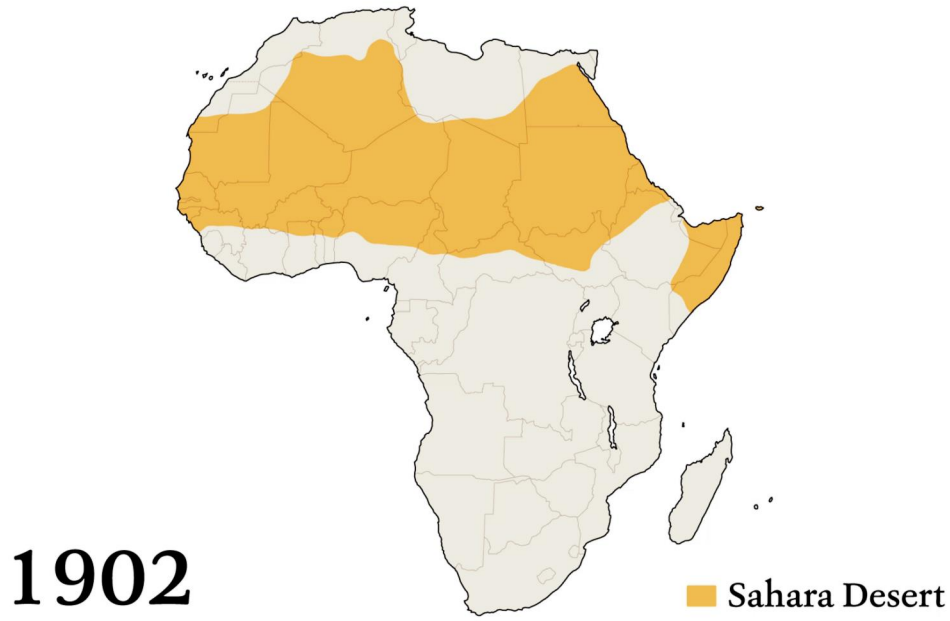
The word "tropical" often brings to mind rainforests, colorful birds, and lush, dripping foliage, but the vast majority of our planet's middle region is actually quite dry. "The ratio is something like 100 to 1," says Jian Lu, a climate scientist at the Pacific Northwest National Laboratory in Richland, Washington. About a decade ago, scientists first noticed that this dry belt seemed to be getting bigger. The dry edges of the tropics are expanding as the subtropics push both north and south, bringing ever-drier weather to places including the Mediterranean. Meanwhile, the smaller

equatorial region with heavy rains is actually contracting, Lu says: "People call it the tropic squeeze."

In a paper published in August, Lu and colleagues tracked how and why the Hadley cell is expanding. They found that since satellite records started in the late 1970s, the edges of the tropics have been moving at about 0.2-0.3 degrees of latitude per decade (in both the north and the south) .The change is already dramatic in some areas, Lu says – the average over 30 years is about a degree of latitude, or approximately 70 miles, but in some spots the dry expansion is larger. The result is that the boundary between where it's getting wetter and where it's getting drier is pushing farther north, making even countries as far north as Germany and Britain drier. Meanwhile, already dry Mediterranean countries are really feeling the change: In 2016, for example, the eastern Mediterranean region had its worst drought in 900 years. The last time the tropics expanded northward (from 1568 to 1634, due to natural climate fluctuations), droughts helped to trigger the collapse of the Ottoman Empire.

There are several reasons for the shift in the Hadley cell, Lu's team reports, including the ozone hole in the Southern Hemisphere and warming black soot in air pollution from Asia, along with rising air temperatures from greenhouse gases. Changes in sea surface temperatures, Lu says, seems to be causing at least half of the shift. That means predicting future tropical expansion is difficult, says Lu. "We can't put a number on it, but we have a rough idea it will keep increasing."

THE SAHARA DESERT HAS GOTTEN 10 PERCENT BIGGER SINCE 1920



Since 1902, the Sahara Desert has grown 10 percent, advancing as much as 500 miles northward over the winter months in some spots. SOURCE: THOMAS & NIGAM, JOURNAL OF CLIMATE, 2018. GRAPHIC BY KATIE PEEK.

The world's largest warm-weather desert is getting bigger. The Sahara already covers a vast 3.6 million square miles – an area nearly as large as the United States. The desert's edges are defined by rainfall; the line is usually drawn where the ground sees just 4 inches per year. When Natalie Thomas and Sumant Nigam, ocean and atmospheric scientists at the University of Maryland, looked at records stretching from 2013 back to 1920, they found that these boundaries for the Sahara had crept both northward and southward, making the entire region about 10 percent larger.

The change, which is expected to reduce some countries' ability to grow food, hardly seems fair. "Morally, how do we deal with the fact that developing countries are paying the price?" says Thomas. One study in the 1990s showed that the limit of where plants could grow in the dry southern edge of the Sahara had moved nearly 81 miles south in the 10 years between 1980 and 1990.

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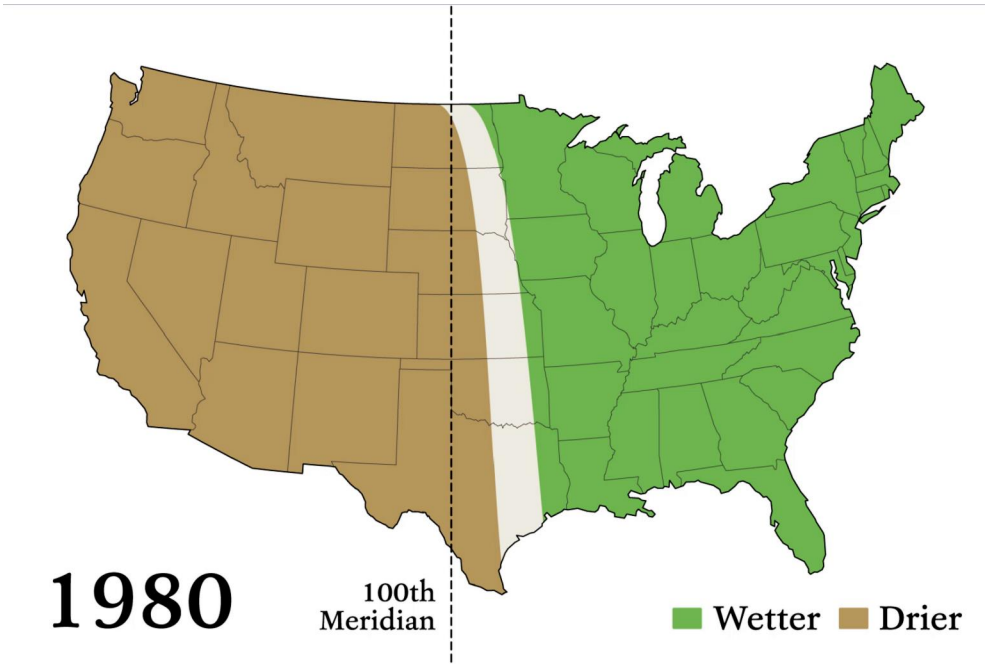
Across most of the Sahara the change is on the order of tens of miles over the study period, but in other spots it's far more dramatic: Libya has gone from being mostly not desert in 1920, to mostly desert in 2013, as the line there has advanced a shocking 500 miles or so in winter months. Lake Chad, which sits on the southern edge of the Sahara, shrank dramatically from 9,600 square miles in the 1970s to less than 770 square miles in the 1990s, in part due to reduced rainfall in the Sahel, the dry region just to the south of the Sahara.

Nigam and his colleague calculate that about two-thirds of the change might be accounted for by natural climate cycles, such as the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation, which help to determine rainfall. But the remaining third, they reckon, is down to climate change – the northern edge of the

desert, for example, seems to be moving because of the climate-driven poleward creep of the tropics.

THE 100TH MERIDIAN HAS SHIFTED 140 MILES EAST



The arid Western plains of North America meet the wetter, eastern region near the 100th Meridian. This climatic boundary has shifted about 140 miles east since 1980. SOURCE: SEAGER ET AL., EARTH INTERACTIONS, 2018. GRAPHIC BY KATIE PEEK.

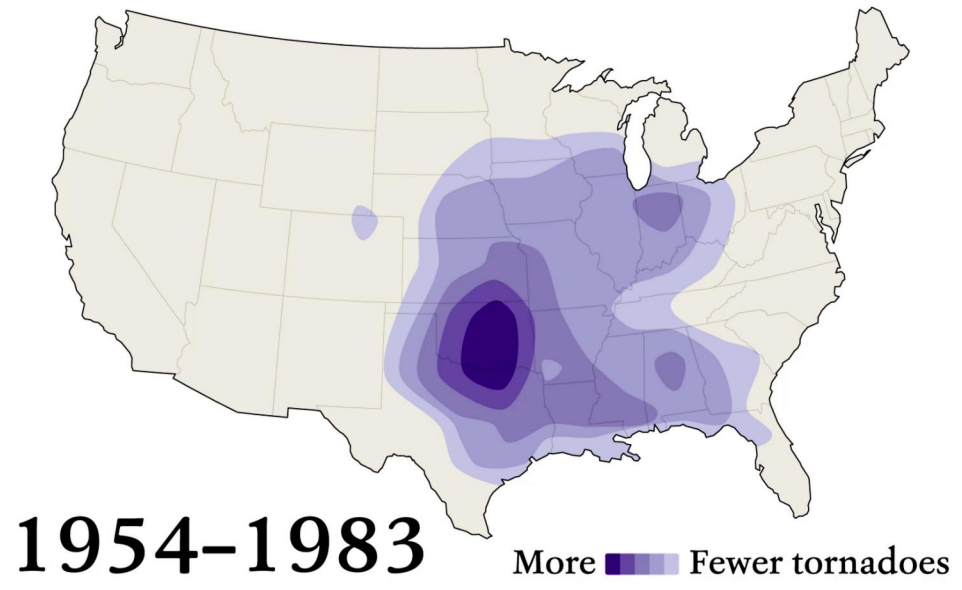
Back in the 1870s, scientist and explorer John Wesley Powell noticed a stark transition between the arid Western plains of North America and the wetter, eastern region. As he wrote, "passing from east to west across this belt a wonderful transformation is observed": a "luxuriant growth of grass" gives way to "naked" ground with the occasional cacti. The line between the two regions goes from Mexico to Manitoba, cutting right through the continent's breadbasket. To the east, farmers grow mainly rain-loving corn; to the west, mainly drought-resistant wheat.

This climatic transition has long been called the 100th Meridian, after the longitudinal line that it roughly matches up with. But in March, climate scientist Richard Seager of the Lamont–Doherty Earth Observatory of Columbia University and colleagues published papers showing the transition is on the move.

The reasons for the existence of the line are many: the Rocky Mountains force the wet air blowing in from the Pacific to rain out before the winds reach the plains; Atlantic storms and winds from the Gulf of Mexico bring moisture to the east. Now things are changing. Rainfall hasn't changed much in the northern plains, but rising temperatures are increasing evaporation from the soil and drying things out. Meanwhile, rainfall is diminishing further south due to shifts in wind patterns. In total, that seems to have moved the line about 140 miles eastward since 1980, Seager calculated. The shift seen so far might be due to natural variability, he says, but it's in line with what we expect to keep happening because of climate change. And it will keep moving east as the planet keeps warming.

U.S. farmers don't seem to report problems or changes yet, Seager says, but he predicts that the country's agriculture will eventually have to adapt, by adding more irrigation, for example, using different seeds, or shifting their crop entirely from one plant to another.

TORNADO ALLEY HAS SHIFTED 500 MILES EAST IN 30 YEARS



Hotspots for tornado formation in the U.S. have shifted east 500 miles since the mid-1980s, along with shifts in temperatures. SOURCE: AGEE ET AL, JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY, 2016. GRAPHIC BY KATIE PEEK.

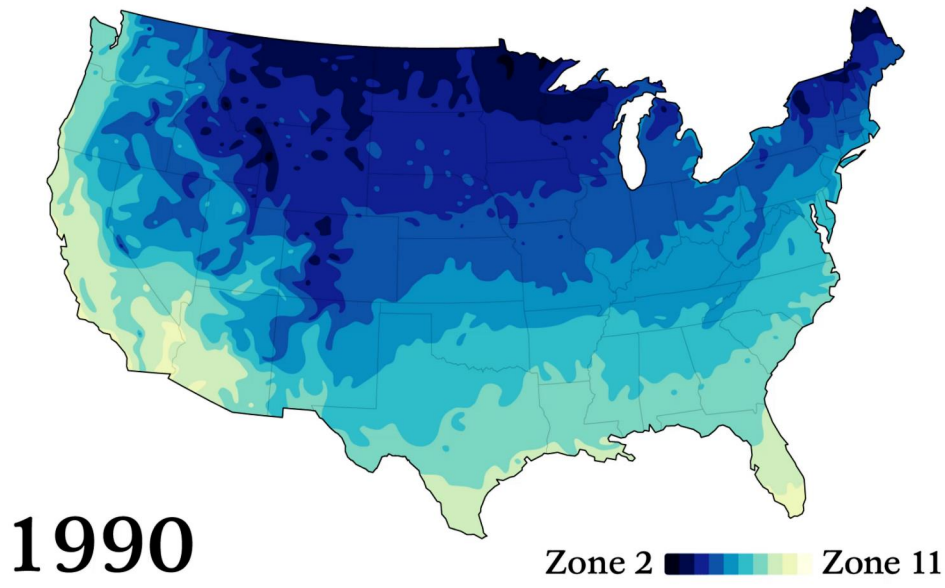
The author of the *Wizard of Oz* likely chose Kansas for the book's setting for a reason: it was smack dab in the middle of "Tornado Alley," the stretch from South Dakota to Texas that's infamous for destructive storms. But things are changing; research shows that tornados are now more likely to hit homes some 500 miles to the east in Southern states, including Tennessee and Alabama.

Earth scientist Ernest Agee of Purdue University in Indiana and colleagues looked at tornado activity going back to the 1950s when modern tornado records began, and compared the first 30 years of records to the next 30. This showed a clear shift in where tornadoes were hitting hardest, both in terms of the total number of tornadoes and the number of tornado days. In the first half of the study period, from 1954 to 1983, an area in Oklahoma was king, with a total of 477 tornadoes. But that area's tornado count decreased dramatically, by 45 percent, in the second half of the study period, from 1984 to 2013. Meanwhile, an equivalently sized area in northern Alabama bumped up 48 percent to 477 large tornadoes. Tennessee's number of days of violent tornadoes doubled, from 14 to 28 days, making the state arguably the new heart of tornado activity, the authors argue.

The researchers don't know exactly why the shift happened. Part of the reason might be attributed to who is reporting tornados, notes co-author Sam Childs, an atmospheric scientist at Colorado State University. "The storm prediction center is based out of Oklahoma City. There were a lot of reports there at first, and that's broadening out with time," Childs says. "But there's definitely a meteorological effect too." The shift in tornadoes matches up with a change in the weather, he notes. The eastern half of the U.S. was about 1.2 degrees Fahrenheit warmer during the second half of the study, making it likely that climate had something to do with the move.

The general link between weather and tornadoes is fairly well established. Tornadoes need several things to form, including warm, wet, buoyant air and high wind shear. As the 100th Meridian moves eastward, it is pushing drier conditions further east (Oklahoma lies right on that line). But it's hard to say why Tennessee is seeing more of them, and the future for tornado activity is hard to predict.

PLANT HARDINESS ZONES ARE MOVING NORTH IN THE U.S. AT 13 MILES PER DECADE



Hardiness zones in the U.S., which track average low temperatures in winter, have all shifted northward by half a zone warmer since 1990. SOURCE: UNITED STATES DEPARTMENT OF AGRICULTURE. GRAPHIC BY KATIE PEEK.

As any gardener knows, the easiest way to keep track of which plants will fare well where you live, or when to plant your tomatoes to avoid a spring frost, is by taking note of your "hardiness zone." In the frozen depths of Alaska and Siberia's zone 1, you might want to plant something like Yarrow to survive overwinter; in zone 5, which cuts through the Corn Belt in the U.S. Midwest, you can plant asparagus in March or April.

Hardiness maps are published around the world, but it's easiest to see change where the idea was first developed, in the United States. The U.S. Department of Agriculture's hardiness map, first published in 1960, is based on the average annual minimum temperature of any given spot – a metric that plays a big part in determining if perennial crops like orange trees will make it through the coldest months. Each zone marks out a 10 degrees F band, from -60 to -50 degrees F in zone 1 to 60 to 70 degrees F in zone 13. When that map was last updated, in 2012, nearly half the country was upgraded to half a zone warmer than it had been in 1990; in other words, all the lines shifted on average a little to the north. That was partly thanks to more detailed mapping techniques, the authors of the map reported, but also because temperatures were warmer in the more recent data set.

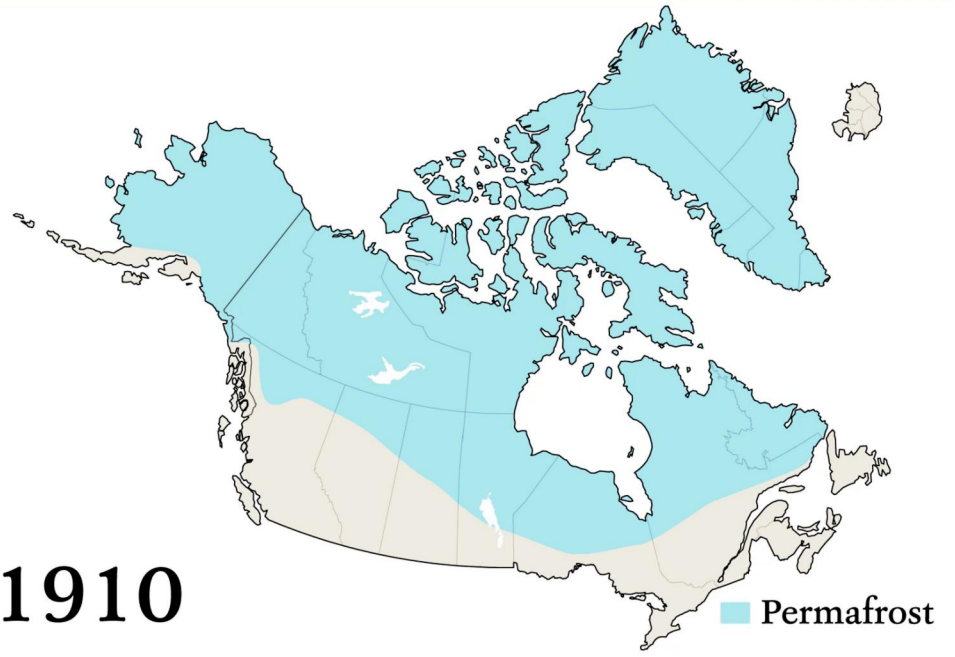
The researchers who produced the 2012 revision stopped short of saying the change was due to climate change, especially since the method of how they produced the map changed so much from one version to the next. But others have followed up on the same idea to show how climate change, specifically, is shifting U.S. hardiness zones.

Lauren Parker and John Abatzoglou of the University of Idaho tracked what would happen to hardiness zones from 2041 to 2070 under future global warming scenarios, and found the lines will continue to march northward at a "climate velocity" of 13.3 miles per decade. That means big changes in store for three major cash crops, they

note. Almonds will see their suitable growing range expand from 73 percent of the continental U.S. from 1971-2000 to 93 percent from 2041-2070. Kiwifruit will bump up from 23 percent to 32 percent during the same period, and oranges from 5 percent to 8 percent.

So the shift in hardiness zones is good news for perennial cash crops in the U.S., but not necessarily good news overall for food security in North America, or globally. "On the plus side, if we can expand the range over which we grow crops, that's a good thing," says Parker. But, she adds, "On the flip side, you also allow for the expansion of weeds and pests."

THE PERMAFROST LINE HAS MOVED 80 MILES NORTH IN 50 YEARS IN PARTS OF CANADA



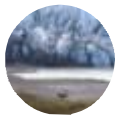
As global air temperatures rise, permafrost is retreating north, moving as far as 80 miles poleward over a half-century in parts of Canada. SOURCE: BERKELEY EARTH. GRAPHIC BY KATIE PEEK.

As the planet warms, the Arctic is feeling it the most: Temperatures in northern regions are rising at about twice the global average. That's having a huge impact on the region's permafrost, ground that typically stays frozen all year round. As the line delineating an average temperature of 0 degrees Celsius moves north, so too does the

permafrost line. "They roughly track together," says Kevin Schafer, a permafrost expert at the U.S. National Snow and Ice Data Center.

Permafrost isn't particularly well documented: It's underground, so out of sight of satellites, and the Arctic is only sparsely covered with meteorological stations. "There aren't a lot of measurements that far north," says Schafer. That means much of the evidence of permafrost thaw so far is either anecdotal or limited to specific well-monitored regions. One study in northern Canada found that the permafrost around James Bay had retreated 80 miles north over 50 years. Studies of ground temperatures in boreholes have also revealed frightening rates of change, says Schafer. "What we're seeing is 20 meters down, it's increasing as high as 1-2 degrees C per decade," he says. "In the permafrost world that's a really rapid change. Extremely rapid."

The future looks similarly dire. One study predicts that by 2100, the area covered by permafrost might shrink from nearly 4 million square miles to less than 0.4 million; most of Alaska and the southern tip of Greenland would be permafrost-free.



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The impacts are expected to be huge on both a local and global level. Right now, permafrost acts like cement, keeping the ground firm and impermeable to water. As it thaws, buildings and infrastructure collapse. In the northern Russian city of Norilsk, buildings are already tilting, cracking, and becoming condemned. In Bethel, Alaska, roads are buckling and homes collapsing. Many of the Arctic's uncountable small lakes will also drain away. "That's going to have a massive impact on the [region's] ecology," says Schafer. Meanwhile, the thaw will also release vast amounts of climate-warming methane into the atmosphere.

THE WHEAT BELT IS PUSHING POLEWARD AT UP TO 160 MILES PER DECADE

Between 1990 and 2015, production dropped in much of Australia's Wheat Belt due to drier than average conditions. The areas that disappear from this map are those where output dropped 50 percent or more. SOURCE: HOCHMAN, GOBBETT, & HORAN, GLOBAL CHANGE BIOLOGY, 2017. GRAPHIC BY KATIE PEEK.

Australia, renowned for its interior deserts and coastal beaches, is also one of the planet's largest wheat exporters – just after Canada, Russia, and the U.S. But the arable land at the nation's southern edge is shrinking, and its potential for growing wheat declining.

In the 1860s, surveyor George Goyder drew a line to show where the edge of Australia's arable land ended. More than a century later, Goyder's line is still considered an important feature in determining the country's "cropping belt." But climate change is making that land drier, effectively pushing the line further south.

Any given patch of land has a "theoretical potential" for the amount of wheat it can support, given its soil, the climate, and other factors. Reductions in rainfall and warmer temperatures have already reduced the theoretical potential of southern Australia by 27 percent since 1990. So far, farmers have managed to adapt to the changing conditions and squeeze the same amount of wheat out of their lands. By tweaking things such as their seeds and harvesting practices, they have gone from harvesting 38 percent of their theoretical maximum in 1990 to 55 percent in 2015. But that can only go on so long – farmers can typically only reach about 80 percent of any given parcel of land's maximum potential. Once they hit that limit, Australian farmers probably won't be able to counteract the effects of the changing climate any longer. Zvi Hochman, of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), says he expects to see actual yields start to drop around 2040. Places like the farming community of Orroroo, currently right on top of Goyder's line, will be "significantly impacted," writes Julia Piantadosi of the University of South Australia in Adelaide – they won't be able to keep farming the way they are doing today.

North America is seeing the opposite phenomenon: Its arable land is romping northward, expanding the wheat belt into higher and higher latitudes. Scientists project it could go from about 55 degrees north today to as much as 65 degrees North – the latitude of Fairbanks, Alaska – by 2050. That's about 160 miles per decade. That's not all good news, as the southern edge gets drier, hotter, and less agriculturally productive. One study showed that U.S. farmers will likely have to change the strains of wheat they grow, while France and Turkey will have to invest heavily in irrigation systems. In Asia, half of the Indo-Gangetic Plains, which account for 15 percent of global wheat production, are predicted to become heat-stressed by 2050, significantly cutting yields.

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Correction, October 23, 2018: *An earlier version of this article incorrectly stated that one degree of latitude measures 100 miles. It is actually nearly 70 miles on average.*

Nicola Jones is a freelance journalist based in Pemberton, British Columbia, just outside of Vancouver. With a background in chemistry and oceanography, she writes about the physical sciences, most often for the journal *Nature*. She has also contributed to *Scientific American*, *Globe and Mail*, and *New Scientist* and serves as the science journalist in residence at the University of British Columbia. **MORE →**