Brownout. With warmer winters, mountain pine beetles have chewed through millions of hectares of forests in British Columbia.

ECOLOGY

Back to the No-Analog Future?

Fossil pollen and climate models suggest a messy world in 2100, as surviving species reshuffle into entirely new combinations, creating "no-analog" ecosystems

Fly over northern Indiana, and you'll see a quilted landscape of corn and soybeans, punctuated by glacial lakes. The gelatinous mud in those lakes has preserved plenty of fossil pollen, from which paleoecologists have reconstructed a record of the region's past. Now, that same fossil pollen is providing a glimpse into Earth's ecological future—and it's not a pretty picture.

It suggests that, if the climate changes over the next 100 years as current models predict, surviving species throughout much of Earth's land area will not simply migrate north and south en masse as unchanging communities, as Charles Darwin once believed. Instead, they are likely to be reshuffled into novel ecosystems unknown today. If that view is even partly correct, then the task of preparing for, or even predicting, the ecological effects of climate change just got a whole lot harder.

Analyses over the past several decades have shown that during the last North American ice age, as the Laurentide Ice Sheet retreated into Canada 17,000 to 12,000 years ago, the region from Minnesota to Ohio to Tennessee supported a forest of spruce, sedge, oak, ash, and hophornbeam—an ecosystem that simply doesn't exist today, despite the fact that all of those species still survive. These odd communities—called "no analog" ecosystems because no modern counterparts for them exist—likely arose from odd combinations of climate variables such as precipitation, temperature, and seasonal variations that also don't exist today, say John Williams of the University of Wisconsin, Madison, and Stephen Jackson of the University of Wyoming in Laramie.

Williams helped demonstrate the connection between no-analog communities and climate during his Ph.D. work at Brown University in the late 1990s, when he compared pollen and climate records for dozens of field sites across the eastern United States. That result, published in 2001, piqued Williams's interest in whether climate change over the next century might lead to a similar type of ecosystem reshuffling—and whether these changes could be predicted. "It was a logical next step," says Williams, "to think about the future."

To find out, Williams and Jackson teamed up with John Kutzbach, a climate modeler at the University of Wisconsin, Madison. They have analyzed the outputs of standard climate models to try to map geographic areas that are likely to experience novel climates, which in turn could result in no-analog communities. In a paper published online in the *Proceedings of the National Academy of Sciences* (*PNAS*) on 27 March, they project that by 2100, depending on which climate scenario and model they use, 4% to 39% of the world's land area will experience combinations of climate variables that do not currently exist anywhere on the globe. Areas with these novel climates are likely to develop no-analog ecosystems.

Jackson, Kutzbach, and Williams fed two standard greenhouse scenarios into their models: the pessimistic A2 scenario, in which CO_2 concentrations reach 850 parts per million (ppm) by 2100, and the more optimistic B1 scenario, in which CO_2 climbs to 550 ppm. They divided the world's landmasses into grid cells measuring 2.8º latitude by 2.8º longitude and, for each cell, looked at what the models predict for four climate variables: mean summer temperature, mean winter temperature, mean summer precipitation, and mean winter precipitation.

For each spot on the map, they compared the forecast climate in 2100 with baseline climate from 1980 to 1999. To test whether these forecast climate changes would be sufficient to reshuffle ecosystems, they compared them with variations in climate that underlie different ecosystems in the same geographic area today (for example, deciduous forest and pine forest).

Not only will novel climates appear, according to the analysis, but existing climates will disappear for 4% to 48% of the world's land area. In other words, the conditions that now exist in these areas will not be found anywhere in the world by 2100. These globally disappearing climates signal the likelihood for significant ecological disruption, if not necessarily no-analog ecosystems. "This is a conservative analysis," says Jackson. "If we added more climate variables, we'd probably end up with more disappearing and novel climates."

New climates are expected to cause ecosystem reshuffling as individual species, constrained by different environmental factors, respond differently. One tree may be limited by summer rains that hold back seedling recruitment, for instance, whereas another species may be limited by winter freezes that control insect pests. Some species may migrate up-latitude or up-elevation, while others stay put. An ecosystem might see many species vanish—but also new arrivals.

Williams and colleagues project that the tropics, including Amazonia, will see the most pronounced no-analog climates, with rising temperatures pushing these already-warm areas outside of any climates currently known today. Soaring temperatures combined with drought could selectively kill taller, canopy-forming trees—rapidly transforming ecosystems by increasing sunlight and drying at ground level.

Within North America, the team predicts that the southeastern United States will see no-analog climates, driven by a selective rise in summer temperatures. The result could be increased wildfires in forests that are poorly adapted to fire, leading to rapid opening of the canopy unless those forests are managed aggressively.

"I applaud their work," says William Hargrove, a landscape ecologist at Oak Ridge National Laboratory in Tennessee. "We've seen an explosion of climate-change models turning out results, but I don't see as much work on the prognostic impact of these results on ecosystems." In

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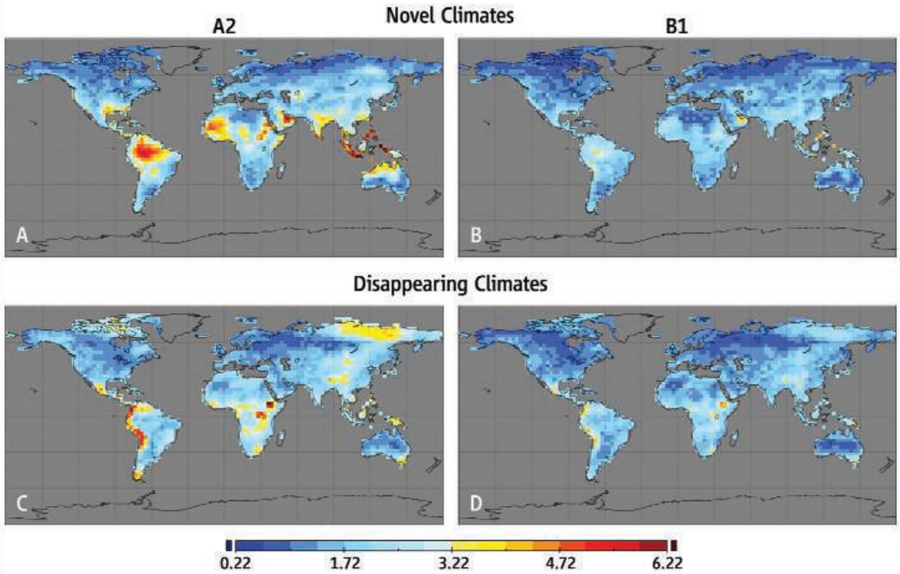
a similar exercise, published in 2005, Hargrove and colleagues mapped changes in seven climate variables across the United States. They predicted a higher rate of vanishing climates by 2100 than did Williams, Jackson, and Kutzbach. Hargrove attributes some of this difference to the fact that his team considered not only climate but also other ecologically relevant variables, such as soil type and landscape topography. "If you consider only climate," says Hargrove, "you may underestimate the magnitude of ecological change."

One of the biggest issues raised by novel and disappearing climates is whether species whose preferred climates disappear locally can migrate to other areas where suitable climates still persist. As described in *PNAS*, Williams, Jackson, and Kutzbach performed a second analysis examining this very question. For each point on the map where the climate changes by 2100, they examined the surrounding areas to determine whether the current climate would persist elsewhere within a 500-km radius. Imposing this constraint increased the proportion of disappearing climates to 14% to 85% of the world's land area, depending on the climate scenario and model.

Migration corridors are often proposed as a strategy to facilitate the movement of species in response to climate change; but this analysis suggests that often there may be no suitable refugia nearby. "Even if these species can migrate quickly enough," says Jackson, "they may effectively have nowhere to go."

Rapid shifts in the pollen record lead some people to predict that future changes could be sudden as well. Some argue that it's already happening, with droughts across the Southwestern United States between 2000 and 2005 killing over 80% of adult piñon trees in some stands, drastically altering the piñon-juniper woodlands. If drought frequency increases in the Southwest, as some climate models predict, then other species could seize the niche vacated by those dead piñons, permanently altering the landscape's canopy structure, hydrology, and fire regime. "It's going to be interesting to see what happens there in the next 20 years," says Jackson. "This ecosystem may or may not come back."

Others remain circumspect. Craig Allen, a landscape ecologist who observed the die-offs firsthand from the U.S. Geological Survey's (USGS's) Jemez Mountains Field Station in New Mexico, points out that the proximate cause of most piñon mortality was beetle infestation. That means many juvenile trees survived, and these could restore piñon populations within decades if further droughts don't intervene.



Brave new world. Pessimistic (A2) and optimistic (B1) greenhouse scenarios predict that novel climates will appear across the tropics by 2100, while current climate types disappear in the tropics and the higher latitudes. Color scale represents degree of difference from current climate, with yellow-orange-red indicating significantly different climate by 2100 and substantial risk for developing no-analog ecosystems.

CREDIT: WILLIAMS *ET AL.*, *PNAS* **104**, 14 (2007)

The prospect of novel climates has people rethinking traditional goals such as maintaining native ecosystems. "That's probably going to be impossible," says Nathan Stephenson, a research ecologist at the USGS Western Ecological Research Center in Three Rivers, California. "But what you can still do, even if you can't maintain native communities, is potentially maintain regional biodiversity and ecosystem functions."

Nowhere is this point of view more evident than in the management of forests—where human intervention has always been heavy. In British Columbia, climate-related surges in mountain pine beetles and fungus have browned millions of hectares of trees in recent years. Ecologists there are thinking about how to maintain a forest that will provide reliable watersheds, wildlife habitat, and lumber supplies into the future. The solution could involve planting different mixtures of tree species or replanting forests using seed stock from warmer areas, says Del Meidinger, an ecologist with the British Columbia Ministry of Forests and Range in Victoria. "You have to plant something that will survive now but will still grow well into the future" in a changed climate, says Meidinger.

Land managers would love to predict how ecosystems will reorganize, what sorts of no-analog communities might emerge, and which species will dominate. Ecologists have produced niche models that predict species' future geographic distributions based on climates in their current locations. But that approach may break down when it comes to future no-analog climates, says Williams. "You're limited by what you can observe today," he says. "It's a real problem for making ecological forecasts for climates that are outside the current range of observation."

One promising approach to making better forecasts is to base them on experimentally determined physiology. Ronald Neilson, a bioclimatologist with the Forest Service's Pacific Northwest Research Station in Corvallis, Oregon, is developing such a model. It predicts drought-induced mortality and fire by calculating how much leaf area can be supported by local moisture levels, based on measured rates of leaf water loss. "What we're simulating at the moment is plant functional types," says Neilson. "We want to get to the species level."

This year, Neilson and Michael Loik of the University of California, Santa Cruz, will take the first step in that direction. They'll begin a seedling transplantation study to measure the physiological tolerances of a single species: Jeffrey pine, in the eastern Sierra Nevada of California. It's an effort-intensive approach, to be sure, but understanding the implications of a no-analog future might require no less.

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