MIT Technology Review

The climate issue

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Welcome to climate change

Mitigation

Why the battle to curb carbon emissions is losing ground

Adaptation

Technologies for living on a hotter, more dangerous planet

Suffering

A picture of life in the future for both the winners and the losers

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At a UN climate meeting in 2007, John Holdren, who would later become President Barack Obama's chief science advisor, famously said, "We basically have three choices: mitigation, adaptation, and suffering." Most writing about technology and climate change still concentrates on mitigation—i.e., reducing emissions, by means of clean energy sources, better batteries, sleek electric vehicles, and so on—or, if all else fails, heroic efforts like engineering the atmosphere to reflect more sunlight back into space. These technologies are often futuristic and cool, and create a comforting narrative that humanity's scientific smarts will save it from its political stupidity.

This issue of MIT Technology Review rests on the premise that while one should never give up on mitigation, it's time to start talking more about adaptation and suffering—about the technologies the human race will need in a catastrophically altered world, and about the economic, political, and social realities of living in it.

We start off with some harsh truths about mitigation. The growth in renewables has made virtually no dent in the use of fossil fuels; it's come largely at the expense of nuclear energy, another low-carbon source (page 8). But a nuclear comeback looks increasingly unlikely now that corruption scandals have sunk South Korea's nuclear program, one of the world's most ambitious (page 22). Even with valiant efforts to use more renewables, countries like India will drag the world's emissions up as they strive for higher living standards (page 14).

We then move to adaptation. America's farming heartland is a crucial source of staple foods for a warming world, and the race is on to find new crop breeds engineered for resilience as the region becomes hotter (page 32). Similarly, hardier strains of coffee might protect farmers in Central America from losing their livelihoods (page 44). Livestock herders in Africa are coming to rely on satellite imaging to pinpoint the increasingly scarce vegetation and watering holes for their flocks (page 48). Californians who lost their houses during last year's wildfires can look to Australia as a case study in how to plan for fires and build homes that will withstand them (page 50). In Mexico, where seaweed blooms caused by warming seas are threatening to strangle the tourist industry, researchers are working on ways to turn the invasive species into food or fuel (page 40). New York City's plan for protecting itself against sea-level rise is a taste of what coastal cities around the world will have to face (page 38). And localized geoengineering techniques might keep the oceans a shade cooler, enough to preserve some of the most valuable coral reefs from destruction (page 56).

IAN ALLEN

Gideon Lichfield is editor in chief of MIT Technology Review.

No less important is the work being done to understand how bad the suffering will be, and where. New predictive models, relying on masses of data, are providing a better idea of where people will be displaced (page 70). Similarly, data-intensive research is reducing the wide band of uncertainty about how much global temperatures will rise (page 84). And other modeling (page 8) is making it increasingly clear that the harms will be unevenly distributed: some regions will even enjoy benefits from warmer temperatures. Meanwhile, India's looming water crisis is a stark warning of what the rest of the world has to look forward to (page 72).

Ultimately, of course, climate change affects everyone. To grasp what that really means, read Paolo Bacigalupi's chilling fictional depiction of a near-future America (page 86), and Roy Scranton's essay on how living with climate change will mean ditching some of our most basic assumptions about what constitutes a normal, good life (page 64). Start preparing mentally for this new world. Because to take action on either mitigation or adaptation, one first needs to be able to visualize the suffering.

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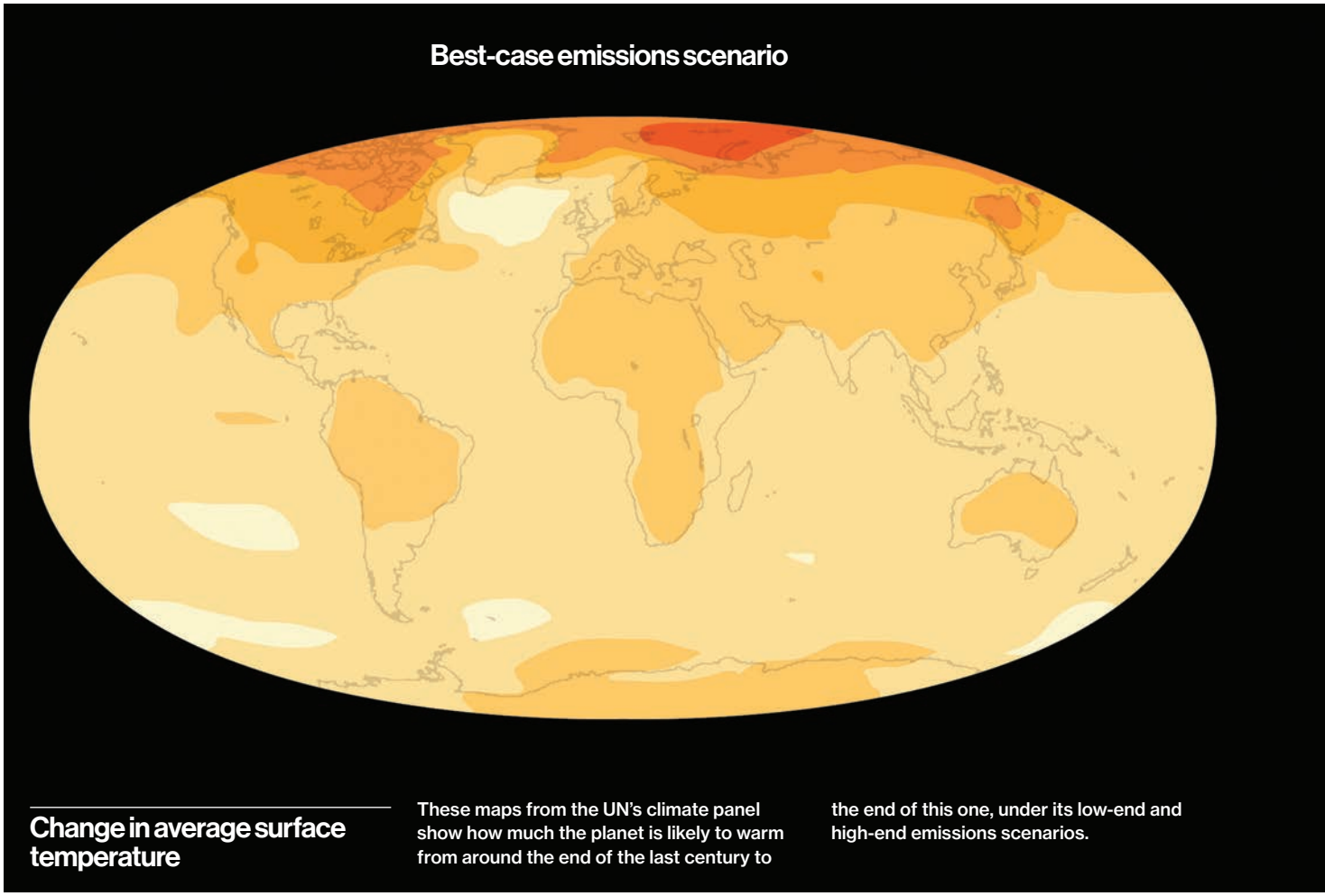


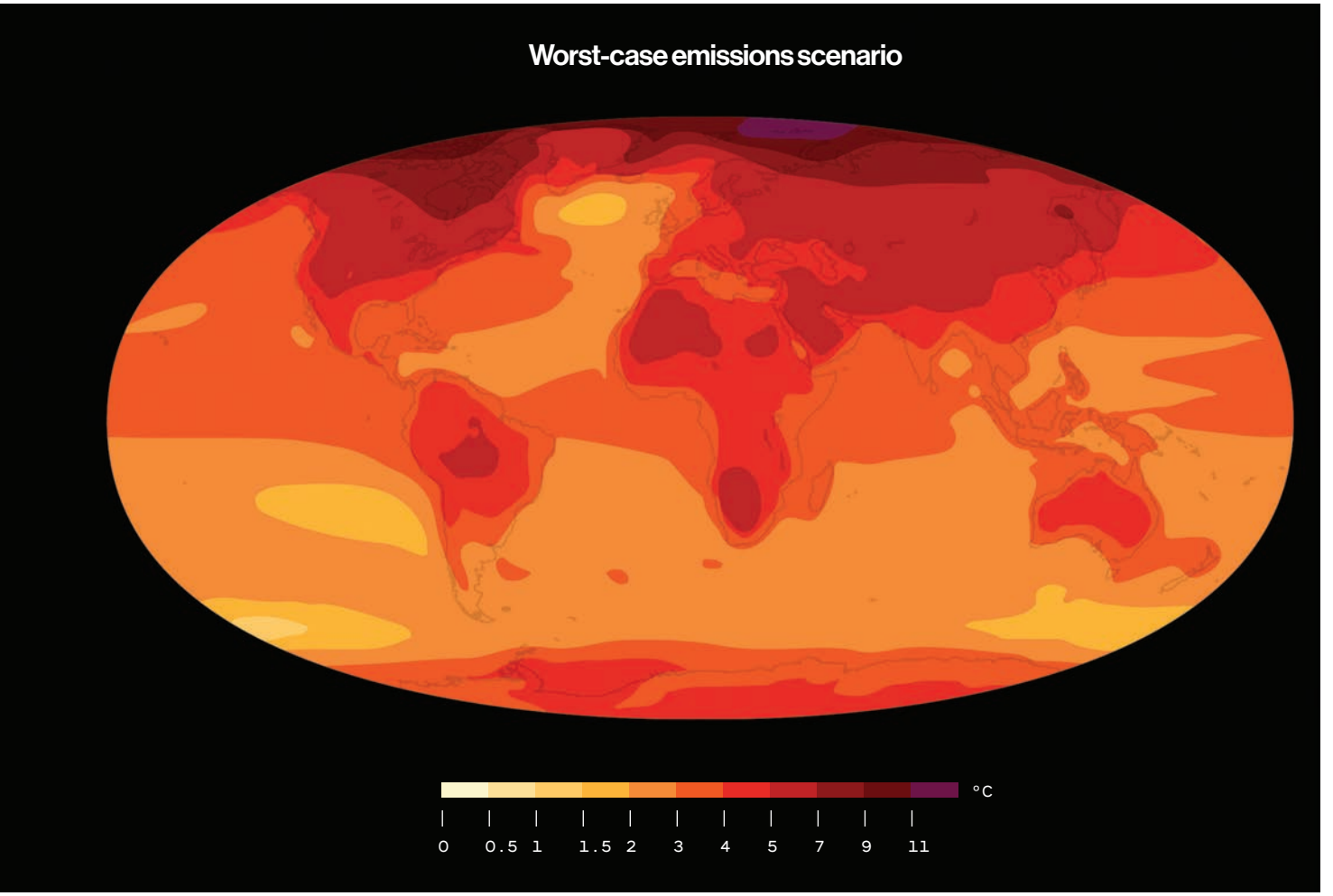
Change in average surface temperature

These maps from the UN's climate panel show how much the planet is likely to warm from around the end of the last century to the end of this one, under its low-end and high-end emissions scenarios.

We're getting better at understanding how much people will suffer from climate change—and how unevenly the impacts will be felt.

By David Rotman

What would *you* pay to save the world?



In contrast to the existential angst currently in fashion around climate change, there's a cold-eyed calculation that its advocates, mostly economists, like to call the most important number you've never heard of.

It's the social cost of carbon. It reflects the global damage of emitting one ton of carbon dioxide into the sky, accounting for its impact in the form of warming temperatures and rising sea levels. Economists, who have squabbled over the right number for a decade, see it as a powerful policy tool that could bring rationality to climate decisions. It's what we should be willing to pay to avoid emitting that one more ton of carbon.

For most of us, it's a way to grasp how much our carbon emissions will affect the world's health, agriculture, and economy for the next several hundred years. Maximilian Auffhammer, an economist at the University of California, Berkeley, describes it this way: it's approximately the damage done by driving from San Francisco to Chicago, assuming that about a ton of carbon dioxide spits out of the tailpipe over those 2,000 miles.

Common estimates of the social cost of that ton are $40 to $50. The cost of the fuel for the journey in an average car is currently around $225. In other words, you'd pay roughly 20% more to take the social cost of the trip into account.

The number is contentious, however. A US federal working group in 2016, convened by President Barack Obama, calculated it at around $40, while the Trump administration has recently put it at $1 to $7. Some academic researchers cite numbers as high as $400 or more.

Why so wide a range? It depends on how you value future damages. And there are uncertainties over how the climate will respond to emissions. But another reason is that we actually have very little insight into just how climate change will affect us over time. Yes, we know there'll be fiercer storms and deadly wildfires, heat waves, droughts, and floods. We know the glaciers are melting rapidly and fragile ocean ecosystems are being destroyed. But what does that mean for the livelihood or life expectancy of someone in Ames, Iowa, or Bangalore, India, or Chelyabinsk, Russia?

For the first time, vast amounts of data on the economic and social effects of climate change are becoming available, and so is the computational power to make sense of it. Taking this opportunity to compute a precise social cost of carbon could help us decide how much to invest and which problems to tackle first.

"It is the single most important number in the global economy," says Solomon Hsiang, a climate policy expert at Berkeley. "Getting it right is incredibly important. But right now, we have almost no idea what it is."

That could soon change.

The cost of death

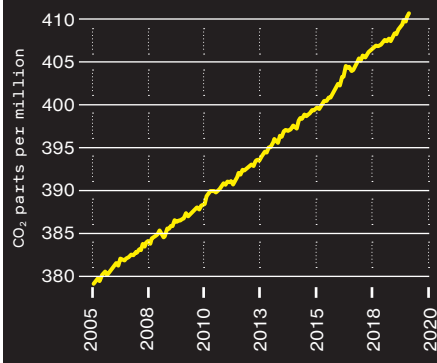
In the past, calculating the social cost of carbon typically meant estimating how climate change would slow worldwide economic growth. Computer models split the world

SOURCE: IPCC, 2013

The world can't seem to get emissions under control

Atmospheric carbon dioxide concentrations have steadily risen this century, increasing the dangers of climate change.

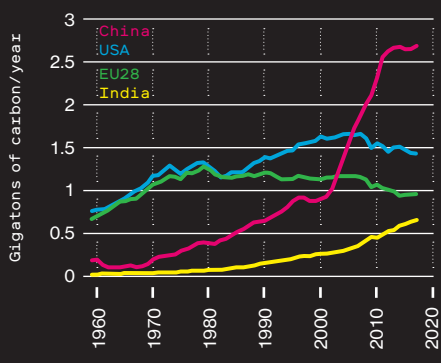
Direct measurements: 2005–present



NOAA

Some countries have begun to decrease carbon pollution or at least keep it steady, but it's soaring in certain fast-developing nations.

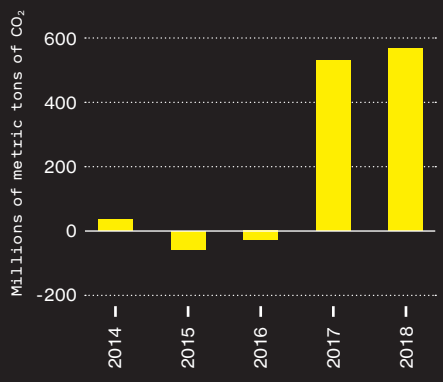
Trends in carbon dioxide emissions from fossil fuels, by country



C. LE QUÉRÉ ET AL./EARTH SYSTEM SCIENCE DATA 2018

Global emissions levels declined slightly earlier this decade, but a growing worldwide economy has pushed them up again.

Change in global carbon dioxide emissions: 2014–2018



IEA

into at most a dozen or so regions and then averaged the predicted effects of climate change to get the impact on global GDP over time. It was at best a crude number.

Over the last several years, economists, data scientists, and climate scientists have worked together to create far more detailed and localized maps of impacts by examining how temperatures, sea levels, and precipitation patterns have historically affected things like mortality, crop yields, violence, and labor productivity. This data can then be plugged into increasingly sophisticated climate models to see what happens as the planet continues to warm.

The wealth of high-resolution data makes a far more precise number possible—at least in theory. Hsiang is co-director of the Climate Impact Lab, a team of some 35 scientists from institutions including the University of Chicago, Berkeley, Rutgers, and the Rhodium Group, an economic research organization. Their goal is to come up with a number by looking at about 24,000 different regions and adding together the diverse effects that each will experience over the coming hundreds of years in health, human behavior, and economic activity.

It's a huge technical and computational challenge, and it will take a few years to come up with a single number. But along the way, the efforts to better understand localized damages are creating a nuanced and disturbing picture of our future.

So far, the researchers have found that climate change will kill far more people than once thought. Michael Greenstone, a University of Chicago economist who co-directs the Climate Impact Lab with Hsiang, says that previous mortality estimates had looked at seven wealthy cities, most in relatively cool climates. His group looked at data gleaned from 56% of the world's population. It found that the social cost of carbon due to increased mortality alone is $30, nearly as high as the Obama administration's estimate for the social cost of all climate impacts. An additional 9.1 million people will die every year by 2100, the group estimates, if climate change is left unchecked (assuming a global population of 12.7 billion people).

Unfairly distributed

However, while the Climate Impact Lab's analysis showed that 76% of the world's population would suffer from higher mortality rates, it found that warming temperatures would actually save lives in a number of northern regions. That's consistent with other recent research; the impacts of climate change will be remarkably uneven.

The variations are significant even within some countries. In 2017, Hsiang and his collaborators calculated climate impacts county by county in the United States. They found that every degree of warming would cut the country's GDP by about 1.2%, but the worst-hit counties could see a drop of around 20%.

If climate change is left to run unchecked through the end of the century, the southern and southwestern US will be devastated by rising rates of mortality and crop failure. Labor productivity will slow, and energy costs (especially due to air-conditioning) will rise. In contrast, the northwestern and parts of the northeastern US will benefit.

"It is a massive restructuring of wealth," says Hsiang. This is the most important finding of the last several years of climate economics, he adds. By examining ever smaller regions, you can see "the incredible winners and losers." Many in the climate community have been reluctant to talk about such findings, he says. "But we have to look [the inequality] right in the eye."

The social cost of carbon is typically calculated as a single global number. That makes sense, since the damage of a ton of carbon emitted in one place is spread throughout the world. But last year Katharine Ricke, a climate scientist at UC San Diego and the Scripps Institution of Oceanography, published the social costs of carbon for specific countries to help parse out regional differences.

India is the big loser. Not only does it have a fast-growing economy that will be slowed, but it's already a hot country that will suffer greatly from getting even hotter. "India bears a huge share of the global social cost of carbon—more than 20%," says Ricke. It also stands out for how little it has actually contributed to the world's carbon emissions. "It's a serious equity issue," she says.

Estimating the global social cost of carbon also raises a vexing question: How

do you put a value on future damages? We should invest now to help our children and grandchildren avoid suffering, but how much? This is hotly and often angrily debated among economists.

A standard tool in economics is the discount rate, used to calculate how much we should invest now for a payoff years from now. The higher the discount rate, the less you value the future benefit. William Nordhaus, who won the 2018 Nobel Prize in economics for pioneering the use of models to show the macroeconomic effects of climate change, has used a discount rate of around 4%. The relatively high rate suggests we should invest conservatively now. In sharp contrast, a landmark 2006 report by British economist Nicholas Stern used a discount rate of 1.4%, concluding that we should begin investing much more heavily to slow climate change.

There's an ethical dimension to these calculations. Wealthy countries whose prosperity has been built on fossil fuels have an obligation to help poorer countries. The climate winners can't abandon the losers. Likewise, we owe future generations more than just financial considerations. What's the value of a world free from the threat of catastrophic climate events—one with healthy and thriving natural ecosystems?

Outrage

Enter the Green New Deal (GND). It's the sweeping proposal issued earlier this year by Representative Alexandria Ocasio-Cortez and other US progressives to address everything from climate change to inequality. It cites the dangers of temperature increases beyond the UN goal of 1.5 °C and makes a long list of recommendations. Energy experts immediately began to bicker over its details: Is achieving 100% renewables in the next 12 years really feasible? (Probably not.) Should it include nuclear power, which many climate activists now argue is essential for reducing emissions?

In reality, the GND has little to say about actual policies and there's barely a hint of how it will attack its grand challenges, from providing a secure retirement for all to fostering family farms to ensuring access to nature. But that's not the point. The GND is a cry of outrage against what it calls "the twin crises of climate change and worsening income inequality." It's a political attempt to make climate change part of the wider discussion about social justice. And, at least from the perspective of climate policy, it's right in arguing that we can't tackle global warming without considering broader social and economic issues.

The work of researchers like Ricke, Hsiang, and Greenstone supports that stance. Not only do their findings show that global warming can worsen inequality and other social ills; they provide evidence that aggressive action is worth it. Last year, researchers at Stanford calculated that limiting warming to 1.5 °C would save upwards of $20 trillion worldwide by the end of the century. Again, the impacts were mixed—the GDPs of some countries would be harmed by aggressive climate action. But the conclusion was overwhelming: more than 90% of the world's population would benefit. Moreover, the cost of keeping temperature increases limited to 1.5 °C would be dwarfed by the long-term savings.

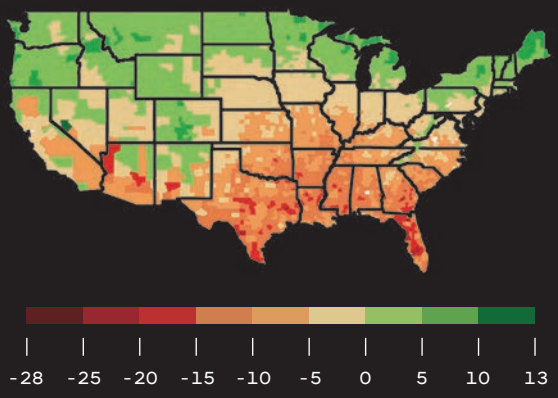
Nevertheless, the investments will take decades to pay for themselves. Renewables and new clean technologies may lead to a boom in manufacturing and a robust economy, but the Green New Deal is wrong to paper over the financial sacrifices we'll need to make in the near term.

That is why climate remedies are such a hard sell. We need a global policy—but, as we're always reminded, all politics is local. Adding 20% to the cost of that San Francisco–Chicago trip might not seem like much, but try to convince a truck driver in a poor county in Florida that raising the price of fuel is wise economic policy. A much smaller increase sparked the *gilets jaunes* riots in France last winter. That is the dilemma, both political and ethical, that we all face with climate change.

David Rotman is editor at large of MIT Technology Review.

The South could be hard hit by 2100

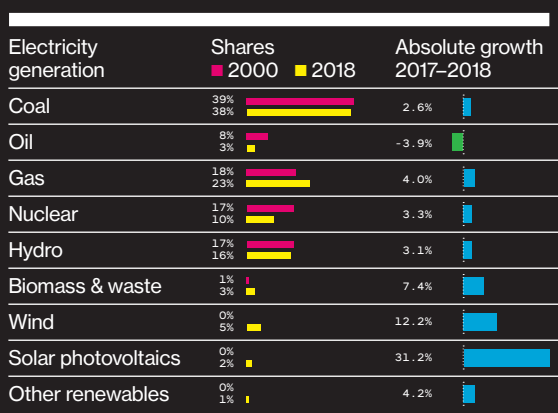
Total economic gain/loss (% county GDP)



HSIANG, KOPP, JINA, RISING, ET AL. 2017

Fossil fuels remain dominant

Global electricity generation by source



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Mitigation

1

"India would need to add about 500 gigawatts of renewables capacity by 2030, nearly seven times the current total, just to meet the growth in demand without building new coal plants. That's simply not going to happen." — James Temple on India's threat to the whole world's climate goals, page 14

Wind turbines (below) operating in Karnataka, a south-western state that's adding huge amounts of solar and wind power.

A farm south of Bangalore relies on solar panels (right) to power a water pump that irrigates the land.

By
JAMES TEMPLE

Photographs by
SAUMYA KHANDELWAL

India's dilemma

No matter how fast the country builds new solar and wind farms, its surging economy will warm the planet—unless others do more to help.

IN THE

A Suzlon Energy turbine operating at ReNew Power's Veerabhadra wind project in Andhra Pradesh.

flat terrain of eastern Karnataka, deep in the interior of the Indian subcontinent, you don't see the Pavagada Solar Park coming. But when it appears, on the far side of a dusty little village, it is, all at once, everywhere.

Dull gray panels unfold in all directions from the barbed-wire fences lining the road, forming a city of silicon that stretches across 20 square miles (52 square kilometers).

When it's complete, the more than $2.5 billion project, three hours north of Bangalore, will be one of the largest solar parks in the world. The millions of panels will be capable of pumping out 2 gigawatts of electricity from this sunbaked stretch of India, the equivalent of a pair of large nuclear power plants.

At least two other solar parks in the works in India promise to be even bigger: a 5-gigawatt project in the state of Gujarat and a 2.3-gigawatt one in Rajasthan.

India has recently completed or approved dozens of giant solar and wind projects, nearly doubling its renewables capacity since 2015. For the last two years, it was the fastest builder of solar projects on the planet after China. All told, the country has around 75 gigawatts of solar, wind, and other renewable sources installed—and more than 45 gigawatts in the pipeline.

In 2015, government officials announced plans to more than quadruple renewables capacity, setting a target of 175 gigawatts by 2022. Later that year, under the Paris climate accords, India committed to produce 40% of its electricity from clean sources and cut emissions intensity (the level of carbon dioxide produced per unit of GDP) to at least 33% below 2005 levels by 2030.

India is now a shining case study in how rapidly generation of renewable power can expand with government investment and support, even in a deeply poor country. But it also underscores the fact that adding clean energy and cutting climate emissions aren't the same thing.

For India to achieve the latter, clean energy would need to replace—not simply augment—coal, which currently generates nearly 55% of the nation's electricity. And that's not happening anytime soon in one of the world's fastest growing and fastest urbanizing economies.

India's GDP could more than quintuple by 2040, more than doubling its energy demand, according to the International Energy Agency. That would represent roughly a quarter of the total global increase over that period. Air-conditioning units alone could increase by 15-fold, as citizens become better off and cities grow hotter.

"However much renewable energy we build, it won't eat into thermal," says Sumant Sinha, founder and managing director of ReNew Power, a wind and solar developer that built several projects within the Pavagada Solar Park. "The reality is that India's emissions will increase very substantially going forward."

Estimates vary widely, but the IEA expects that carbon emissions from India's power sector will rise 80% through 2040 even with the renewable generating plants currently planned. By then India could overtake the US as the world's second largest emitter, undermining efforts to curb global warming. If India can't pull

off the necessary reductions, even with its substantial policies and investments, it means that wealthy nations will need to step up their efforts even more.

DRIVING DEVELOPMENT

In the initial decades of international wrangling over climate action, India clung to an attitude of "common but differentiated" responsibilities, arguing (not unreasonably) that developed nations, as the world's biggest emitters historically, have the "primary obligation to take action," according to an analysis last year in the Annual Review of Environment and Resources.

That began to change under the last government, but it shifted rapidly after Prime Minister Narendra Modi's Bharatiya Janata Party took power in 2014. The nationalist government recognized renewables as an opportunity to address overlapping public and political concerns, including energy security, international prestige, air pollution, and climate change—and roughly in that order.

Initially, the country focused on feed-in tariffs, a policy tool designed to drive new projects by guaranteeing set prices to energy producers for years. But the primary tactic now is for federal and state agencies to auction off the right to build a certain amount of new wind or solar generation.

These auctions have sparked aggressive bidding wars, driving down the price of renewable generation in India. Solar bids have reached levels as low as 2.44 rupees (around 3.5 US cents) per kilowatt-hour, in line with the subsidized price for large solar farms in the US.

In many cases, state-sponsored companies have also created massive "plug and play" parks, taking care of land acquisition, permitting, and other headaches on behalf of project developers. "The infrastructure is at your doorstep, and all you have to do is bring your panels, plug in, and go," says Kanika Chawla, senior program lead at the Council on Energy, Environment and Water in New Delhi.

This, plus the fact that the government enforces long-term power purchase agreements between power generators and utilities, has helped lower risks, lure developers, and drive down capital costs.

In the case of the Pavagada Solar Park, the state-run Karnataka Solar Power Development Corporation obtained the land by striking lease deals with nearly 3,000 local farmers in Pavagada, a cluster of villages in the northeastern part of the state. Years of drought had drained the plains, depressing the water tables by hundreds of feet. Nearly all the region's farmers, once known for growing peanuts, now leave their lands fallow. Many have migrated to swelling cities like Bangalore or Hyderabad, seasonally or permanently, in search of work as porters, touts, or waste sorters.

Karnataka Solar agreed to pay landowners around 21,000 rupees ($300) per acre (0.4 hectares) annually for their sun-rich, water-poor property, a price that ticks up 5% every other year over a 25-year term. That's about three times the profit in their best years from growing peanuts, says Seshagiri Rao, an agronomist in Bangalore, who is from Pavagada. Proposing a lease rather than a sale also helped close the deal for many of the area's farmers, for whom holding onto and passing along their heritage lands was important.

Six companies successfully bid for the rights to finance and build projects within the park, including Fortum, Tata Power, and ReNew. With the development work out of the way, it took only three to four months to get each of ReNew's three projects online, says K.S. Viswanath, the company's top executive in Karnataka.

When I visited in early March, yellow forklifts were driving across the leveled field of the company's final, 150-megawatt block, dropping pallets of solar panels in the rows between naked racks. Workers returned to the fields in the midafternoon, after the worst of the midday heat. Two by two, they lifted the panels and bolted them into place.

The Pavagada Solar Park was around 70% complete at that point, which is a little behind schedule, but the full project is likely to come online by the end of this year.

Pranesh Krishna Murthy manages a family-owned farm south of Bangalore. After installing a solar-powered water pump and drip irrigation, they've been able to cultivate more land and thirstier crops like watermelons and bananas.

A PROBLEM OF TRANSMISSION

India has shown that a developing nation can rapidly add clean energy, at costs below those associated with coal plants, while still expanding its economy and creating jobs.

"The scale of renewables that India is trying to add in seven years took Germany two decades," says Arunabha Ghosh, chief executive of the Council on Energy, Environment and Water. "And we're doing it much earlier in our development."

But India is not Germany. It's still likely to take decades before the nation's renewables start to replace coal and bring down emissions, given how fast energy needs are growing and how hard it is to integrate intermittent sources like wind and solar.

To date, India has largely been harvesting the "low-hanging fruit" of the clean-energy transition, adding low-cost renewables on top of existing infrastructure, says Rahul Tongia, a foreign-policy fellow at Brookings India. But growing amounts of wind and solar generation, both of which fluctuate dramatically, will place increasing strains on the nation's grid.

This is true everywhere, but it will be a particular challenge in India, given the shoddy state of transmission and distribution infrastructure—and the fact that the nation is building so many megaprojects, which can flip on and off all at once as the sun sets, clouds pass, or the wind dies.

Integrating this much variable generating capacity—which at the targeted 175 gigawatts will represent nearly 20% of the electricity mix—will require more coordination, better policies, and upgraded transmission lines to swap electricity across states, Tongia and his colleagues concluded in a Brookings report late last year.

But cutting deeply into India's carbon emissions would demand a radical and expensive overhaul. That would include developing a much more flexible, modern grid; adding huge amounts of storage; and implementing market-based reforms, like time-of-day pricing, that let utilities and customers react quickly to shifting levels of supply and demand.

And, of course, it will require far, far more renewable energy plants or other sources of clean power. Tongia estimates that India would need to add about 500 gigawatts of renewables capacity by 2030, nearly seven times the current total, just to meet the growth in demand without building new coal plants.

That's simply not going to happen, so coal "will be essential to meet ever-growing power demand," he wrote in a paper in March.

One of the biggest obstacles to further progress is that the nation's utilities can't afford the necessary investments. Electricity theft is rampant, households and farmers are heavily subsidized, and businesses, which pay inflated rates, are starting to look for ways to flee the system—by buying power from other suppliers or setting up their own solar projects.

In fact, the struggling utilities can barely maintain existing infrastructure. They resist connecting and servicing areas where they won't meet their costs, and shut off power at times when supplies are tight or simply to save money.

Last spring, following a three-year, $2.5 billion government-funded effort to link transmission lines to the most remote parts of the country, Modi trumpeted that "every single village of India now has access to electricity."

But the government set a low bar, ticking the box so long as 10% of households in a village, and institutions like schools and hospitals, were connected. That means as many as 90% of rural households in many villages still aren't wired, and even those that are may get power only a few hours a day. At least tens of millions of Indians still lack electricity.

Sidhappa Ji (above), a blacksmith in Halaguru, hammers metal beams into sickles, using a solar-powered blower supplied by Selco to stoke his fire.

A solar panel rises from the edge of Ji's metal shed (right). It's only 10 steps from a utility pole, but he doesn't have the necessary paperwork to obtain electricity.

Workers at the Pavagada Solar Park (opposite page) place panels onto racks at ReNew Power's final project within the 20-square-mile site in eastern Karnataka.

As many as 90% of rural households in many villages still aren't wired, and even those that are may get power only a few hours a day.

Fixing all this is likely to require far more funding and a broad regulatory overhaul, including penalties for utilities that fail to provide power and reforms that move prices closer to market rates. But the latter is an extremely unpopular notion in India, where the belief that the state should deliver cheap power is deeply held, dating back to the earliest promises of independence.

OFF-GRID

In Halaguru, a small town south of Bangalore, a blacksmith named Sidhappa Ji hammers glowing orange beams into sharp-edged sickles, in a hot metal shed 10 steps from an electricity pole. But because he doesn't have legal documents for the property, he can't obtain electricity, a problem shared by many in India's slums.

Selco, a Bangalore-based social enterprise, has been working on the opposite end of the spectrum from the gigantic parks, supplying solar panels, batteries, and other tools to homes, farms, and businesses in rural villages.

Through its foundation, the organization develops customized solar-powered tools for micro-entrepreneurs, including the blower that Ji uses to stoke his fire. The nonprofit has also created water pumps, photocopiers, and cattle-milking contraptions that run directly off solar panels and batteries, and it's working on chili-powder pounders, banana-chip choppers, and puffed-rice puffers.

Given the country's sprawling scale and fragmented grids, decentralized renewable power will need to play a large role in electrification, says Pratim Raha, a program manager at the Selco Foundation. That, in turn, will also ensure that clean energy sources can account for as much as possible of the projected rise in energy consumption in the decades to come.

"If your narrative is 'The grid will come and solve all problems,' that's not right in India," Raha says.

"THE BURDEN OF ADJUSTMENT"

All the complexities discussed so far concern the challenge of slowing emissions from electricity generation. India has barely even begun cleaning up other climate-polluting sectors, including transportation, industry, and agriculture.

If the nation can't bring down emissions as a whole before 2040, it presents a global danger. The UN's climate-change body has concluded that the world needs to cut carbon dioxide emissions 45% from 2010 levels by 2030, and eliminate them entirely by midcentury, to have a decent chance of preventing 1.5 °C of warming. India is the world's fourth largest emitter, contributing 7% of emissions, behind China (27%), the US (15%), and the European Union (10%), according to the Global Carbon Project.

But it's fundamentally unfair to ask the country to cap its climate pollution and stunt its growth now, given that richer countries have pumped out far more carbon dioxide to get to where they are today. They've enjoyed decades of accumulating economic growth thanks largely to cheap fossil fuels.

India's per capita energy consumption is around one-tenth of America's—and even if it doubles by 2030, it will be only half what China's was in 2015, according to a recent analysis led by Navroz Dubash, coordinator of the Initiative on Climate, Energy, and Environment at the Centre for Policy Research in New Delhi.

By any analysis, India needs to consume more energy just to provide reliable electricity to all its citizens and lift hundreds of millions of them out of poverty. And as its summers get hotter, air-conditioning will increasingly become not a luxury but a public-health necessity.

"India is a deeply poor society and a deeply energy-poor society," Dubash says. "We're not making the argument that therefore we should do nothing [to reduce emissions]. But you cannot ignore that when you think about the burden of adjustment—and how that should be distributed around the world."

In other words, if the world truly hopes to avoid shooting past dangerous warming thresholds, richer nations will need to cut faster and deeper to offset those that are less developed, or just too impoverished to decarbonize quickly. Arguably, wealthier countries should also help poorer ones reduce emissions, whether that's by providing low-interest capital or subsidized technology, or by developing cheaper clean-energy solutions. If they don't want to do it because it's the right thing to do, then they should do it for the self-interested reason: climate change doesn't recognize borders.

James Temple is MIT Technology Review's senior energy editor.

New economics for climate change

Mariana Mazzucato says we should rethink public innovation policies to transform how we tackle global warming.

By David Rotman
Portrait by David Vintiner

The Green New Deal proposed by Representative Alexandria Ocasio-Cortez and other progressives has dramatically changed the US debate on climate change. It calls for decisive and deliberate public investments to tackle climate change and other social challenges, particularly inequality.

This kind of directed investment is known as "industrial policy," and it has long been controversial among economists. But Mariana Mazzucato, an economist at University College London and founder of its newly created Institute for Innovation and Public Purpose, has thought a lot about the need for such approaches—what she likes to call mission-oriented innovation policies.

Mazzucato, author of *The Entrepreneurial State* and more recently *The Value of Everything*, stresses that public funding has been crucial to key technological advances from the internet to biotech. We sat down with her to ask about the Green New Deal and how industrial policies might be used to take on climate change and other big societal challenges.

Industrial policy often gets a bad name among economists. Why are you so keen on it?
First of all, there are different types of industrial policies. There is the effective and there is the ineffective kind. The problematic industrial policies are ones that are just fueling growth in a limited part of the economy, and it doesn't become a systematic way to transform the economy. I think functional, effective industrial policies are ones that change behaviors across different industries—rather than those that "pick" a couple of industries to subsidize. They are about economic transformation.

Is the Green New Deal an example of industrial policy?
It depends on how it gets interpreted. I was speaking with Alexandria [Ocasio-Cortez] about that back in September.

The Green New Deal will be much more effective if it is economy wide. And that is very much the spirit that [Ocasio-Cortez] and others in the Democratic Party are arguing for. This isn't just about renewable energy. It's about greening the entire economy. A Green New Deal is not just about renewables but also about getting every part of the manufacturing sector to transform itself in a green direction.

Why reference the New Deal pushed by President Roosevelt to get us out of the Great Depression?
There are two bits to the Green New Deal. One is the direction-setting that Roosevelt provided in getting new projects and infrastructure off the ground. This is where it is important to move away from a sectoral approach toward an economy-wide transformation. Another important part regards the word "deal," or a new social contract between government, business, and citizens.

The greater the degree to which the Green New Deal can become a conversation about the direction of investment and innovation, but also the distribution of the rewards from a new public-private partnership, the more interesting it will be. What is the deal we want with these companies? What are the conditions we should be attaching?

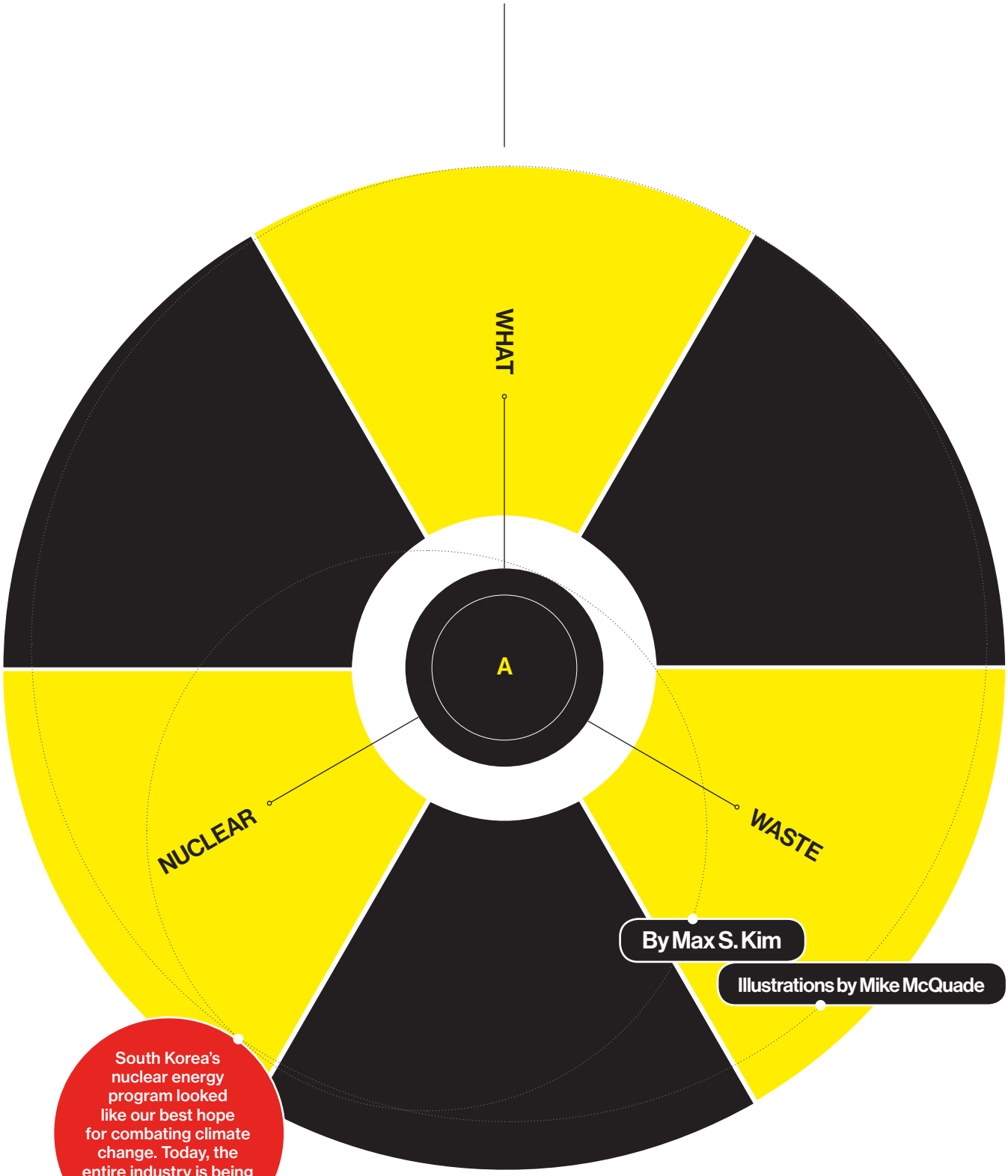
Is it possible to address climate change while also achieving growth?
A Green New Deal should create new opportunities for investment, so that growth and sustainability move hand in hand. Growth has both a rate and a direction, and the GND is about the direction that can get us greener growth and that at the same time unlocks massively hoarded private investments. It should also put more pressure on profits being reinvested back into the economy rather than used for areas like share buybacks.

One of your books, *Rethinking Capitalism*, is critical of how many economists think about solving big problems like climate change. Why?
The mainstream economic framework sees policymaking as just fixing market failures. You're waiting for something to go wrong, and then you bandage it up. But a green transformation needs to be more ambitious. It should be about co-creating, co-sharing markets alongside the private sector.

Steering investment toward public missions can stimulate investment and innovation, but this should be done without micromanaging. Set a direction and then use the full array of government instruments to fuel the bottom-up experimentation and exploration.

And keep focusing on the objective—in this case, reducing emissions.
Yes, keep your eye on the prize.


STATION PLAN
(IN FEET)
NUCLEAR POWER PLANT
SHEET
4 OF
NUCLEAR
UNIT No.1
60
0
30



A NUCLEAR WASTE

South Korea's nuclear energy program looked like our best hope for combating climate change. Today, the entire industry is being dismantled. What went wrong?

By Max S. Kim

Illustrations by Mike McQuade

Three days after a tsunami battered the Fukushima Daiichi nuclear power plant in Japan, South Korean president Lee Myung-bak was celebrating. It was March 14, 2011, and he was in the United Arab Emirates, on a dusty, featureless stretch of desert 30 miles (48 kilometers) from the nearest village. Lee was presiding over a groundbreaking ceremony for a construction project that the two countries said marked the start of a "hundred-year friendship." A retinue of dark-suited South Korean officials and Emirati dignitaries in flowing white thawbs toured the site. Then Lee and the UAE's Crown Prince Mohammed bin Zayed smiled and posed for photographs on a red carpet.

Two years earlier, a South Korean consortium had won an $18.6 billion contract to build four nuclear reactors on the ground where Lee now stood—at the time, the single biggest reactor deal in history. The plant—named Barakah, after the Arabic word for a divine blessing—was a personal triumph for Lee, who had reportedly swung the deal with a desperate 11th-hour phone call to bin Zayed, and a victory for his country, whose Korea Electric Power Corporation, Kepco, had led the bid and won out against more experienced French competition.

It made for a great underdog story. A small, resource-poor nation that relied heavily on imported energy, South Korea had kick-started its nuclear program in the 1970s by buying reactors on turnkey contracts from Canada, France, and the United States. But Kepco and its nuclear affiliate, KHNP, quickly developed their own model based on an American design. The first homegrown reactor was operational by 1995, and more soon followed. Eventually South Korea, which is roughly the size of Indiana, became the most reactor-dense country in the world, with 23 reactors providing about 30% of its total electricity generation. The Emiratis had been impressed.

More was at stake in the UAE than just South Korea's national pride, however. What the country was doing could help solve the climate crisis. While renewable-energy production has grown dramatically, many scientists, engineers, and environmental activists believe a nuclear power system is the only truly scalable alternative to fossil fuels. Yet over the years the high capital costs, uncertain profits, and safety concerns associated with nuclear power have discouraged investors and led governments back to cheaper, dirtier fuel sources like coal and gas.

The French state-owned company Areva, for example, had a project in Finland that was already billions of dollars over budget and years behind schedule. The US's $6.8 billion Watts Bar Unit 1 reactor in Tennessee had taken 23 years to complete, and cost more than 18 times its original $370 million price tag. Areva had bid for the Barakah project, but its $36 billion proposal was reportedly almost twice as high as Kepco's.

South Korea, which is roughly the size of Indiana, eventually became the most reactor-dense country in the world, with 23 reactors providing about 30% of the country's total electricity generation.

The Korean bid rekindled the hope that nuclear could be clean, safe, and cheap enough to replace fossil fuels.

How did Kepco manage it? Lee Hee-yong, a former Kepco executive who had led the bid, told me the key was repetition—building to the same template over and over, rather than designing customized plants each time as was typical. This increased expertise and efficiency, and the result was lower prices. "Prior to the UAE deal, we had been continuously building reactors for the past 30 or 40 years," he told me in the office of his two-person boutique energy consultancy in Seoul. "The fact that we maintained a strong supply chain and network of specialized workers was key to keeping costs low."

The timing of the UAE deal was auspicious: France and Canada were stagnating as civil nuclear powers, says Howard Neilson-Sewell, a Canadian nuclear industry veteran and advisor to the Barakah project. "South Korea was right on the cusp of taking over the world market."

Not anymore. Less than a decade after Barakah broke ground, Korea is dismantling its nuclear industry, shutting down older reactors and scrapping plans for new ones. State energy companies are being shifted toward renewables. Lee's legacy has collapsed, and the hope that Seoul's nuclear program could help combat climate change has dwindled to nothing.

So what went wrong? Critics blame politics, ideology, and environmental idealism. The reality: greed, corruption, and scandal. It's a reminder that the grandest plans for fighting climate change can fall prey to simple human venality.

DISASTER STRIKES

"Watching Fukushima was a tremendous shock, especially because I live next to a nuclear power plant myself," Kim Ik-joong told me when we met earlier this year at a coffee shop close to the headquarters of one of Seoul's most renowned civic-rights groups. Activists of various stripes were gathered around us, talking animatedly, and some came over to greet him: Kim, 59, is one of the country's best-known antinuclear campaigners. Charismatic and well-spoken, he was originally a microbiology professor at Dongguk University but has become the face of the antinuclear movement as a prolific lecturer and pundit on the evening news.

Up until the Fukushima disaster, that movement had been limited to a scattered assortment of local groups. The crisis in Japan brought things closer to home. It "just didn't feel like someone else's business," says Kim.

Kim himself grew particularly uneasy about the overcrowding of South Korea's reactors, which are mostly packed into a narrow strip along the densely populated southeastern coast. The density was a way of cutting costs on administration and land acquisition. But putting reactors close to one another—and to large cities—was risky.

"An accident at just one of these plants would be far more devastating than Fukushima," says Kim. "These reactors are dangerously close to major industrial areas, and there are four million people living within a 30-kilometer radius of the Kori plant alone." Hyundai's auto plant in Ulsan, a city of 1.2 million, is just 20 km from the nearest nuclear power plant. Fukushima, by comparison, had only around 78,000 people living within the same distance.

Kim's cause found political support. In 2012, Moon Jae-in, who was running for president, personally recruited him to his energy policy team. Moon had recently announced a nuclear phase-out as a campaign pledge. Kim felt an affinity to Moon: both of their hometowns stood in the shadow of a nuclear power plant.

"He had done a lot of research on the issue himself, and already had very firm personal convictions about exiting nuclear," Kim says with a smile. "Back then, there were still a lot of people in [Moon's] Democratic Party who were against a nuclear-exit policy, so Moon made the announcement in Japan, away from anybody who would try to dissuade him."

However, Moon lost the 2012 election to Park Geun-hye, the conservative successor to Lee Myung-bak. (South Korean presidents can serve only a single term.) Park continued Lee's nuclear expansion policy, pledging to increase South Korea's reactor fleet to 39 units by 2035 and making sales trips to potential client states such as the Czech Republic and Saudi Arabia.

But rumors started swirling that the UAE deal had come with a number of compromising provisions. The most serious allegation was that Lee had secured the project by secretly promising armed support to Abu Dhabi in the event of a military conflict. In 2011, South Korea did begin deploying special forces to the UAE, but Lee denied any connection.

It was a sign that South Korea's nuclear success might not just be a simple story of efficiency and expertise.

A SHOCKING DISCOVERY

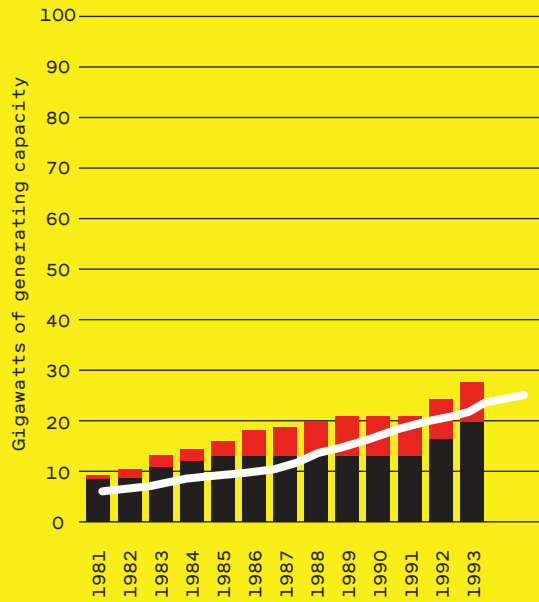
On September 21, 2012, officials at KHNP had received an outside tip about illegal activity among the company's parts suppliers. By the time President Park had taken office, an internal probe had become a full-blown criminal investigation. Prosecutors discovered that thousands of counterfeit parts had made their way into nuclear reactors across the country, backed up with forged safety documents. KHNP insisted the reactors were still safe, but the question remained: was corner-cutting the real reason they were so cheap?

Park Jong-woon, a former manager who worked on reactors at Kepco and KHNP until the early 2000s, believed so. He had seen that taking shortcuts was precisely how South Korea's headline reactor, the APR1400, had been built.

After the Chernobyl disaster in 1986, most reactor builders had tacked on a slew of new safety features.

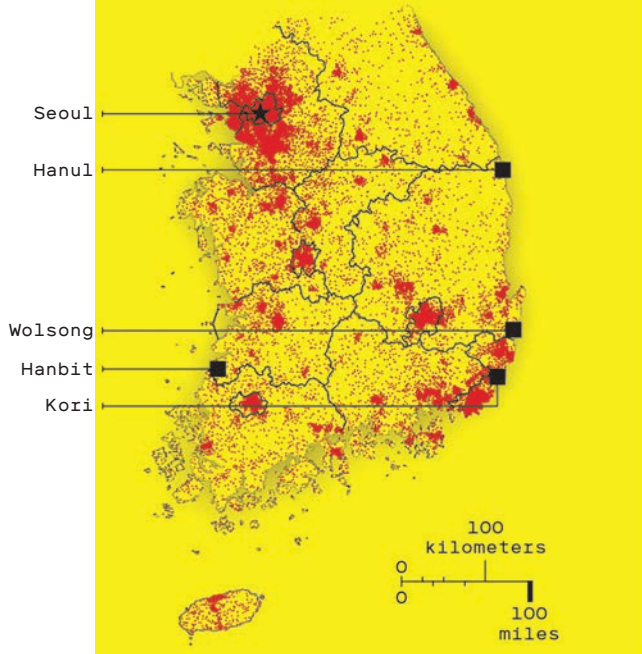
Slow and steady

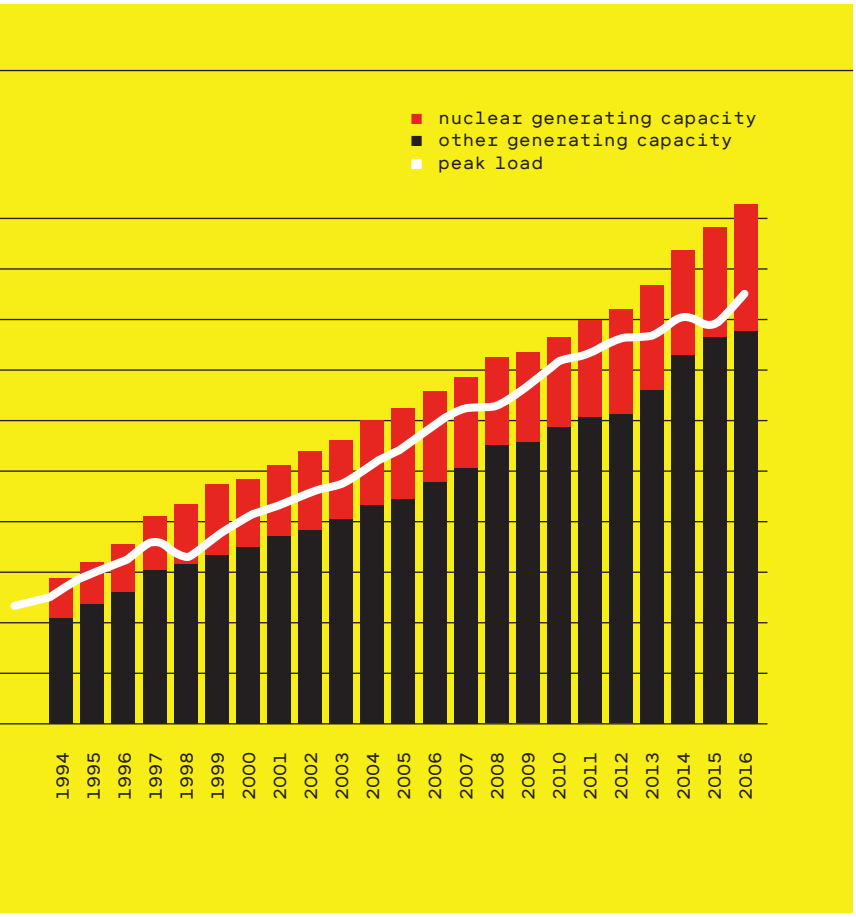
Since the 1980s, South Korea has been reliant on the continuous expansion of nuclear to meet its energy needs.



Where they're located

Most of South Korea's nuclear reactors are clustered in its densely populated southeast.





SOURCES: KOREA ENERGY ECONOMICS INSTITUTE, WORLD NUCLEAR ASSOCIATION

"An accident at just one of these plants would be far more devastating than Fukushima," says Kim. "These reactors are dangerously close to major industrial areas, and there are four million people living within a 30-kilometer radius of the Kori plant alone."

KHNP followed suit but later realized that the astronomical cost of these features would make the APR1400 much too expensive to attract foreign clients.

"They eventually removed most of them," says Park, who now teaches nuclear engineering at Dongguk University. "Only about 10% to 20% of the original safety additions were kept."

Most significant was the decision to abandon adding an extra wall in the reactor containment building—a feature designed to increase protection against radiation in the event of an accident. "They packaged the APR1400 as 'new' and safer, but the so-called optimization was essentially a regression to older standards," says Park. "Because there were so few design changes compared to previous models, [KHNP] was able to build so many of them so quickly."

Having shed most of the costly additional safety features, Kepco was able to dramatically undercut its competition in the UAE bid, a strategy that hadn't gone unnoticed. After losing Barakah to Kepco, Areva CEO Anne Lauvergeon likened the Korean unit to a car without airbags and seat belts. When I told Park this, he snorted in agreement. "Objectively speaking, if it's twice as expensive, it's going to be about twice as safe," he said. At the time, however, Lauvergeon's comments were dismissed as sour words from a struggling rival.

By the time it was completed in 2014, the KHNP inquiry had escalated into a far-reaching investigation of graft, collusion, and warranty forgery; in total, 68 people were sentenced and the courts dispensed a cumulative 253 years of jail time. Guilty parties included KHNP president Kim Jong-shin, a Kepco lifer, and President Lee Myung-bak's close aide Park Young-joon, whom Kim had bribed in exchange for "favorable treatment" from the government.

Several faulty parts had also found their way into the UAE plants, angering Emirati officials. "It's still creating a problem to this day," Neilson-Sewell, the Canadian advisor to Barakah, told me. "They lost complete faith in the Korean supply chain."

The scandals, however, were not over.

ANOTHER WHISTLEBLOWER

Earlier this year, at a small bakery in Seoul, I met Kim Min-kyu. A slight 44-year-old man with earnest, youthful eyes, Kim used to be a senior sales manager at Hyosung Heavy Industries, a manufacturer of reactor parts. In 2010, he was put in charge of selling to KHNP and

quickly discovered that double-dealing was as routine as paperwork.

"Suppliers who were supposed to be competing with one another colluded to decide who would win [KHNP bids]," Kim told me. "You'd have a group of white-haired executives from competing firms sitting across from each other, playing rock-paper-scissors to decide who would take certain contracts." Dummy bids would then be supported by fake documents, doctored to ensure that the designated loser would fail. On one occasion, he says, an irate KHNP procurement manager called him to point out an amateurish forgery in a fake bidding document—and demanded he do it again, properly.

Some of these practices constituted serious lapses in safety. In May 2014, Kim oversaw the delivery of 11 load center transformers bound for the Hanul Nuclear Power Plant in North Gyeongsang province, only to discover that their safety licenses hadn't been renewed. Load center transformers manage the flow of power to key emergency functions at reactors; any malfunction, Kim told me, would be "like a hurtling car suddenly stalling."

Yet a secret agreement between Hyosung and competitors had designated it the winner, and the transformers were installed into two reactors, their integrity unquestioned. "I personally knew of around 300 cases where those transformers caught on fire. They're incredibly unstable," says Kim, his brow furrowed. "My hometown is actually just a few kilometers from those reactors, and an accident there could endanger my relatives who live nearby."

In 2015, fearing a Fukushima-like accident, Kim decided to report the corruption through his company's internal whistleblowing system. The only result was that he was fired.

"How naïve I was," he says, flashing a rueful grin. He eventually went to the country's competition regulator, which referred the case to prosecutors. In 2018, he took his story to the media. A few months later, on the basis of tips from Kim, prosecutors charged six employees from Hyosung and co-conspirator LS Industrial Systems with collusion—an outcome that Kim believes only scratches the surface of the corruption.

More untruths soon came to light. In 2018, after years of government denial, former defense minister Kim Tae-young admitted that the rumors about the military side agreement with the UAE were, in fact, true: he had overseen it himself in a desperate attempt to seal the Barakah deal. "There was low risk of a dangerous situation arising, and even if it did, we believed that our response could be flexible," he told South Korean media. "In the event of an actual conflict, I figured that we would ask for parliamentary ratification then."

Balance of power

2017

SOURCE: INTERNATIONAL ATOMIC ENERGY AGENCY

MOON RISING

In September 2016, a magnitude 5.8 earthquake—the strongest recorded tremor in South Korea's history—struck the southeastern city of Gyeongju. Kim Ik-joong, the antinuclear activist, lives in the city and remembers being shocked by the rattling windows and blaring emergency sirens. He fled to a nearby rice paddy, and when he returned home several hours later, a sinking anxiety set in. Gyeongju was the heart of the world's largest cluster of nuclear reactors, with its own plant and two more in adjoining Busan and Ulsan. The quake confirmed Kim's fears: the seismic faults underneath the reactors were more earthquake-prone than previously thought. The next morning, on a visit to the nearby Wolsong plant, officials assured Kim and his politician friend Moon Jae-in that no damage had been done, but Kim couldn't shake the feeling that the problem was being ignored.

"When I first started campaigning against nuclear power, KHNP managers told me that an earthquake greater than a magnitude of 5.0 would never happen in South Korea," he says. "But there it was." Several days after his visit to the Wolsong plant, Kim discovered that one of the plant's seismographs had been broken for years.

Though South Korean law requires seismic fault assessments of any potential reactor site prior to construction, Kim says that the statute's vague wording and

President Moon Jae-in's critics have denounced the nuclear phase-out as ideological. But more and more South Koreans have developed a mistrust of what they call "the nuclear mafia."

loose enforcement have rendered it ineffective. "South Korea still hasn't done a comprehensive capable fault assessment," says Kim. "Earthquake risk wasn't sufficiently accounted for at all in reactor site selection." In fact, South Korea's first comprehensive fault map was only started in 2017 and is expected to take until 2041 to complete.

The corruption scandal and earthquake stoked public appetite for Moon Jae-in's policy of nuclear exit. But the coup de grâce was delivered by the failings of the industry's political champions themselves.

Park Geun-hye's presidency fell apart in 2017 as a much larger corruption scandal was uncovered. Accused of receiving bribes from the nation's top conglomerates and abusing her presidential power, she was impeached on March 10, 2017, and sentenced to 24 years in prison in April 2018. Lee Myung-bak met a similar fate just months later: found guilty of bribery and embezzlement, he was sentenced to 15 years in prison.

Moon took office shortly after Park's impeachment, and he has held fast to his promise of a nuclear exit.

"The current phase-out policy stemmed from the four foundational principles we proposed at the time [of the 2012 campaign]," says Kim Ik-joong. "Older reactors wouldn't receive life-span extensions; no additional reactors would be built; electricity use would be made more efficient; and we would shift toward renewables."

The phase-out will take 60 years. Two new reactors that were already halfway completed when Moon took office are still scheduled to come online by 2022 and 2023, and those in operation now will live out their lifetimes. Meanwhile, the administration continues to court potential buyers like the Czech Republic and Saudi Arabia. But there has been no boom: in fact, while Lee promised to export 80 reactors, so far South Korea has yet to export a single one.

Moon's critics, many of them still adherents of the disgraced presidents Lee and Park, have denounced the phase-out as "ideological"—a deliberate reversal of his predecessors' accomplishments for political purposes. Yet the country's shrinking appetite for nuclear suggests a deeper disillusionment.

"On principle, I don't trust anything that KHNP built," says Kim Min-kyu, the corruption whistleblower. More and more South Koreans have developed a general mistrust of what they refer to as "the nuclear mafia"—the close-knit pro-nuclear complex spanning KHNP, academia, government, and monied interests. Meanwhile the government watchdog, the Nuclear Safety and Security Commission, has been accused of revolving-door appointments, back-scratching, and a disregard for the safety regulations it is meant to enforce.

A decade after it began, Lee Myung-bak's dream of South Korean nuclear ascendency seems to have finally sputtered out. A similar reversal is beginning in China, until recently seen as nuclear energy's biggest champion. There, as in South Korea, Fukushima awakened public fears and forced the government to adopt tougher safety standards, which now threaten to push the cost of nuclear power out of reach. Of the world's other major producers of nuclear power, only Russia is still aggressively building more reactors both at home and abroad. The decline of Korea's nuclear industry may have had prosaic domestic causes, but its effect on the fight against climate change may be very global indeed.

Max S. Kim is a freelance writer based in Seoul.

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Adaptation

2

"There are six levels of bushfire exposure, from Low to Flame Zone. The second highest category means a steel-clad exterior and roof, a completely enclosed subfloor area, and bushfire-tested windows, doors, and skylights. A Flame Zone house was recently costed at $213,000 just for the windows." — Bianca Nogrady on living with fire, page 50

The threat to the world's breadbasket

So far, the US corn belt has avoided the ravages of climate change. But that is going to change over the next few decades.

By Adam Piore

Photographs by Kathryn Gamble

CHRISTIE HEMM KLOK

It's a bitter cold March morning in Ames, Iowa,

and the sprawling cornfields outside of town are buried beneath a couple of inches of ice and snow. But it's hot and humid inside the custom-built grow chambers on the campus of Iowa State University.

Blindingly bright lights beat down on a trio of squares, each containing close to 7,000 pounds (3,175 kilograms) of soil, sunk five feet (1.5 meters) into the floor. The steady churning of fans, ensuring air circulation and uniform temperatures throughout the room, echoes off the walls. Every few inches, a suite of infrared thermometers and moisture sensors track the microclimates surrounding the leaves of the plants.

Inside these growth chambers, it's the future. And Jerry Hatfield, an affable agronomist who heads the US Department of Agriculture's National Laboratory for Agriculture and the Environment, doesn't like what he sees.

Three years ago, Hatfield used the growth chambers to find out how local crops would perform under the temperatures predicted for the region in 2100, which are expected to rise roughly 4 °C on average, or about 7.2 °F. He simulated a growing season, from April 1 through October 30, for three different strains of corn used by farmers in the area. In one chamber, Hatfield started the temperature at just around 50 °F (10 °C) to mimic conditions in early April, raised it well above 100 °F (38 °C) to simulate the

hot summer days (as high as 114 °F in the chamber with 2100 conditions), and then brought it back down again for autumn. In a second chamber, he simulated the region's current, cooler climate norms.

The differences between the plants in the two chambers were stark. While the leaves looked the same, the impact of that extra 7.2 °F was far worse than projected by even the most pessimistic scientific literature. The number of corn kernels per plant plummeted, in some cases by 84%. Some plants produced no kernels at all.

Inside growth chambers like this one, plants will be grown under simulated conditions.

"Either we're going to change the crops that we produce or we're going to have to think about how we genetically manipulate that plant to have a higher tolerance to higher temperature."

It was just the first in a series of alarming results. In the months that followed, Hatfield and his colleagues simulated the rising temperatures and altered rainfall patterns expected to hit the wheat fields of Salina, Kansas, as soon as 2050. Yields fell as much as 30% with low precipitation and as much as 70% with the combination of high temperatures and low precipitation expected in the decades ahead.

To date, it's been relatively easy for American farmers to shrug off climate change. After all, under the most optimistic models, projected US yields for corn and soybeans—which are grown on 75% of the arable land in the Midwest—are actually expected to increase through 2050, thanks to warmer weather that will benefit the relatively cool northern climes. But after that, if Hatfield is right, yields will fall off a cliff, devastating farmers and leaving much of the world hungrier.

By 2050, the world's population is expected to grow to 9.7 billion. As living standards and diets also improve around the world, food production will have to increase by 50% at a time when climate change will help make both sub-Saharan African and East Asia unable to meet their own needs without imports. Already US corn and soybeans account for 17% of the world's caloric output. The UN Food and Agriculture Organization projects that American exports of corn must almost triple by 2050 to meet the shortfall, while US soy exports would have to rise by more than 50%. All this extra food has to be grown without using significantly more land. That means it's going to be all about yield—the productivity of the crop.

And that is what has Hatfield so worried. A growing body of scientific literature suggests that climate change is likely to decimate yields unless we can find new ways to help plants cope with the droughts, vast temperature fluctuations, and other extreme weather that's likely to become commonplace in the decades ahead.

"If something isn't done, we will see major drops in production across large areas of the corn belt and Great Plains," Hatfield says. "Either we're going to change the crops that we produce or we're going to have to think about how we genetically manipulate that plant to have a higher tolerance to higher temperature."

THE END OF GOLDILOCKS

There is, of course, a familiar ring to the dire predictions. World leaders in the early 1970s were so worried that rising populations, increasing pollution, and soaring food prices would create an acute food crisis by the dawn of the 21st century that the UN convened a conference in Rome. "Time is short," the member states declared after the conference, in 1975. "Urgent and sustained action is vital."

In the years that followed, however, high-yield crops, a wider use of irrigation, farm mechanization, and the introduction of synthetic fertilizers and pesticides led to a "Green Revolution," dramatically increasing agricultural production in many places around the globe.

Now the pace of growth has begun to slow. Water is short in many areas, limiting further expansion of irrigation. And it's hard to imagine using even more fertilizers and pesticides. "It's already an open question whether we will be able to keep inventing these new technologies and management practices that allow productivity to more than keep up with demand," says Marshall Burke, a Stanford economist who focuses on climate change. "But climate is for sure going to make that a lot harder."

What's more, global warming is already making its effects felt. In 2011, Columbia University economist Wolfram Schlenker and Stanford ecologist David Lobell looked at what happened to crop yields as temperatures rose between 1980 and 2008. They found that global maize production

(excluding the US) fell 3.8% and wheat production dropped 5.5% relative to what it would otherwise have been. The increase in hot days and nights explains about half of all variation in corn yield. Higher temperatures help up to a point, between roughly 50 °F and 84 °F, but hotter than that and yields plummet.

To get a sense of what this all might do to global food prices, Schlenker suggests looking at what happened in 2012, the last time the American Midwest experienced a summer with temperatures comparable to what climatologists project will become the norm by the end of the century. The region's production of corn fell by 25% and soybeans by 10%. That constitutes about a 4% to 5% drop in total global caloric production—conditions under which we can expect food prices to spike by as much as 30%, he says.

Despite a few such bad years, however, Midwest farmers have enjoyed a decades-long rise in productivity, masking the worries about the future. There is a "Goldilocks" zone for temperature, humidity, and rainfall, and climate change has, for the most part, pushed the middle of the United States further into it, says Gene Takle, former longtime director of Iowa State's climate science program. The largest change in Iowa to date has been increased rainfall in April, May, and June—it's up by almost 25% over the last three decades. This extra rain, caused by the interaction of wind patterns with warming waters in the Gulf of Mexico, has forced farmers to spend more money on drainage tiles and the like to adapt, and it has shifted the planting season. But the combined result of technological advances and more favorable climate is that yields have risen 28% across the Midwest. "There's pretty good agreement that climate change has been favorable to agriculture to this point," Takle says.

Plants in the chamber will be closely monitored by a suite of sensors.

The USDA scientists measure how each plant does under the varied conditions.

These trends will reverse, though; where the experts disagree is on precisely when. Takle cites one model showing that the positive trend in productivity will turn around by 2035, undoing all the gains seen since 1981. And yields will only continue to fall from there. "We're on the cusp right now," he says.

On a recent day, he pushed a piece of paper across a table. It was full of colorful charts and bullet points, detailing the impact of climate change to date on local agriculture, with the positives spelled out in green and the negatives in red. Among the red points: more pests were surviving the winter, and waterlogged soil reduced the number of days farmers could work the fields. (In 2013, northwest Iowa had 700,000 acres—283,000 hectares—that couldn't be planted for that reason.) But there was plenty of green, too.

Then he turned the page to show how things would look in 2050. There was no green on this page—only a long list of red. Intense spring rains will make field work early in the season harder, Takle expects. There will be more flooding; the warmest day will be 7 °F hotter. Every other year will see at least one five-day period when extreme heat will cause corn and soybean pollination to fail and vegetative growth to stall.

"We have a lot of problems coming down the pike," he says.

NEW GENETICS

The job of Hatfield, the USDA agronomist, is to monitor the impact of environmental conditions on the country's farmers and identify potential solutions. Sitting in his office on a recent day, he ticked off a long list of worries. The brown marmorated stink bug appeared in the US in the late 1990s, and as temperatures rise over the next 30 years, its range will expand all the way up to Canada, damaging a wide array of crops. The Palmer amaranth, an herbicide-resistant weed that lives in particular microclimates and has so far threatened mainly soybean and cotton crops in the South, will likewise spread northward and become ubiquitous.

Then there's the increasing soil salinity in North and South Dakota, which could take significant tracts of land out of rotation in less than a decade if current trends continue unabated. The problem is that thanks to the changing climate and changing financial incentives, farmers in the Dakotas who have traditionally grown wheat, sugar beets, hay, and canola in rotation are increasingly switching to corn and soybeans. But the new crops are poorly suited to the wet early springs of the Dakotas, allowing the water table to rise and evaporate, leaving behind salt that damages the soil.

The biggest worry is what climate change will do to crop yields in America's breadbasket in the decades ahead. Hatfield has become convinced that no policy fix or change in management practices alone will be enough to overcome the natural limits of plants and the coming extremes of weather. Which is why he has decided to turn to advanced genetics.

In the coming months, Hatfield plans to repeat his experiment simulating future growing seasons. But this time he will examine precisely how the conditions affect which genes are turned on and off in corn and wheat. The hope is to identify ways to control these molecular-level switches to help the plants adjust to the conditions they will face.

It's early days for the work on corn, wheat, and soybeans. But in other crops, breeders have identified adaptations and harnessed them to solve challenges posed by climate change. Some of the most successful have been seen in the rice-growing areas of the world.

Rice can tolerate a certain degree of flooding—can actually benefit, because the flooding can kill weeds. As long as the rice stalks are partly above water, the plants can absorb the air they need. But if the tops of the plants are submerged, they can suffocate.

In 2006, researchers cloned a gene called *Sub1* in a local South Asian rice strain. The gene confers "submergence tolerance" on rice. When the plant is underwater, the gene is turned on and puts the plant into suspended animation. The gene turns off as soon as the top of the rice shoot is back above water. Unlike some traits that increase stress tolerance, the *Sub1* gene does not seem to significantly reduce yields when there are no floods—and when there are, the plant resumes growing with extra vigor afterwards, says Susan McCouch, a professor of plant breeding and genetics at Cornell University.

In 2009, the International Rice Research Institute engineered the trait into eight varieties of rice and began to distribute them to farmers. It is now used by 10 million farmers, on about 10 million hectares of land.

"You want to eat in the future? That's what's at stake. But we're going to have to figure it out, because we have no other choice."

WANT TO EAT?

Though nothing comparable to the water resistance in rice has yet been found for corn, commercial seed companies have been breeding drought-resistant strains for more than a decade. Robert Reiter, head of R&D for Bayer's crop science division, explains how the company searches for resilient breeds. First, it digitizes DNA sequence information and catalogues known traits for several million lines of plants. Using the data, it then trains machine-learning algorithms to screen millions of other strains for useful traits.

For instance, Bayer has bred traits picked up from heat-tolerant and drought-resistant strains in Mexico into high-yielding strains adapted to the US market. Reiter says that during a 2012 drought in the US Midwest, yields were more than double what they were in 1988, the last time a drought of comparable severity struck.

But the approach has its limits. "Plants can only tolerate a certain level of stress, and timing is a big factor," he says. "If you have extremely high temperatures during the process of flowering, you will see some impact on the yield … What we can do is just try to minimize the impact."

Hatfield hopes to overcome some of these limitations by simulating future growing conditions. Such simulations, he hopes, could help identify unknown genetic pathways that plants might use to adapt to future changes in weather and growing conditions.

It's a complex puzzle that we've only begun to work on. And Hatfield notes that it's difficult to account for the combination of factors Midwestern farmers are likely to face, including changing precipitation patterns, extreme heat, dramatic swings in weather, a whole host of new pests, and perhaps challenges we have not yet even anticipated. But he's clear about why he's doing it.

"You want to eat in the future?" he says. "That's what's at stake. But we're going to have to figure it out, because we have no other choice."

Adam Piore is a freelance journalist.

The "mind-boggling" problem of keeping New York dry

Climate change threatens the city's 520 miles of shoreline, but the political hurdles are just as daunting.

By Courtney Humphries

Until a few years ago, Hunter's Point South Waterfront Park in Long Island City, Queens, was an industrial landfill. Now it's a modern-day version of the marshes that once flanked the East River, with a running path that zigzags along the water's edge atop a grassy berm, and an inlet filled with marsh grasses to let water flow in and out with the tides.

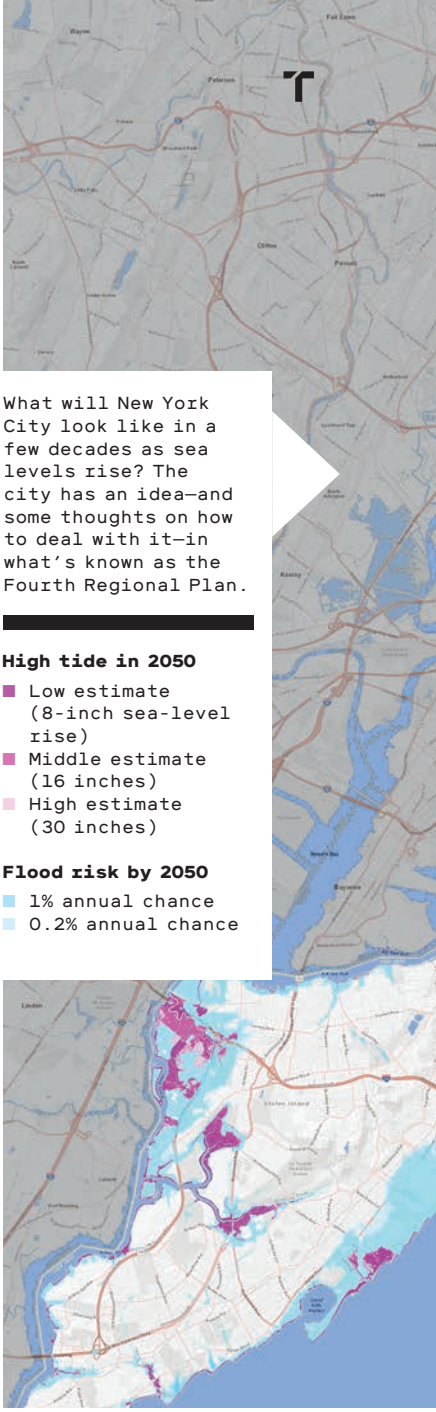
The park, completed in 2017, is also a fortification. The marshland is designed to absorb flooding from storms and sea-level rise, while hills, berms, and concrete walls block or redirect floodwaters to protect the neighborhood.

Nearly seven years ago, the swollen river flooded Long Island City during Superstorm Sandy, pouring through streets and damaging cars and basements. (It also killed more than 40 people across New York City.) But that hasn't turned people away from the water.

As the climate warms, the city will have to reconfigure much of its urban fabric, particularly the 520 miles (837 kilometers) of shoreline. "It's a mind-boggling scale," says Ellis Calvin, a planner and data research manager at the independent nonprofit Regional Plan Association (RPA), as we stand at the water's edge. By the middle of the century, the New York City Panel on Climate Change estimates, temperatures in the city could be hotter on average by 4 to 6 °F (about 2 to 3 °C), with several heat waves per summer. Sea levels could rise 11 to 21 inches (28 to 53 centimeters) by the 2050s and up to six feet (1.8 meters) by 2100—doubling the size and population of the 100-year-flood zone, the area that has a 1% annual chance of flooding. The borough with the most land affected by all this will be Queens.

New York is ahead of many coastal cities in plans for adapting to climate change. But according to the RPA, an analysis of state disaster resiliency plans in New York, New Jersey, and Connecticut by Harvard architecture professor Jesse Keenan suggests that more than $27 billion of planned investments to recover from Sandy have not been made.

Climate resilience is expensive and onerous. Seven projects in the region got federal funding in a post-Sandy design competition called Rebuild by Design, but several years later, not one has broken ground. Last fall, the city abruptly changed plans for the first phase of the "Big U," a project that would create and connect 10 miles of parks, barriers, and flood walls around the low-lying area from East 57th Street down to the Battery and up West 42nd Street. The city eschewed an innovative approach that would allow a newly redesigned East River Park to partially flood during storms, deciding to spend more money to raise the park 8 to 10 feet, adding fill that may cover natural habitats. Amy Chester, managing director of Rebuild by Design, says that when cities move from concepts to implementation, "a lot of the innovation falls to the side."



What will New York City look like in a few decades as sea levels rise? The city has an idea—and some thoughts on how to deal with it—in what's known as the Fourth Regional Plan.

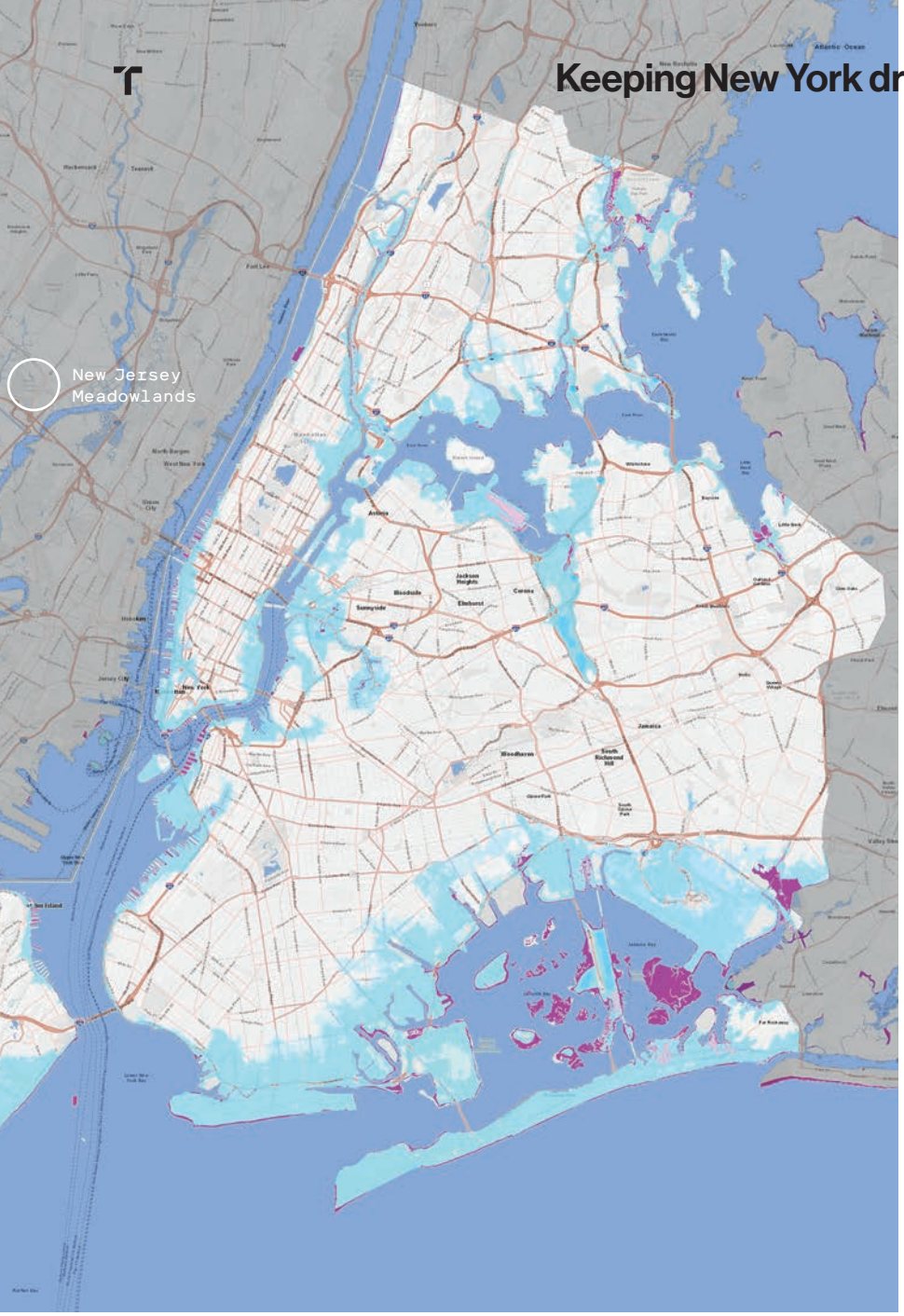
High tide in 2050
- Low estimate (8-inch sea-level rise)
- Middle estimate (16 inches)
- High estimate (30 inches)

Flood risk by 2050
- 1% annual chance
- 0.2% annual chance

SOURCE: NEW YORK CITY DEPARTMENT OF CITY PLANNING; REGIONAL PLAN ASSOCIATION

More than 2 million people will be living in areas vulnerable to flooding.

The plan calls for housing buyouts in flood-prone communities like Jamaica Bay, Long Island's south shore, and the Jersey Shore. It recommends banning new development in these areas immediately, and redirecting funds meant for upkeep toward housing buyouts.



national wetlands park that grows over time as sea levels rise.

More than 60% of the city's power comes from plants that will be at high risk of flooding.

The plan calls for existing power plants to be upgraded, replaced, preserved, or relocated on a case-by-case basis. It suggests flood-proofing facilities when possible by elevating them. It recommends that power plants form a network in case any are knocked out of commission during a severe storm, and calls for increased capacity to cope with the higher demand that will be likely during hot spells.

Subways, railroads, highways, and airports will flood frequently.

Teterboro Airport in Hackensack, New Jersey, handles much of the freight bound for New York City—and it could be under a foot of seawater by midcentury. The plan calls for it to be phased out. Newark and JFK airports should be expanded, the plan says, to handle the extra capacity. Subway systems will become dangerous, given the likelihood of flooding and power outages. The plan recommends creating a government body to modernize the entire subway system—with funding coming from fees on motorists entering the city, among other sources.

40% of all water treatment plants will be at a high risk of contamination or running dry.

The plan calls for creating a network of water supply systems between Long Island, New York, and New Jersey, affording flexibility in case any one water source is contaminated or destroyed by a storm. The plan suggests this could be paid for by utilities.

New Jersey's Meadowlands will be underwater.

The Meadowlands—20,000 acres just five miles outside New York City—is home to essential infrastructure like warehouses, commuter and freight rail, and roads into the city. The regional plan calls for phasing out every bit of this infrastructure over time, ceding the land to the water, and making the Meadowlands a

ALREADY HOT, AND GETTING HOTTER

Near the equator, climate change is no mere theory—it's already disrupting lives and economies. In the following pages we investigate how people in low latitudes are working to stave off the worst—or at least adjust to the new realities.

Yucatán Peninsula

MEXICO

HOW TO SURVIVE A SEAWEED PLAGUE

Climate change brought an infestation of seaweed to Mexico's Caribbean coast. Now researchers are scrambling to stop an ecological crisis.

By LAUREN ZANOLLI

The posh seaside resorts of Puerto Morelos are still in view when the captain playfully sounds the horn to alert the crew to the target ahead—a huge, golden-brown stain stretching toward the horizon. Suddenly, instead of the famed cerulean waters of Mexico's Caribbean coast, we're surrounded by thick mats of seaweed, a sulfurous tinge in the air.

This is exactly where the crew of a specialized *Sargassum* collection boat wants to be. The boat belongs to Grupo Dakatso, a consortium of five companies working on new seaweed collection technology. The small catamaran has a specialized conveyor belt positioned at the bow that draws piles of seaweed from the water into large mesh collection bags. All the crew can manage above the roar of the engine are whistles and hand signals as the bags, each holding 300 kilograms (660 pounds), are filled within a minute or two.

Since the spring of 2018, Mexico's Caribbean coast and the shorelines of 19 other countries in the region have been inundated with unprecedented amounts of *Sargassum* seaweed. Tourists expecting pristine white beaches have instead been confronted with endless piles of slimy, decaying vegetation. While it's normal for the brown macroalgae to appear on Caribbean shorelines in smaller amounts, outlier blooms have been increasing in size and regularity over the past 10 years. The one that occurred last year is believed to be the worst ever in the

THIS PAGE AND PREVIOUS SPREAD: TITO HERRERA

region. Now efforts are mounting not just to contain the ecological crisis but to capitalize on it.

Usually *Sargassum* arrives in the Caribbean from its namesake sea in the eastern Atlantic. But researchers believe the 2018 influx came from a new source: the equatorial waters between Brazil and West Africa, where pesticide and fertilizer runoff from the Amazon and Congo Rivers fed the algae bloom. This bloom was amplified by climate change, says Brigitta van Tussenbroek, an ecologist at the National Autonomous University of Mexico in Puerto Morelos: rising ocean temperatures help the seaweed proliferate faster. Deforestation in the Amazon rain forest also feeds the bloom—not only does it increase the pesticide and fertilizer runoff, but it is itself a massive contributor to climate change.

"We, us humans, are to blame for the *Sargassum* problem," says Dagoberto Ruiz Lavín, general director of Grupo Dakatso, which local hotels and the government had contracted to clear away the seaweed. "The future generations are going to have it much worse if we don't do anything," he says. "The *Sargassum* is not going to stop coming."

In ordinary conditions, *Sargassum* is a normal, even healthy, part of the ocean. But in vast quantities, the seaweed brings a litany of harms to coastal ecosystems. Mats of it block much-needed sunlight from coral reefs, causing disease or death. As the seaweed dies and decays, bacteria suck up oxygen in the water while nitrogen, phosphorus, and other nutrients are released in massive quantities. If the seaweed is left to rot on land, as it is on Mexico's beaches, the same nutrients threaten to leach into groundwater. In the Yucatán Peninsula, where the only source of fresh water is a unique regional network of underground rivers, water contamination is a serious worry. And while seaweed can draw carbon dioxide from the atmosphere, just as trees do, it's beneficial for the environment only if the seaweed is harvested and processed, and the resulting CO_2 is stored away permanently (see "How to cool an ocean," page 56).

Van Tussenbroek says the cumulative effects of *Sargassum* overgrowth are enough to disrupt the equilibrium of an ecosystem. As one example, *Sargassum* kills the seagrasses that help keep sand in place, so beaches erode faster. She estimates that after the 2018 crisis, the local ecosystem might be able to reset itself in anywhere from 10 to 50 years, but if there's another large, unmitigated influx or a major hurricane, changes could be permanent.

To date, Mexico's official response to the *Sargassum* crisis has been limited to marine barriers—similar to those used in oil spills—and beach clean-up crews armed with rakes and wheelbarrows. It's a Sisyphean task: once the beach is clean, the next tide of seaweed is never far behind.

José Ángel Durán Désiga, a weary-eyed but surprisingly young municipal bureaucrat, explains the limitations of the government's response from his office near the beach in Playa del Carmen. As director of the Office of Environment and Climate Change in the municipality of Solidaridad, Durán Désiga is at the forefront of the *Sargassum* challenge. But under Mexico's centralized government system, he says, local officials lack the resources or authority to do much about it.

"The coast will continue to exist, but it will be in a different ecosystem," Durán Désiga says. "It might be without the reefs. There might be more and different kinds of fish. It will be more complicated for tourists to enjoy the water."

David Valero, a PhD researcher at the Yucatán Center for Scientific Research, is working on a process to convert seaweed into biogas that can be used for electricity generation.

"The future generations are going to have it much worse if we don't do anything. The *Sargassum* is not going to stop coming."

Even if seaweed collection could be vastly scaled up, one big question remains: what to do with it all?

Seaweed is already used widely in cosmetics and food additives. Energy companies like ExxonMobil have invested in research on microalgae—a type of microscopic organism that sometimes causes red and brown tides—with the idea of creating a low-emissions transportation fuel by extracting oil from it. Seaweed, a macroalgae, hasn't drawn the same kind of attention as a biofuel source, in part because seaweed can be difficult to farm on a mass scale. Seaweed has been tested as a feedstock for biogas via a process called anaerobic digestion, which involves placing it in a tank, letting it decompose, and then capturing the resulting gases, like methane, which can be used for energy. But seaweed is rich in a polymer called lignin that must be broken down in order to create methane. Now, Mexican researchers are searching for ways to get around that problem.

At the Yucatán Center for Scientific Research, a complex of government-funded labs set amid a lush jungle on the outskirts of Mérida, the Yucatán state capital, the smell of *Sargassum* is in the air. David Valero, a PhD researcher specializing in anaerobic digestion, is part of a team working to design a seaweed-to-biogas process that is more efficient and can handle seaweed directly from the beach or sea with minimal need for processing to remove sand or plastic.

Valero and his colleagues have been working both to speed up the seaweed breakdown process—by pre-treating the *Sargassum* with a local fungus—and to increase the efficiency of the bioreactor using activated carbon. He says they are close to commercializing their technology, which creates biogas that can be used directly

for electricity generation. He estimates that each ton of *Sargassum* can produce the equivalent of 720 kilowatt-hours of energy or 63,600 liters (16,800 gallons) of natural gas.

One lab over, biologist Francisco Larqué Saavedra has other plans for *Sargassum*. Long interested in sustainable food production, he's built a bank of native mushroom species over the past 30 years. In 2018, he started looking for a strain that could grow in seaweed. His team grew mushrooms in plastic bags stuffed with *Sargassum* that was pasteurized and processed beforehand, yielding about 800 kilograms of edible mushrooms for every metric ton of dried seaweed. Larqué Saavedra hopes to persuade hotel owners to start mushroom farms on-site, to make use of the seaweed piling up at their door and generate both food and jobs.

The region is a long way from achieving his vision. The Association of Hotels of the Riviera Maya reported a 10% decrease in occupancy last year as a result of the seaweed. Tourism accounts for more than 8% of Mexico's GDP, and Quintana Roo, the Mexican state on the east coast of the Yucatán Peninsula, accounts for 40% of Mexico's foreign visitors. Hotels and restaurants generate 25% of Quintana Roo's GDP, and their workers would have a hard time finding jobs in another industry. Fewer tourists means lower government revenue, and thus less money to fund *Sargassum* removal. The economic upheaval from a loss of tourism would also boost the drug cartels, whose violence has recently been encroaching on the peninsula's tourist areas.

So by strangling tourism, the seaweed is also cutting off oxygen to anyone who tries to stop its invasion.

Lauren Zanolli is a freelance journalist who writes about climate change, energy, and environmental pollution.

STRONG COFFEE

Researchers working on new breeds of coffee have chanced upon varieties that might withstand the extreme weather caused by climate change.

By DIEGO ARGUEDAS ORTIZ

Turrialba
Cartago Province
COSTA RICA

The round plastic container in William Solano's hands holds the coffee blend of the future. It's not a novel macchiato or a whole-bean medium roast from a boutique shop: it's a new hybrid variety of coffee that might fare better in our changing climate.

"This one is called Centroamericano," says Solano, a coffee breeder at the Tropical Agricultural Research and Higher Education Center (CATIE), in Costa Rica, as he shows me a petri dish with dozens of plant embryos that look like tiny popcorn. Experts like him create hybrids by combining two genetically distant and complementary coffee strains, hoping to get the best characteristics from each parent.

Centroamericano was not created with climate change in mind. Its breeders were aiming for disease resistance, yield, and taste. And on those terms, Centroamericano was already a success story. It produces a high-quality beverage, yields over 20% more coffee beans than average per hectare, and shows high tolerance to coffee leaf rust, a much-feared plague. But one winter, the bean revealed a surprise. On the night of February 6, 2017, at a trial site in Laos where dozens of coffee varieties were being tested, temperatures dropped so dramatically that frost blackened and severely injured most of the trees in the plot. By 7 a.m., only three rows still survived: those with Centroamericano and two other hybrid varieties from Central America.

Scientists are now realizing that such hybrids might be better at withstanding the temperature extremes

TITO HERRERA

likely to be brought on by climate change. A 2015 study by Christian Bunn and colleagues at the International Center for Tropical Agriculture (CIAT) calculated that under a mid-range estimate of how severe climate change will be, the global area suitable for coffee will shrink about 50% by 2050, even as demand increases. "With a changing climate, suddenly weather-related stress become much more important," says Bunn.

So why did the hybrids survive? When parents contribute very different genes to an offspring, as in their case, the resulting organism possesses what scientists call "hybrid vigor." "It's a widely known effect in other areas, but no one had studied it in coffee," says Benoît Bertrand, a researcher for the French Agricultural Research Centre for International Development and a leading authority on coffee breeding.

▲

William Solano (above) is developing new hybrid varieties of coffee that might fare better in a changing climate.

Although the concept is often used in maize production and is fairly common in poultry and rice, it was Bertrand's team that initially applied it to coffee in the 1990s, creating Centroamericano and a handful of other hybrids.

This vigor is critical for coffee, a crop notorious for its lack of diversity. The coffee grown in Latin America has an especially shallow genetic pool, making it particularly vulnerable. The region is dominated by two arabica varieties initially brought in by Europeans. Although dozens of different Latin American strains descended from them, at times mixing with a third arrival, entire generations of coffee trees have been effectively intermarrying with their cousins.

Bertrand's team wanted to break this genetic bottleneck. Working with CATIE and with Central America's national coffee institutes, they created what are known as "F1 hybrids"—first-generation offspring of two genetically distant parents—by combining the best local varieties with genetically diverse Ethiopian strains from CATIE's collection. They did this manually, by taking pollen from one plant and pollinating flowers from another, which means these varieties are not considered genetically modified organisms (though such breeding is just a more ancient form of genetic modification).

When results came in from trial sites, the data showed vastly superior performance from the new varieties. Their hybrid vigor was 20% to 50% higher than their parents', yield was up, and some varieties were disease-tolerant. "The hybrids are boxing in a different category," says Christophe Montagnon, scientific director of World Coffee Research (WCR), a nonprofit that ran the trial in Laos where Centroamericano showed its resilience.

F1 hybrids sound great, but they're expensive. You can't take their seeds and plant them, because their genes aren't stable; in a first-generation offspring from two genetically distant strains, if you plant 100 seeds you'll get many different types of trees as the parents' genes reshuffle to create new combinations. "You will lose all the stability of the hybrid—all the vigor," says Lucile Toniutti, a molecular breeder at WCR.

Experts have to choose one specific plant they like and clone it in a lab. This involves cutting leaves into bits and placing them in a growth hormone so they balloon into the embryos Solano showed me at CATIE. The process takes over 18 months and consumes loads of cash: each F1 hybrid seedling can cost around 80 US cents, which is two to three times pricier than traditional varieties.

It's a crucial problem to solve, because 1.8 million people around Central America, both farmers and the seasonal workers who harvest the beans, depend financially on coffee. While some farmers might be able to switch to cocoa, rubber, or other crops, says CIAT's Bunn, many people would be forced out of rural communities. Many would seek to migrate north to Mexico and the US.

"I am 100% certain that the future of coffee depends on hybrids' success," says Solano. In March, he drove to Starbucks's experimental coffee farm in Costa Rica to deliver 50 new hybrids to be tested. More varieties will come, from his lab and others, and breeders will increasingly focus on resilience to climate change.

And if the hybrids don't stand up to climate change as well as hoped? "Our most pessimistic predictions will be made reality," he says.

Diego Arguedas Ortiz is a science and climate change reporter in Costa Rica. He's @arguedasortiz on Twitter.

PREPARING FOR THE COMING STORM

The weather will get worse, but that doesn't mean disasters have to.

By KAREN HAO

In the aftermath of Hurricane Irma, Valencia Gunder brought relief to Miami's poorest neighborhoods, and laid the groundwork for a new approach to community resilience.

Miami

US

ALICIA VERA

The call came three days before Hurricane Irma hit Miami.

An elderly woman, living in a local housing project and relying on a wheelchair for mobility, had no food, no water, and no emergency oxygen. On the other end of the line, Valencia Gunder, a community leader and activist, had nothing left to give. In the days before, Gunder had depleted her personal savings, buying emergency food and supplies for anyone who'd called asking for help. Now the grocery stores were barren and she had only $200 left, which she'd stowed away for the aftermath of the storm.

For most of 2017, Gunder had sat on the executive steering committee of Greater Miami's 100 Resilient Cities initiative, an effort to shore up the region against the worsening effects of climate change. The committee had tried to make a plan to protect the most vulnerable—an estimated 30% of people in the area live below the poverty line, and twice as many struggle to make ends meet. But now Irma's 180-mile-per-hour (290-kilometer-per-hour) winds were ripping through the Caribbean, headed for South Florida, and Gunder knew their preparation wouldn't be enough. "I was stuck," she says, her voice cracking as she remembers the feeling of desperation. "That was it. That was the final straw. I was like, we have to do something."

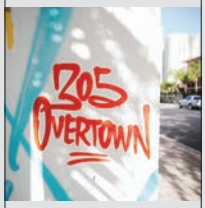
As wealthier residents booked last-minute flights to escape the storm, Gunder worked against the

clock. She found an emergency shelter for the elderly woman and sent out a series of requests to other activists and community leaders. By the time her power cut out on the morning of Irma's landfall, she had launched a social-media campaign and secured an empty warehouse to serve as headquarters for a grassroots post-hurricane relief operation.

In her adrenaline-fueled rush to save Miami's poorest from devastation, she didn't realize she'd laid the groundwork for a whole new way of building community resilience. That approach is now being adopted by cities around the US that, like Miami, are grappling with intensifying hurricanes, droughts, and floods.

The modern study of community disaster resilience has its roots in a devastating heat wave that struck Chicago in 1995. That July, temperatures approached 110 °F (43 °C) with severe humidity; 739 people died, making it the deadliest event of its kind in US history. City officials lamented it as a "unique meteorological event" whose human toll couldn't have been avoided. But years later, when sociologist Eric Klinenberg revisited the mortality data, he drew entirely different conclusions that are now foundational to our understanding of how natural phenomena turn into natural disasters.

He discovered that two low-income minority communities had suffered opposing fates, though they were separated only by a major road. In one, the predominantly African-American North Lawndale, people had died at 10 times the rate of the other, the mostly Latino South Lawndale. The disparity, he realized, was a product of each community's history. The city had neglected North Lawndale for years, and its local economy had declined in the face of sparse public services and



"That was it. That was the final straw. I was like, we have to do something."

investment. As employers, businesses, and residents abandoned the neighborhood, rates of violent crime skyrocketed. Many elderly residents were afraid to leave their un-air-conditioned homes, where they succumbed to heatstroke. South Lawndale, by contrast, was a hub for Mexican-American immigrants, whose population was constantly being replenished by new arrivals. This fueled local businesses and created a lively street scene that made elders feel safe to set out for air-conditioned businesses and facilities.

"Yes, the weather was extreme," Klinenberg later said in an interview. "But the deep sources of the tragedy were the everyday disasters that the city tolerates, takes for granted, or has officially forgotten."

Klinenberg's findings taught experts and government practitioners that mitigating suffering is as much about building up the social health and economic stability of communities as it is about physical adaptation. A body of scholarship arose from that idea, and in 2018 the Urban Sustainability Directors Network, an organization focused on fostering innovation in cities, published a white paper on a new model for community-led "resilience hubs."

A resilience hub, it said, was a physical location like a school, church, or community center that local residents could trust. In normal times, the hub would serve its usual function as well as offer resources like financial advice, job-seeking services, or evening classes. During a natural disaster, it would become an operations center for distributing emergency relief, or a temporary shelter for people who had to leave their homes.

The morning after Irma roared through, Gunder wasn't thinking about resilience hubs. Ignoring the flooding in her own house, she met a small group of volunteers at the empty warehouse, which she dubbed the community emergency operations center, or CEOC. They pooled together the little money they had and went straight to any stocked grocery stores to buy hot dogs and buns. Then they dragged Gunder's grill from her home to low-income neighborhoods, one by one.

Everything was chaos. Streets were flooded; windows were shattered; roofs had caved in from falling trees. Over two million homes and businesses lost power in South Florida, and tens of thousands would still be without it a week later. People who hadn't eaten since before the storm lined up at Gunder's makeshift food station in droves, confused by her generosity. A man who said he worked for the school board came up, sobbing and begging for food in exchange for labor. "This food is for everybody," she had to reassure him. "We came to feed people for free."

In the first two days, her team stretched their funds to feed around 400 people. But on the third day, as she watched the line of people grow in Overtown, a predominantly African-American neighborhood, she realized she needed more money. Overwhelmed by the scale of need, she called the Miami Foundation, a local nonprofit, and began to cry. Luckily, the foundation had been receiving donations to support the hurricane relief efforts, and it had worked with Gunder before. It wired her $10,000, completely changing the scope of her operation.

Every morning, she met with volunteers at the CEOC and formulated an action plan. Then they dispatched teams to set up a network of food stations across the low-income neighborhoods. In each neighborhood, the volunteers would split into two groups: one to grill and hand out food, the other to knock

on doors to notify and check in on people. Both groups also collected data: how many people they fed, who needed medical attention, and basic demographics like the size and total income of each household. All that data was then funneled back to headquarters at the CEOC and compiled to identify hot spots of need. As word of what Gunder was doing spread through the press and social media, local governments, nonprofits, and other emergency response teams began calling to ask where to direct their aid and supplies.

The numbers spoke for themselves. In a week and a half, the CEOC had fed 23,000 people and revealed a completely new model for how to deliver resources efficiently to the most vulnerable communities.

Today, Miami is using the CEOC as a foundation for a resilience hub network. The 100 Resilient Cities steering committee is working with community leaders and nonprofits across the city's neighborhoods to identify trusted spaces for the new hubs. In March, representatives from Miami and other cities around the country—including Washington, DC; Providence, Rhode Island; and Ann Arbor, Michigan—met to learn from one another's efforts.

For Gunder, all this is just the beginning. Her face glows when she talks about the new hub network, but her mind races impatiently to what comes after. She dreams of a day when the neighborhoods she's worked with will finally shed their poverty and blossom to their full potential. "I know that even though these communities have all of these social ills, they embody this beautiful resiliency," she says. "It just takes a little bit of guidance and searching to find."

Karen Hao reports on artificial intelligence for MIT Technology Review.

JEROME DELAY/AP; COURTESY OF SNV

GPS FOR COWS IN WESTERN AFRICA

Climate change makes it even harder to find water on the edge of the Sahara. Now herders in Mali rely on images from space to direct them to the nearest watering hole.

By TIM MCDONNELL

Gao region

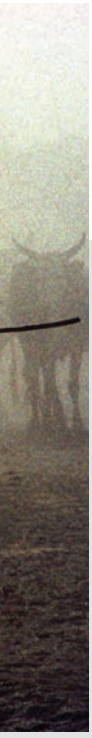
MALI

For most of his 50 years, Abdoul Ag Alwaly, a cattle herder in northern Mali, used the same way of finding water for his cows. He would pay a motorcyclist or camel driver to roam the desert surrounding the city of Gao and check the levels of scattered creeks and wells. The process was expensive, time-consuming, and risky—sometimes he'd march his herd for days only to find that he'd received a bad tip, or that another herd had gotten there first.

In recent years climate change has made the search even harder, Alwaly says. Where he lives, in the Sahel, the vast strip of arid scrubland south of the Sahara Desert, temperatures are rising faster than the global average, droughts are more frequent, and vegetation is scarcer. Erratic rainfall has made traditional watering holes unreliable. Animals frequently perish during the search, Alwaly says, and competition for water can easily turn violent.

So he's trying a new approach. Over the last year, Alwaly, who leads a local union of livestock herders, has started to look for leads in satellite images. "With your phone and 25 francs"—about four US cents—"you'll know, and can move with a lot more certainty," he says.

Across the continent, rising temperatures and unpredictable rains are a serious threat to millions of small farmers and herders. Real-time, hyper-local satellite data can be used to detect early warning signs of drought and crop failure. As satellite



imaging gets cheaper, more prolific, and higher in resolution, and the massive quantities of data it yields become easier for computers to manage and interpret, a growing number of private companies and nongovernmental organizations are finding ways to put it directly into the hands of people who deal with the effects of climate change every day.

Alwaly uses an experimental service offered by the telecom company Orange. It analyzes a daily feed of pictures from the European Space Agency's Sentinel satellites to give nomadic herders in northern Mali up-to-date information about where they can find water and feed. Alwaly can call or send a text to a call center in Mali's capital city, Bamako, and a technician will review a color-coded satellite image showing a pale landscape shot through with vegetation and offshoots of the Niger River. That will point to where the water is—no camel ride necessary.

Introduced in November 2017, the service has fielded 1,300 phone calls and 88,000 text messages from more than 50,000 users, according to SNV, a Dutch NGO that helped develop it.

Since the first Earth-observing satellite went into orbit in 1972, images taken from space have made visible humanity's footprint on the planet. We can watch glaciers and rain forests shrink as cities and mega-farms grow, glean insights about water, soil, and other natural resources, and monitor disasters like wildfires and drought.

Today, satellite imaging can not only track these large, long-term trends but give farmers real-time information on particular parts of their farms. In the early days, the pixels in satellite images were measured in square kilometers, but now commercial satellites can reach resolutions of 30 square centimeters (one square foot), while public-access data from government agencies like NASA typically has a resolution of 10 to 100 square meters. Just as important, the number of Earth-observing satellites in orbit is increasing rapidly—it's up to more than 700, according to a Union of Concerned Scientists database. That makes it easier to find an image of any given location taken in the last day or two.

An experimental service provides farmers and herders in Mali with information on weather patterns, availability of grass and water, and even herd movements, based on satellite data (pictured below).

Before the service was available, cattle herder Abdoul Ag Alwaly would pay a motorcyclist or camel driver to check the levels of creeks and wells.

Satellite-guided precision agriculture is already common in the US and Europe. Only just emerging in Africa, it could be particularly useful for farmers and herders who are spread over vast areas but who carry cell phones in their pockets.

Nearly 1,000 miles (1,600 kilometers) south of Gao, in central Ghana, cocoa—the country's top cash crop—is highly vulnerable to rising temperatures, drought, and warm-weather-loving pests. Agronomists project that the land area suitable for cocoa production there could contract significantly by 2030. To help farmers boost their productivity under those conditions, agricultural field agents are using a new tablet-based app to create what are called Farm Development Plans. Launched in July by the SAT4Farming consortium, consisting of the nonprofit Rainforest Alliance and Grameen Foundation, the Netherlands-based Satelligence and Waterwatch Projects, and the French commodity crop trader Touton, the app uses machine-learning software trained to analyze satellite images of cocoa farms taken both in visible light and in the near-infrared spectrum, which documents wavelengths that plants reflect during photosynthesis. The images, combined with field-based agronomic science and farmer surveys, allow the software to generate regular checkups of tree health—based on metrics like the density of vegetation and the closeness of trees—and recommendations for how to improve it.

That kind of assessment is simple enough to do from the ground for a single farm. But a sky-high view allows farm consultants—who, in Africa, can have thousands of clients over a large area—to spot troubled farms at a glance throughout a difficult growing season. Then they can make adjustments—a different pruning pattern, or a targeted dose of fertilizer—in response to drought or other difficulties. "If I recommend that a farmer add a few hundred kilos of fertilizer, but the satellite shows that nothing has changed, then we can assess what might have gone wrong," says Selasse Gidiglo, a SAT4Farming program officer.

Satellite images aren't perfect. Clouds and dust often block the view, especially over desert and tropical areas. The images also don't eliminate the need for on-the-ground surveys—they may show a herder a source of water without revealing that it's on private property or that the vegetation is something animals can't eat. "The fact that something is green in the satellite image doesn't mean it's necessarily suitable for livestock," says Peter Hoefsloot, an Amsterdam-based analyst who helped develop the service Alwaly uses.

"The whole possibility of it is quite strange to me," says Nana Kwame Korang, a cocoa farmer in Sunyani, Ghana, who works with SAT4Farming. "But if it can give me a higher yield during dry periods, I like it very much."

Tim McDonnell is a journalist covering science, business, and the environment in the US, sub-Saharan Africa, and elsewhere. Follow his work at www.timmcdonnell.org.


EUSSEN
QUEENSLAND
FIRE & RESCUE

AUSTRALIA
IS TRYING TO
ADAPT TO A FUTURE
WITH BIGGER,
BADDER
BUSHFIRES.

CODE

BUT CAN IT
CHANGE
QUICKLY ENOUGH?

RED

By_**BIANCA NOGRADY**

In 2013, three wildfires tore through the eucalyptus forests of the Blue Mountains, forcing 80,000 people to evacuate, including the author and her family.

OPPOSITE: SAEED KHAN/AFP/GETTY IMAGES; THIS PAGE: TOAN TRINH

The Blue Mountains are burning. I stand in the doorway of our home and take a long look around: the handmade rugs, the jumble of artworks, the shelves crammed with books, the scattered toys. The house is a tinderbox: wooden walls, doors, balcony, window frames, all built into a lushly forested hillside. I picture all of it flaming into indistinguishable piles of ash.

"Please don't burn," I whisper, as if it will make a difference.

I lock up, and join my husband and two children in a car laden with what few precious items we could cram into it.

It's October 21, 2013, and not one but three wildfires are roaring through the eucalyptus forests. The oil-infused leaves of the gum trees are what lend the Blue Mountains their characteristic hue—but they also make them particularly combustible. The authorities have issued a chilling warning to 80,000 people across 27 mountain villages: Nobody, not even the fire service, can guarantee your safety, and the best course of action is to get out.

So we do.

In the end, our town was spared. And while the blazes eventually claimed more than 200 houses around the fringe of the wilderness, mercifully, they took no lives.

Australia's colonial history is dotted with fires so enormous they have their own names: Black Sunday (1926), Black Friday (1939), Black Tuesday (1967), and Ash Wednesday (1983). The worst, Black Saturday, struck the state of Victoria on February 7, 2009. Fifteen separate fires scorched the state over just two days, fueled by a record-breaking heat wave, strong winds, and a desiccated landscape. The flames razed entire towns and killed 173 people. Compared with all these, my Blue Mountains experience barely rates a mention.

"Australia's certainly one of the most flammable continents," says Geoff Cary, an associate professor of bushfire science at the Australian National University. That is true, but the country is not alone in facing terrible fires. In recent years California, Chile, and British Columbia have all been ravaged by record-breaking blazes. Even nations where wildfires are unfamiliar—such as Sweden and the United Kingdom—have seen unprecedented outbreaks, blamed on rare heat waves and droughts.

In fact, while Australia is notorious for spectacular blazes, it actually ranks below the United States, Indonesia, Canada, Portugal, and Spain when it comes to the economic damage caused by wildfires over the past century.

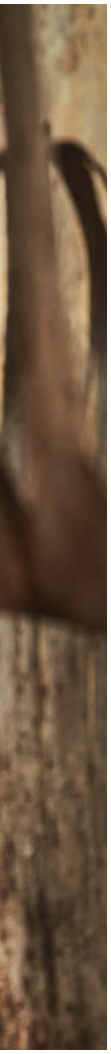
There is one significant difference, however. While other nations argue about the best way to tackle the issue, the horrors of Black Saturday led Australia to drastically change its response.

In its final report, the Black Saturday Royal Commission—which interviewed more than 400 witnesses—said that it would be a mistake to treat the tragedy as a one-off event. "With populations at the rural–urban interface growing and

Stringent building codes introduced after Black Saturday regulate houses in fire-prone areas. Author Bianca Nogrady's new Blue Mountains home, for example, required a steel-clad exterior and roof, and fire-tested doors, windows, and skylights.

the impact of climate change, the risks associated with bushfire are likely to increase," it said. Since then there have been significant changes, including new approaches to house design and construction, and shifts in urban planning, evacuation policy, and emergency warning systems.

And one of the biggest changes was also one of the most basic: taking another look at the way fire risk is rated.



HAROLD DAVID

BEYOND EXTREME

Australia's Fire Danger Index was developed by local fire researcher Alan McArthur and has been in use since 1967. It uses humidity, temperature, wind speed, and long- and short-term drought effects to gauge the risk and potential severity of fire. Originally, the highest level of warning was "Extreme." But in 2009, the authorities added a new, higher tier: "Catastrophic/Code Red."

Today, Black Saturday–type weather is a one-in-20-year event. "In any given season there's roughly a 5% chance that we'll get a clanger of a day like that," says Justin Leonard, a research leader in bushfire urban design at CSIRO, Australia's government science agency. But by 2050 that is projected to increase to a 15% chance. By 2100, it's around 30%.

That's why Code Red was introduced, as another level to reflect the fact that bushfires are getting worse, and that new responses are required.

"If Black Saturday taught us anything, it's that some fires are bigger than others, and that they're not something that you want to be standing in front of and trying to defend your house on those days," says Richard Thornton, CEO of the Bushfire and Natural Hazards Co-operative Research Centre.

Code Red is an admission that there are some blazes rescuers and firefighters simply cannot tackle, and that the vast majority of homes are not designed to withstand. It signals that leaving your property well before the fire front approaches is the best option for survival; two thirds of the victims of Black Saturday perished in or near a house. Code Red means *Get out early*.

"In the Victoria region, the inevitability that a big fire will run on that day is nearly absolute—it just depends where in the landscape it's going to turn up," says CSIRO's Leonard. "In a sense we're abandoning, and resigning to the inevitability that when we have those days, we're going to lose thousands of houses and hopefully only one or two people."

Accepting that grim reality doesn't mean Australians are willing to lose buildings completely, however.

CODE RED IS AN ADMISSION THAT THERE ARE SOME BLAZES FIREFIGHTERS SIMPLY CANNOT TACKLE. CODE RED SIGNALS THAT LEAVING YOUR PROPERTY IS THE BEST OPTION FOR SURVIVAL. CODE RED MEANS "GET OUT EARLY."

BUILDING AND REBUILDING

The enormous metal chimney jutting out from the jumbled complex of low white buildings on Sydney's leafy north shore is the first clue that CSIRO's fire testing facility is a little out of the ordinary. This is where experts are testing and measuring a new generation of building materials to see if they are strong enough to survive the Code Red future.

The site's centerpiece is a blackened gas-fired furnace three meters square, its inside mottled with drips of what I discover is melted concrete. (No, I didn't know concrete could melt either.) This is where windows, doors, and other housing components are tested to see if they can withstand the destructive power of a full-throttle bushfire: temperatures reaching 1,300 °C (nearly 2,400 °F) and radiant heat over 100 kilowatts per square meter. For comparison, just 2 kW per square meter is enough to cause second-degree burns to bare skin.

Testing a window for bushfire resistance involves first building it into a brick frame and then placing it a carefully calibrated distance from the furnace. A sheet of stainless steel four millimeters (0.16 inches) thick sits between the window and the furnace to make sure the blast of heat is uniform.

The temperature cranks up, but the test isn't just about surviving the initial onslaught of heat. A window or shutter going through this process has to maintain its integrity for at least 30 minutes after the heat is switched off. Any cracking, warping, or reignition during that cool-down period results in an automatic fail.

It's an expensive process—a single test can cost around AU$16,000 (US$11,300), regardless of the outcome. The steel radiation sheet must be replaced every few tests, and the gas bills are enormous. "This place is pretty harsh on everything," says Brett Roddy, a CSIRO lab manager, with a laugh. "We have to replace a lot: lights, people, kit."

My own house—the one I briefly abandoned in 2013—wouldn't have the faintest chance of passing any of these tests, with its wooden window frames, decking, cladding, and door. But since 2009, there have been much more stringent rules for any house built within 100 meters of fire-prone vegetation.

I discovered this shift myself in 2015, when we built a new home on a block of land in another part of our small town.

There are six levels of bushfire exposure, from Low to Flame Zone. Our new home, thanks to the dense, sloping eucalyptus forest just 30 meters away, is in the second highest category, known as Bushfire Attack Level 40, or BAL-40.

Getting building approval meant meeting the new requirements: a steel-clad exterior and roof, a completely enclosed subfloor area, and bushfire-tested windows, doors, and skylights.

"I just got a Flame Zone house costed, and it was AU$300,000 [US$213,000] just for windows," says Ingrid Donald, the Blue Mountains architect who designed our new home.

The regulations are not about making a house "bushfire-proof" but ensuring that it survives well enough to protect its occupants, should they find themselves sheltering in it when the fire front passes. The most recent innovations are products such as steel window shutters and low-carbon, fiber-reinforced cement composite board—construction materials that can perform better in the face of a terrifying blaze.

Some people, though, are thinking more ambitiously. Sean O'Bryan, a partner at Baldwin O'Bryan Architects, suggests that the answer is in a more radical kind of earth-sheltered house. "We're pretty confident we can design buildings that are completely bushfire-proof," he says. The houses his firm designs are covered with a minimum of 500 millimeters of soil. "You just get all that mass of insulation from the heat of a bushfire," O'Bryan says. The only outward-facing elements are windows: "Obviously the windows have to got to be protected in different ways … but we can get them to a point where we just put shutters over the front of them."

HUMAN ELEMENTS

Still, there's a fundamental weak spot in Australia's bushfire building standard, and that's people.

"They believe it's somebody else's problem, it will happen to somebody else and not me, that I'm much better prepared than everyone else around me," says Bushfire and Natural Hazards CRC's Richard Thornton. "The constant refrain that we have across all of these fires … has been people understand that they live in a bushfire-prone area, like you do in the Blue Mountains, but they don't believe it's a problem for them."

A 2018 study among communities affected by bushfire in the state of New South Wales found that around half of agricultural holdings were underinsured, partly because insurance was so costly. Estimates from the Black Saturday fires in Victoria suggest that 80% of those affected were underinsured and 13% were not insured at all. The insurance industry blames "charity hazard"—the notion that people assume the government will step in and help them.

People also aren't good at fire safety measures. Expert advice says it's important to maintain a home's "asset protection zone"—that is, to make sure the area around a house contains as little flammable material as possible. The greater the bushfire threat, the larger that area needs to be. Other countries have a similar approach: the US National Fire Protection Association's "Home Ignition Zone" is an area 100 feet (30 meters) out from a home where residents are advised to keep vegetation to a minimum and remove flammable materials such as firewood.

But keeping this up takes time and effort. "If you believe that your chance of being impacted by bushfire is once in 50 years, maybe, why would you spend one of your weekends each year doing something about it when there's all the other things about bringing up kids, going to work, doing all the other things you have to do?" Thornton says.

One person with a suggestion of what to do is Rachel Westcott, a researcher who has been trying to promote the idea of "fire fitness"—a more practical vision of preparedness that accepts fires as a bigger part of the landscape now.

"Fire fitness means to be prepared and be ready, but it means integrating that into everyday life," says Westcott, who recently completed her PhD at the Bushfire and Natural Hazards Cooperative Research Centre and Western Sydney University. "It means having that fitness to be able to face that hazard and deal with it safely and make the right response choices and come out of it more or less unscathed." She notes that public resources are being invested to help people become more bushfire ready,

Baldwin O'Bryan Architects designs homes (above) that are covered with soil and feature outward-facing windows that can be shuttered. CSIRO's fire testing facility includes a gas-fired furnace (below) for testing the resilience of new building materials.

but the level of awareness and readiness is not rising as fast as spending is.

Her research found that fear-based safety campaigns don't work for everyone, and even when they do, their effect plateaus and fades over time. Fire fitness, she argues, is about creating incentives: for example, workplace leave that is specifically intended for employees to prepare their properties ahead of severe fire weather, and insurance discounts or tax breaks for well-prepared properties and people.

As Australians keep building further and further into fire zones, fire fitness becomes ever more important. In the Blue Mountains, new blocks of land are constantly being released for sale. They're cheap, they're bushy, and many are in the flame zone.

Australians' unwillingness to part company with the bush, despite the threat, is evident even among people already traumatized by fire. Few want to relocate to safer territory. After Black Saturday, the Victoria state government started a land buyback scheme for some people who lost homes in the fires. One report suggested that while 550 homes were eligible, only 27 landowners took up the offer. A similar phenomenon is seen in other fire-afflicted places, such as California and Greece, where survivors are quick to start rebuilding their scorched houses and communities. One report on 11 major California fires between 1970 and 2009 found that 94% of damaged buildings were rebuilt, either by the original owners or by someone else. In Greece, development laws have loopholes that enable people to build in highly fire-prone areas, often without consideration for building regulations.

Susan Templeman, the federal member of Parliament for the Blue Mountains, is one of those who lost nearly everything to fire yet are willing to risk it again to remain in their communities. Her home was destroyed in the same bushfires that my family fled, but she and her husband have since rebuilt on the same spot. Unlike many people, she was able to afford the increasing costs of building a code-worthy home in fire zones. But it still took the family over four years to design and build a home that is as bushfire resistant as possible. "We think our house is going to be fairly resilient to heat and embers," she says. So would they entrust their lives to it if—when—fire returns to their area? "As interesting as it would be to test that," she says, "I don't believe that we would stay."

COURETSY PHOTOS

GETTING IT RIGHT

On a hot January day this year, I drove to nearby Mount Victoria, the small village where one of the three Blue Mountains fires began. It's clear where the fire struck: I drove past one block of land for sale that still carries the remnants of a house that went up in flames. Somebody will probably buy the plot soon. Most of the other houses on the same street are shiny and new—testament to residents' will to defy the odds.

FEW PEOPLE WANT TO RELOCATE TO SAFER TERRITORY, EVEN IF THEY HAVE BEEN TRAUMATIZED BY FIRE. AFTER BLACK SATURDAY, THE GOVERNMENT INITIATED A LAND BUYBACK SCHEME FOR THOSE WHO LOST THEIR HOUSES IN THE FIRE. THOUGH 550 HOMES WERE ELIGIBLE, ONLY 27 LANDOWNERS TOOK UP THE OFFER.

In February, Australians marked the tenth anniversary of Black Saturday. Yet even as the nation mourned in remembrance, large areas of Tasmanian wilderness smoldered after two weeks of uncontrollable blazes. Barely a week has gone by this summer without someone, somewhere in the country, being told to grab what they can and get out.

So are the changes in policy, regulation, and building codes having an impact? Are Australians learning the lessons of Black Saturday fast enough?

Richard Thornton says Australia's relationship with fire has always been different from other countries'. "Europeans have dealt with and lived with agricultural fire for a long time, but not necessarily forest fires as such," he says. And while US states like Florida and Louisiana have been doing prescribed burns for decades, Thornton argues that other regions have the attitude of "extinguish at all costs," which means that when fires do occur, they get enormous. The problem is compounded by infestations of mountain pine beetle across the US and Canada, which leave behind huge areas of dead trees as fuel for forest fires.

CSIRO's Justin Leonard says Australia has some of the best examples of getting bushfire-ready building right, particularly in contrast to the lightweight, polyvinyl chloride–clad, bitumen-roofed pine frame houses that dominate in the United States.

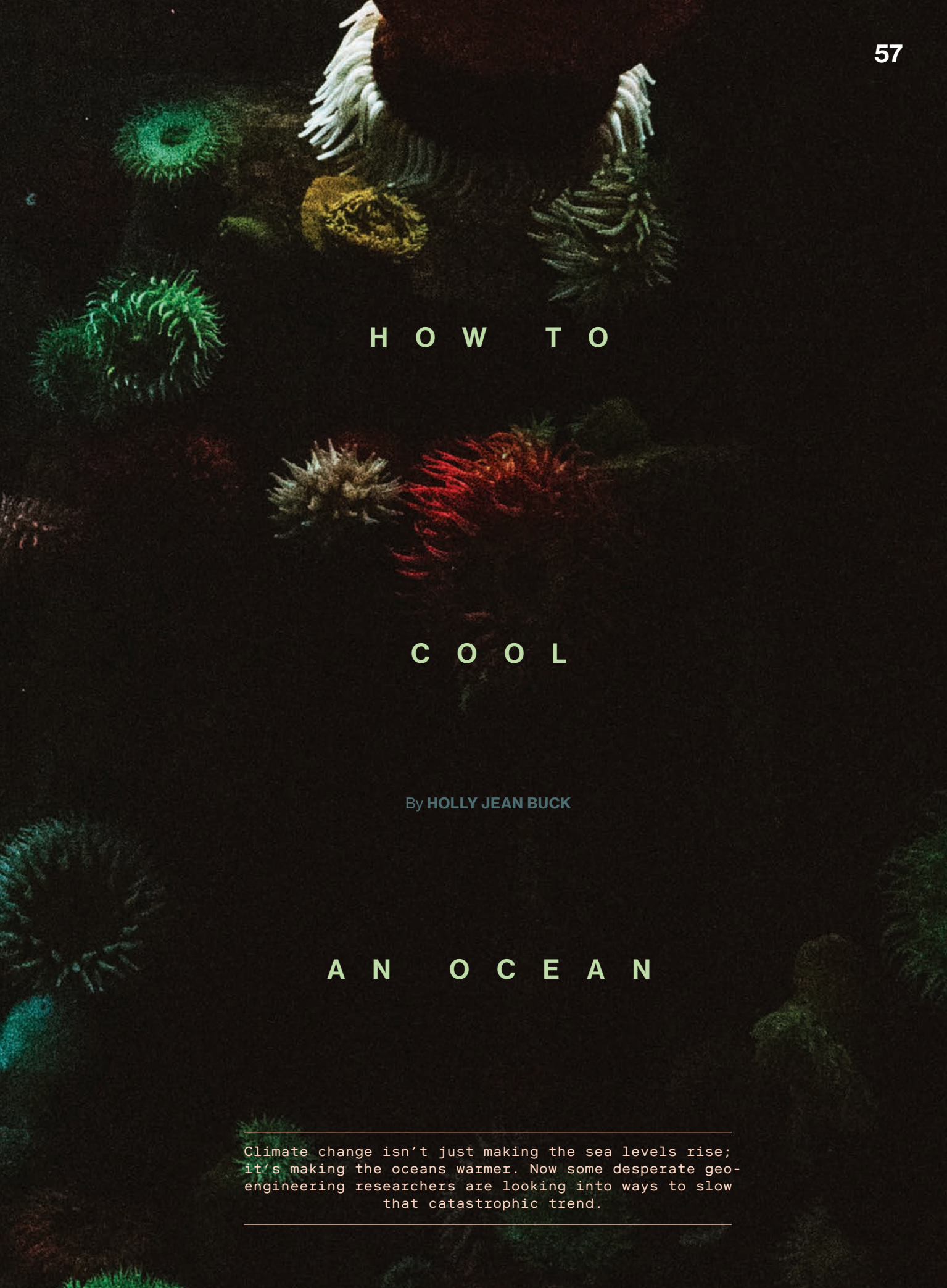
But he also believes a lot of its efforts still fall into the "epic fail" category. The stringent bushfire building code is, he suggests, a minimum standard for homeowners who aren't really aware of, or prepared for, the true threat they face.

Even then, he says, it's not enough: "Either the safety net has to be robust enough that it can perform well in the absence of an expert or informed user, or we've got to work out how to shift the demographic of attitudes in the community."

But perhaps attitudes are starting to shift in the right direction, particularly when it comes to choosing to evacuate early rather than stay and defend. Thornton points out that very few people have died in big fires since Black Saturday.

"It's always a portentous thing to say," he notes. "Whether that's good planning, and therefore everything that we've changed since Black Saturday has worked, or whether that's just good luck—we're not sure yet."

Bianca Nogrady is a science writer based in Australia and the author of The End: The Human Experience of Death.



HOW TO COOL AN OCEAN

By **HOLLY JEAN BUCK**

Climate change isn't just making the sea levels rise; it's making the oceans warmer. Now some desperate geo-engineering researchers are looking into ways to slow that catastrophic trend.

Coral reefs smell of rotting flesh as they bleach. The riot of colors—yellow, violet, cerulean—fades to ghostly white as the corals' flesh goes translucent and falls off, leaving their skeletons underneath fuzzy with cobweb-like algae.

Corals live in symbiosis with a type of algae. During the day, the algae photosynthesize and pass food to the coral host. During the night, the coral polyps extend their tentacles and catch passing food. Just 1 °C of ocean warming can break down this coral-algae relationship. The stressed corals expel the algae, and after repeated or prolonged episodes of such bleaching, they can die from heat stress, starve without the algae feeding them, or become more susceptible to disease.

Australia's Great Barrier Reef—actually a 2,300-kilometer (1,400-mile) system made up of nearly 3,000 separate reefs—has suffered severe bleaching in the past few years. Daniel Harrison, an Australian oceanographer looking at what might be done to buy more time for the Great Barrier Reef, says the situation is getting dire. "There might be as little as 25% of shallow-water coral cover left from pre-anthropogenic times. We don't really know, because nobody started surveying before 1985," he tells me. "You've got less than 1% of the ocean in coral reefs, and 25% of all marine life. We're looking at losing all of that really quite quickly, in evolutionary terms. In human-lifetime terms."

Coral reefs are not just about colorful fish and exotic species. Reefs protect coasts from storms; without them, waves reaching some Pacific islands would be twice as tall. Over 500 million people depend on reef ecosystems for food and livelihoods. Even if the temperature increase eventually stabilizes at 1.5 °C a century or two from now, it's not known how well coral reef ecosystems will survive a temporary overshoot to higher temperatures.

The corals are like the canary in the coal mine, Harrison says: "They're very temperature-sensitive. I really do think it's just a harbinger of things to come. You know, the coral ecosystem might collapse first, but I think there might be quite a few more ecosystems that'll follow it. Life is very resilient, but ecosystems as we know them aren't."

Arctic ecosystems, mountain glaciers, and the redwood forests in California are also at high risk from even small changes in global mean temperature. So are species that can't move quickly and find another suitable niche. "It's the things that already live at the kind of extreme ends of the scale, and that can't move, right?" says Harrison. "So coral reefs—you know, they're stuck in already some of the warmest waters. If it gets too hot for them there, then a) they can't move, and b) they've got nowhere to go anyway. And the same with the extremely cold ecosystems. And the same with the redwood forests. Trees can't up and move quickly enough to keep up with climate change."

THE SALT SPRAYER

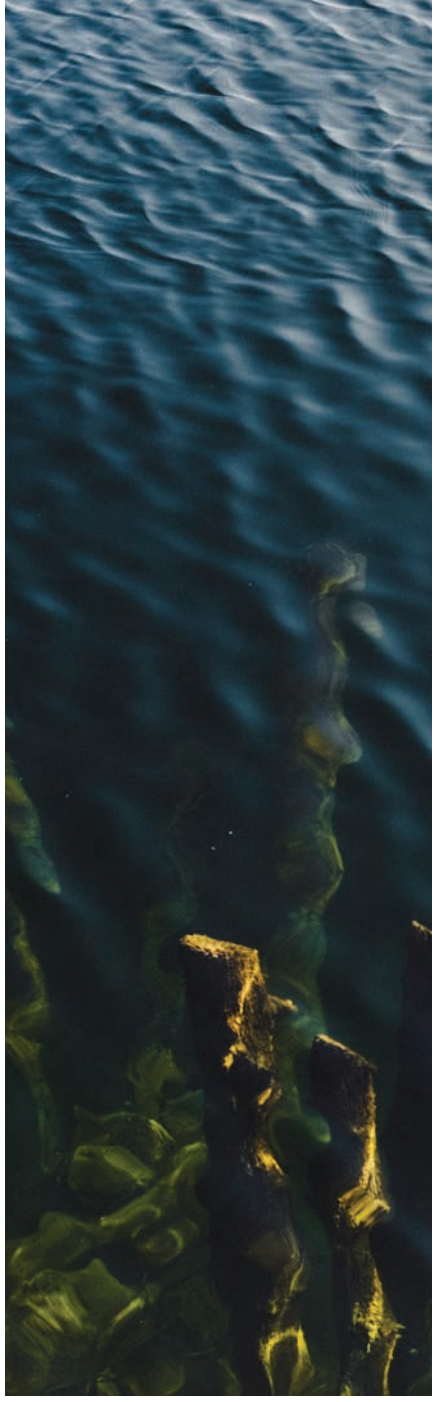
Harrison's working group formed teams to look at different ideas that could help the reef stay alive. For example, the ocean is full of cooler water at lower depths. They wondered if they could just pump some of that water upward but realized it would be infeasible to move enough water to cool the whole reef.

Instead the researchers homed in on the idea of marine cloud brightening—a form of solar geoengineering, in that it increases the planet's reflectivity. Spraying tiny salt particles from seawater up into the low layer of clouds that blankets much of the ocean's surface would form cloud micro-droplets. These droplets would make the clouds reflect more sunlight and could also make them last longer, cooling the area. The modeling Harrison's team has done so far suggests that with this method it might be possible to cool the water by between 0.5 and 1 °C.

The Marine Cloud Brightening Project, an international collaboration led by atmospheric scientist Robert Wood and colleagues at the University of Washington, thinks that this could be a scalable approach. Kelly Wanser, a senior advisor to the project, describes other ways scientists are thinking of sustaining corals, such as genetically modifying or breeding them to withstand warmer waters, or moving robust corals into new areas and replanting them. But, she says, "the scale of the problem is like reinforcing the Rocky Mountains. It's massive."

By contrast, brightening marine clouds is relatively simple. Essentially, it entails building devices to spray seawater. "There's certainly some technical challenges to be overcome, but the basic process of just taking seawater and filtering it and then spraying it out, at submicron size, is not that difficult," Harrison says. His modeling results suggest that there would probably need to be some stations a little way out at sea, just off the edge of the continental shelf—floating platforms or ships that would spray particles into the air. The whole project could cost $150 to $300 million per year. Expensive, but then the reef brings in an estimated $6 billion each year to the Australian economy. In Harrison's conception, you wouldn't need to brighten the clouds all the time, or even every summer. Rather, it would be done when the coral was at risk of bleaching, which would require about two

PREVIOUS SPREAD: UNSPLASH/SCOTT WEBB



UNSPLASH/THOMAS-PEHAM

THE CORALS ARE LIKE THE CANARY IN THE COAL MINE.

weeks of forewarning to cool the water down to the maximum extent.

"But, I mean, there's some real unknowns here, right?" Harrison says. "Because no one's ever done any field work on this."

Even though the engineering might be relatively simple, it's hard to know how well marine cloud brightening would work, because clouds are really complex. "If you look out the window on an airplane, you can see clouds with all sorts of different structures," says Ben Kravitz of Indiana University, who works on comparing geoengineering model simulations. "They're moving. Some of them are a couple meters across, some of them are tens of kilometers across. Some of them are organized, some are not. Basically, you can't fit all that behavior in any single model."

Adding to this complexity are "teleconnections" in the climate system—that is, clouds in one place affect weather in another place. When you're trying to cool large areas, these long-distance effects are relevant. That's why "it scares me, the thought of doing marine cloud brightening," says Anthony Jones, a climate scientist at the University of Exeter. "The teleconnections are almost unavoidable, and if you can cool a certain area significantly, you are going to change the climate and the weather response."

Newer climate models may yield better estimates of how effective marine cloud brightening could be. Wanser of the Marine Cloud Brightening Project says the next step is to build and test nozzles for spraying seawater. But it's been difficult to raise funding, because the project is seen as a geoengineering experiment, and people are fearful of geoengineering. "I think we talked to all of the relevant government agencies who could support this, and essentially there's no one willing to say 'We'll just do it as the cloud-aerosol basic science,'" she says. "They're like, 'No, the cat's out of the bag—this is geoengineering. We would have to get approval.'"

So cloud brightening is a technique that might help save marine ecosystems, but we don't know how well it would work, and we can't find out because the stigma of geoengineering makes it hard to get research funding. Luckily, it isn't the only option for trying to cool the oceans.

THE SEAWEED FORESTS

Trees suck up carbon dioxide, and so planting masses of new forests has been proposed as a way to lower carbon dioxide concentrations in the atmosphere and thereby cool the earth. But there's only so much land available. Enter "ocean afforestation," a concept

outlined in a 2012 paper by Antoine de Ramon N'Yeurt of the University of the South Pacific and colleagues. This proposal for cultivating seaweed for carbon removal has several steps. First, the seaweed needs to grow and be harvested. Then it's put into an anaerobic digester—a large, oxygen-free tank that breaks the organic material down. That produces biogas, which is about 60% methane and 40% carbon dioxide. The methane can be used as a biofuel, while the carbon dioxide needs to be stored to keep it from going back into the atmosphere. (One idea is to store it inside a tube that would rest on the sea floor, though it could also be injected underground.) The advantage of using seaweed in this way is that it's fast-growing and doesn't require dry land, so it won't be competing with food production or forests.

N'Yeurt and his fellow researchers calculated that afforesting 9% of the world's ocean surface and processing the resultant biofuels could replace fossil-fuel energy, increase sustainable fish production, and remove 53 billion tons of carbon dioxide from the atmosphere each year. With current emissions at about 40 billion tons a year, this could mean actually lowering the CO_2 level overall.

"Quickly implementing Ocean Afforestation would be an effort on the order of putting a man on the moon, but both less expensive and likely a much better return on investment," the paper's authors wrote. But such an effort requires coordination from multiple scientific and engineering fields to even form demonstration projects. There aren't institutions that work on this kind of holistic research and development.

On the other hand, as with cloud brightening, the basic technology of ocean afforestation is pretty simple. It requires advances in things like low-energy techniques for growing and harvesting seaweed, efficient gas separation, and carbon capture and storage—all building on things we already know how to do. The US government's Advanced Research Projects Agency for Energy has a $22 million program called Mariner, an acronym for "macroalgae research inspiring novel energy resources," for exploring innovations that could kick-start a seaweed industry.

Seaweed cultivation can have other benefits, too, such as cleaning up agricultural pollution. Fertilizer runoff from industrial agriculture pours nitrogen and phosphorus into the oceans. A 2017 paper in Nature Scientific Reports said that China's seaweed industry already removes 75,000 tons of nitrogen and 9,500 tons of phosphorus from coastal waters each year—and that just 150% more seaweed cultivation could remove all the phosphorus flowing into Chinese

RECKONING WITH GEOENGINEERING IN ALL ITS FORMS MEANS COMING TO TERMS WITH LOSS.

UNSPLASH/STEVE HALAMA

coastal waters, though much more would be needed to deal with the excess nitrogen.

To capture these benefits we'll need a well-designed system, but right now the industry is mostly unregulated. Why does seaweed need regulating? For one thing, to prevent the spread of invasive species or diseases. For example, a bacterial disease called ice-ice infects a red seaweed called *Kappaphycus*, turning its branches into ghastly white icicles. The disease caused millions in crop losses in the Philippines and then spread to farms in Tanzania and Mozambique.

Another challenge is how to make seaweed farming an explicit part of climate policy. The definition of a carbon sink under the UN Framework Convention on Climate Change was written for trees. It doesn't quite fit the profile for seaweeds—the carbon they draw down is easily decomposed and released again. Of course, there are ideas about how to sequester the biomass—sinking it into the deep sea, or into submarine canyons. But the current UN policy means that seaweed will be primarily cultivated for food, biofuels, and other products, rather than with carbon sequestration expressly in mind.

Yet another obstacle to using seaweed for carbon removal is climate change itself, which is already decimating natural kelp forests, for instance. One scientific report describes the urchin barrens that are settling in where kelp forest used to be; these warm-water species mow down everything in their path. Apparently, they are "almost immune to starvation" and some species live for over five decades. When they are stressed by hunger, their jaws and teeth actually enlarge, and they form fronts that march across the sea floor hunting for food. They're just one instance of how climate change makes all kinds of agriculture trickier.

PUTTING THE BRAKES ON GLACIERS

Besides upsetting ecosystems, ocean warming will, of course, raise sea levels. They are already 13 to 20 centimeters (5 to 8 inches) higher than in 1900. In the 20th century, most of this rise came from ocean waters expanding as they got warmer, but now the effects of melting glaciers and ice sheets have far overtaken thermal expansion. The rise produced by melting glaciers is projected to be staggering—on the order of meters per century.

But what if we could engineer specific glaciers to keep them from melting? John Moore, a glaciologist and leader of China's geoengineering research program, has recently been looking into this, and he wrote a comment with colleagues in Nature that outlines a few ways to do it.

One example involves two Antarctic glaciers scientists have a nervous eye on: Pine Island and Thwaites. Warm ocean water comes in underneath them. Conventional wisdom says this is unstoppable and irreversible, because of the bedrock slope and geometry. But Moore suggests that building artificial islands in front of the glaciers could buttress them, pinning down the ice and holding it back the way natural rocks and islands do.

Another technique would be to extract water from below the glaciers to keep them from sliding off into the ocean. Glaciers sit on subglacial streams, or thin layers of water, but drying these streams could slow their slide into the sea.

Moore says he sees this as a "very democratic, egalitarian way" of dealing with sea level rise: "Instead of trying to build walls around all the world's coastline—which actually means the rich countries will do it more than the poor countries, of course—you can deal with the problem at the source, where you have something on the scale of a hundred kilometers to deal with instead of tens of thousands of kilometers of coastline to deal with." The engineering expertise exists, he says—"Look at things such as the construction of the Suez Canal or the building of Hong Kong's new airport."

"When we've talked about this with glaciologists, there's a lot of horror at first," Moore adds. "Clearly you're going to have to put some people [in Antarctica] with a lot of stuff. That definitely will mess with the environment and the ecology. But if you compare the damage due to the collapse of the ice sheet, that's kind of dwarfed."

LIVING IN THE RUINS

Moore's ideas might be just a thought experiment for now, but we need more thought experiments. Reckoning with geoengineering in all its forms means coming to terms with loss—to explore what it means to "live in the ruins," in anthropologist Anna Tsing's phrase. Geoengineering comes as a shock to the mind of people who don't currently feel as if they are living in the ruins, who haven't yet come to terms with the losses being experienced.

In Beijing, though, where Moore lives, it's different, particularly because of air pollution. "There's no denial—everyone can see what we're doing," he says. "We've made this mess; we should clear it up. You can't rely on nature to do it."

Holly Jean Buck is a fellow at UCLA's Institute of the Environment and Sustainability. This is an adapted excerpt from her upcoming book After Geoengineering: Climate Tragedy, Repair, and Restoration (September 2019, Verso Books).

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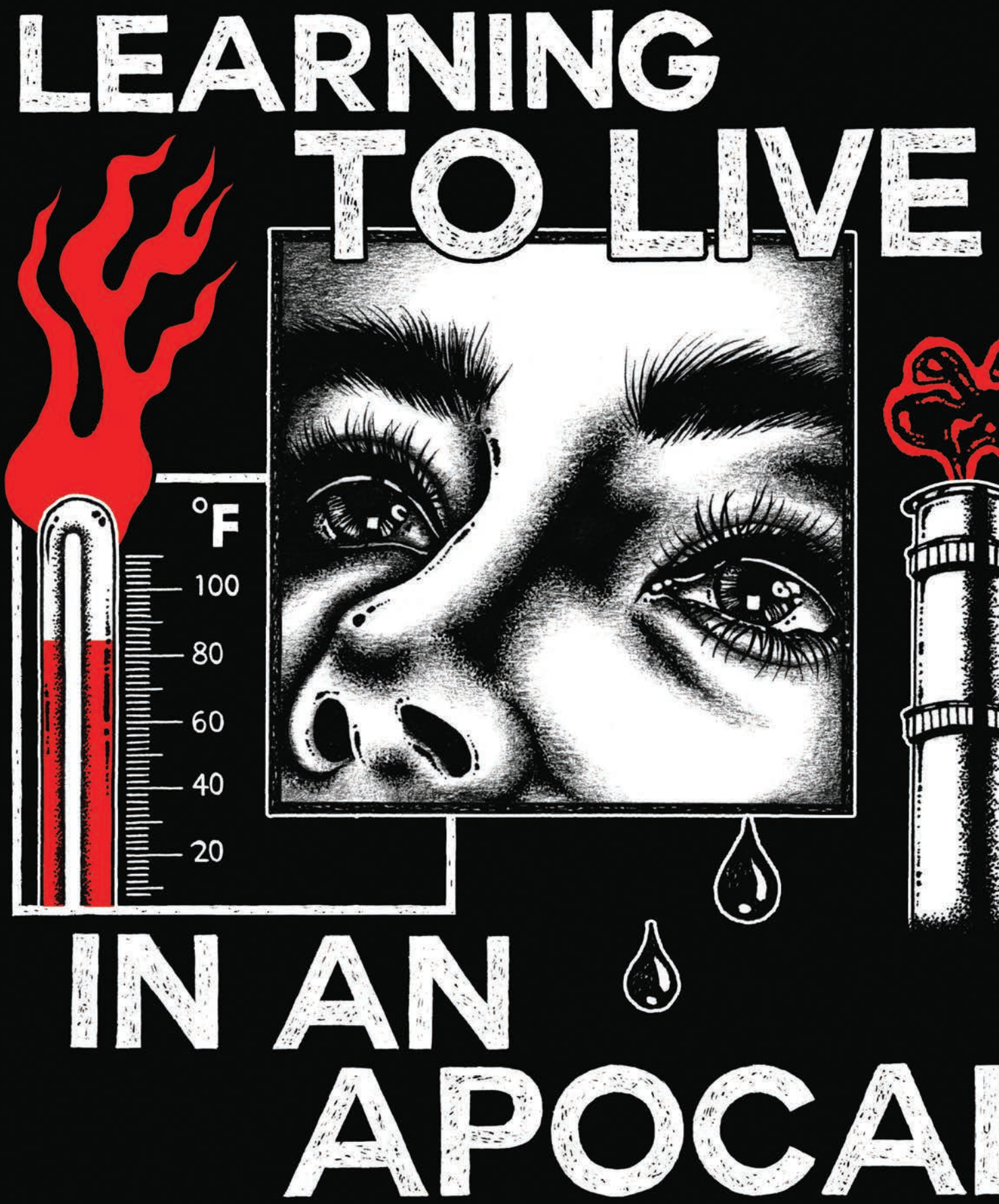
Suffering

"Year-round agricultural plenty; air-conditioned environments; vacations at the beach; skiing; morning coffee; a glass of wine at night; safety from natural disasters; abundant clean water; private ownership of houses and cars and land ... None of this is sustainable the way we do it now." — Roy Scranton on learning to live in a hotter world, page 64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Can we cope when our world changes irreversibly?

BY ROY SCRANTON

ILLUSTRATIONS BY KELSEY NIZIOLEK

The fantasy version of apocalypse always begins with the long-awaited event – a missile launch, escaped virus, zombie outbreak – and moves swiftly through collapse into a new, steady state. Something happens, and the morning after you're pushing a squeaking shopping cart down a highway littered with abandoned Teslas, sawed-off shotgun at the ready. The event is key: it's a baptism, a fiery sword separating past and present, the origin story of Future You.

Catastrophic global climate change, however, is not an event at all, and we're not waiting for it. We're living it right now.

In August 2018, in a summer of forest fires and shattered heat records, the strongest, oldest ice in the Arctic Sea broke up for the first time on record, presaging the final throes of the Arctic death spiral. In September 2018, the secretary general of the United Nations, António Guterres, gave a speech warning: "If we do not change course by 2020, we risk missing the point where we can avoid runaway climate change." The months following saw the US government crippled by a fight over whether to build a wall on the southern border to keep out climate change refugees, news that greenhouse-gas emissions have not decreased but in fact have accelerated upward, and a populist revolt in France sparked by opposition to a gas tax.

LYPSE

In the first weeks of 2019, new scientific reports appeared suggesting that we may have passed the point of no return. One found that particulate aerosols may be having twice the cooling effect previously estimated, meaning that more global warming would be happening were it not being tamped down by air pollution—and that curbing emissions would be likely to cause a spike in short-term warming. Another argues that the melting of Greenland's ice sheet may have crossed a tipping point and is expected to contribute substantially to sea-level rise this century. Another shows that Antarctica is losing six times more ice mass annually than it was 40 years ago. Yet another announced the discovery of a Manhattan-size cavity in Antarctica's Thwaites glacier, further evidence of the ongoing catastrophic collapse of the West Antarctic Ice Sheet, which could raise sea levels by 2.5 meters or more within a century.

Another report describes how extreme climate events such as droughts and heat waves decrease the amount of carbon dioxide that soil can absorb by as much as half, meaning that not only does global warming increase extreme weather, but extreme weather increases global warming. Yet another shows significant warming in Arctic permafrost, with Siberian permafrost having warmed almost a full degree Celsius between 2007 and 2016. That portends increasing Arctic methane emissions from the decay of thawing organic matter, a prediction borne out by another study showing a rapid increase in atmospheric methane levels from 2014 to 2017.

This growth in atmospheric methane is so strong that it would effectively nullify commitments made in the Paris climate agreement: "Thus even if anthropogenic CO_2 emissions are successfully constrained," says one paper, "the unexpected and sustained current rise in methane may so greatly overwhelm all progress from other reduction efforts that the Paris Agreement will fail." Yet another study shows that early spring rains in the Arctic brought on by global warming increase methane emissions from permafrost by 30%.

Meanwhile, the oceans are warming 40% faster than previously thought, according to recent research. Given current trajectories of carbon emissions and feedback dynamics, it is likely that mean global surface temperatures will be between 2 °C and 3 °C higher than preindustrial levels by 2050, which may well push Earth's global climate trajectory beyond the point where human action could stabilize it. A recent synthesis study argues that even 1.5 °C warming has at least a possibility of initiating "a cascade of feedbacks [that] could push the Earth System irreversibly onto a 'Hothouse Earth' pathway." Even more dismaying, a 2017 study argues that what many (including the UN's Intergovernmental Panel on Climate Change) identify as the "preindustrial baseline" for global warming starts too late and doesn't take into account factors such as early industrial emissions. This means we should probably add at least another 0.2 °C to measurements of current anthropogenic global warming over preindustrial norms, just to be on the safe side—which suggests, depending on how you measure it, that we may be approaching that 1.5 °C redline not in 20 years but in 10, or five, or three.

A new dark age

Imagine 2050. I'll be 72 years old. My daughter will turn 33. Wide swaths of now-inhabited coastlines and equatorial jungles and deserts will likely be uninhabitable, either underwater or too hot for humans to live in. People all around the world will likely have seen countless local and regional climate disasters, lived through major global economic shocks and catastrophic crop failures, and become used to random acts of violence as angry and sometimes starving citizens act out against increasingly repressive governments struggling to maintain control. In response to all this political, environmental, and economic instability, anxious populations will likely have traded their freedom in exchange for promises of safety, while security forces built more walls and nations began to fight over once-abundant resources like potable water.

If the political and social ramifications of global warming are anything like what happened during the last major climate fluctuation, the "Little Ice Age" of the 17th century, then we should expect a similarly horrific succession of famines, plagues, and wars. Historian Geoffrey Parker estimates that second-order effects of 1 °C global cooling that started around 1650 may have wiped out a third of the human population. Records from parts of China, Poland, Belarus, and Germany indicate losses of more than 50%.

In all likelihood, what's coming will be worse. According to Lloyd's of London, which in 2015 commissioned a study on food security, any single significant shock to the global food system "would be expected to generate major economic and political impacts." But as Earth's climate transforms into an environment human civilization has never before witnessed, we should realistically expect not one shock but an unending series of them. And this is presuming that global warming continues only at current rates, rather than accelerating nonlinearly as a result of the cascading feedbacks previously mentioned.

All of this will happen day by day, month by month, year by year. There will certainly be "events," like the events we've seen in the past decade—heat waves, massively destructive hurricanes, the slowdown in vital Atlantic Ocean currents, and political events connected to climate change, such as the Syrian civil war, the Mediterranean refugee crisis, France's *gilets jaunes* riots, and so on—but barring nuclear war, we are unlikely to see any one global "Event" that will mark the transition we're waiting for, make climate change "real," and force us to change our ways.

The next 30 years are likely, instead, to resemble the slow disaster of the present: we will get used to each new shock, each new brutality, each "new normal," until one day we look up from our screens to find ourselves in a new dark age—unless, of course, we're already there.

This was not the apocalypse I grew up with. It's not an apocalypse you can prep for, hack your way out of, or hide from. It's not an apocalypse with a beginning and an end, after which survivors can rebuild. Indeed, it's not an "Event" at all, but a new world, a new geological era in Earth's history, in which this planet will not necessarily be hospitable to the bipedal primate we call *Homo sapiens*. The planet is approaching, or already crossing, several key thresholds, beyond which the conditions that have fostered human life for the past 10,000 years no longer hold.

This is not our future, but our present: a time of transformation and strife beyond which it is difficult to see a clear path. Even in the very best case—a swift, radical, wholesale transformation of the energy system upon which the global economy depends (which would entail a complete reorganization of human collective life), coupled with massive investment in carbon capture technology, all occurring under the aegis of unprecedented global cooperation—the stressors and thresholds we confront will continue to put immense pressures on a growing human population.

Earth's climate is not a thermostat—we cannot just dump a bunch of carbon into the atmosphere and then pause it like a video game.

Goodbye, good life

Global warming cannot be properly understood or addressed in isolation. Even if we somehow "solved" geopolitics, war, and economic inequality in order to rebuild our global energy system, we would still need to address the ongoing collapse of the biosphere, the carcinogenic toxins we've spread across the world, ocean acidification, imminent crises in industrial agriculture, and overpopulation. There is no realistic plan for global-warming mitigation, for instance, that doesn't include some kind of control on population growth—which means what exactly? Education and birth control seem reasonable enough, but then? A global one-child policy? Mandatory abortions? Euthanasia? It is easy to see how complex and contentious the problem swiftly becomes. What's more, Earth's climate is not a thermostat. There is little reason to suppose that we can dump a bunch of carbon into the atmosphere, radically shock the entire global climate system, and then pause it like a video game.

It is psychologically, philosophically, and politically difficult to come to terms with our situation. The rational mind quails before such an apocalypse. We have taken a fateful leap into a new world, and the conceptual and cultural frameworks we have developed to make

sense of human existence over the past 200 years seem wholly inadequate for coping with this transition, much less for helping us adapt to life on a hot and chaotic planet.

Our lives are built around concepts and values that are existentially threatened by a stark dilemma: either we radically transform human collective life by abandoning the use of fossil fuels or, more likely, climate change will bring about the end of global fossil-fueled capitalist civilization. Revolution or collapse—in either case, the good life as we know it is no longer viable. Consider everything we take for granted: perpetual economic growth; endless technological and moral progress; a global marketplace capable of swiftly satisfying a plethora of human desires; easy travel over vast distances; regular trips to foreign countries; year-round agricultural plenty; an abundance of synthetic materials for making cheap, high-quality consumer goods; air-conditioned environments; wilderness preserved for human appreciation; vacations at the beach; vacations in the mountains; skiing; morning coffee; a glass of wine at night; better lives for our children; safety from natural disasters; abundant clean water; private ownership of houses and cars and land; a self that acquires meaning through the accumulation of varied experiences, objects, and feelings; human freedom understood as being able to choose where to live, whom to love, who you are, and what you believe; the belief in a stable climate backdrop against which to play out our human dramas. None of this is sustainable the way we do it now.

Climate change is happening—that much is clear. But the problem remains beyond our grasp, and any realistic solution seems unimaginable within our current conceptual framework. Although the situation is dire, overwhelming, intractable, and unprecedented in scale, however, it is not without historical analogues. This is not the first time a group of humans has had to deal with the failure of their conceptual framework for navigating reality. This is not the first time the world has ended.

When cultures collapse

Poets, thinkers, and scholars have pondered cultural catastrophe again and again. The ancient Sumerian Epic of Gilgamesh tells the story of humans surviving civilizational collapse caused by ecological transformation: Gilgamesh "brought back wisdom from before the flood." Virgil's Aeneid tells of not only the fall of Troy but also the survival of the Trojans. Several books of the Torah tell how the Babylonian king Nebuchadnezzar conquered the Jewish people, destroyed their temple, and exiled them. That story provided later generations with a powerful model of cultural endurance.

One historical analogy stands out with particular force: the European conquest and genocide of the indigenous peoples of the Americas. Here, truly, a world ended. Many worlds, in fact. Each civilization, each tribe, lived within its own sense of reality—yet all these peoples saw their lifeworlds destroyed and were forced to struggle for cultural continuity beyond mere survival, a struggle that the Anishinaabe poet Gerald Vizenor calls "survivance."

The philosopher Jonathan Lear has thought deeply about this problem in his book *Radical Hope*. He considers the case of Plenty Coups, the last great chief of the Apsáalooke people, also known as the Crow tribe.

Plenty Coups guided the Crow through the forced transition from life as nomadic warrior-hunters to peaceful, sedentary ranchers and farmers. This transition involved a harrowing loss of meaning, yet Plenty Coups was able to articulate a meaningful and even hopeful way forward.

The experience of Chief Plenty Coups and the Crow, as Lear explains, is that after the coming of the white man and the passing of the buffalo, "nothing happened." That is, when the Crow way of life collapsed, the Crow people could no longer find meaning for individual acts and occurrences within a rich web of shared signification, values, and goals. The Crow had survived, but they did not live as Crow had lived. In a strong sense, occurrences no longer had any meaning at all—which is to say there was no longer any such thing as an "event." The Crow faced the destruction of their conceptual reality.

This is not the first time a group of humans has had to deal with the failure of their conceptual framework for navigating reality. This is not the first time the world has ended.

Despite this, Plenty Coups offered his people a vision of a future in which meaning and events might once again become possible. He framed his vision through a dream he'd had of the disappearance of the buffalo. Within the dream, a chickadee teaches Plenty Coups to listen carefully, learn from his enemies, and "learn to avoid disaster by the experiences of others."

"The traditional forms of living a good life were going to be destroyed," writes Lear. "But there was spiritual backing for the thought that new good forms of living would arise for the Crow, if only they would adhere to the virtues of the chickadee."

Today the Crow—just like the Sioux, the Navajo, the Potawatomi, and numerous other native peoples—live in communities that struggle with poverty, suicide, and unemployment. But these communities are also home to poets, historians, singers, dancers, and thinkers committed to indigenous cultural flourishing. The point here is not to glamorize indigenous closeness to "nature," or to indulge a naive longing for lost hunter-warrior values, but to ask what we might learn from courageous and intelligent people who survived cultural and ecological catastrophe.

We must go on

Like Plenty Coups, we face the destruction of our conceptual reality. Catastrophic levels of global warming are practically inevitable at this point, and one way or another this will bring about the end of life as we know it.

So we have to confront two distinct challenges. The first is whether we might curtail the worst possibilities of climate change and stave off human extinction by limiting greenhouse-gas emissions and decreasing atmospheric carbon dioxide. The second is whether we will be able to transition to a new way of life in the world we've made. Meeting the latter challenge demands mourning what we have already lost, learning from history, finding a realistic way forward, and committing to an idea of human flourishing beyond any hope of knowing what form that flourishing will take. "This is a daunting form of commitment," Lear writes, for it is a commitment "to a goodness in the world that transcends one's current ability to grasp what it is."

It is not clear that we moderns possess the psychological and spiritual resources to meet this challenge. Coming to terms with the situation as it stands has already proved the struggle of a generation, and the outcome still remains obscure. Successfully answering this existential challenge may not even matter at all unless we immediately see substantial reductions in global carbon emissions: recent research suggests that at atmospheric carbon dioxide levels around 1,200 parts per million, which we are on track to hit sometime in the next century, changes in atmospheric turbulence may dissipate clouds that reflect sunlight from the subtropics, adding as much as 8 °C warming on top of the more than 4 °C warming already expected by that point. That much warming, that quickly—12 °C within a hundred years—would be such an abrupt and radical environmental shift that it's difficult to imagine a large, warm-blooded mammalian apex predator like *Homo sapiens* surviving in significant numbers. Such a crisis could create a population bottleneck like other, prehistoric bottlenecks, as many billions of people die, or it could mean the end of our species. There's no real way to know what will happen except by looking at roughly similar catastrophes in the past, which have left the Earth a graveyard of failed species. We burn some of them to drive our cars.

Nevertheless, the fact that our situation offers no good prospects does not absolve us of the obligation to find a way forward. Our apocalypse is happening day by day, and our greatest challenge is learning to live with this truth while remaining committed to some as-yet-unimaginable form of future human flourishing—to live with radical hope. Despite decades of failure, a disheartening track record, ongoing paralysis, a social order geared toward consumption and distraction, and the strong possibility that our great-grandchildren may be the last generation of humans ever to live on planet Earth, we must go on. We have no choice.

Roy Scranton is the author of We're Doomed: Now What? (Soho Press, 2018) and Learning to Die in the Anthropocene. He teaches at the University of Notre Dame.

The coming migration catastrophe

Climate change will make people move in large numbers. If we don't know where they'll go, we're courting disaster.

By
Susan Cosier

In 2006, the British economist Nicholas Stern warned that one of the biggest dangers of climate change would be mass migration. "Climate-related shocks have sparked violent conflict in the past," he wrote, "and conflict is a serious risk in areas such as West Africa, the Nile Basin, and Central Asia."

More than a decade later we're still trying to create models that might tell us where people might move, and when. Last year a report for the World Bank, the first to model migration due to climate change on a large scale, estimated that as many as 143 million people in sub-Saharan Africa, South Asia, and Latin America could have to relocate within their countries by 2050.

But is that a number we can trust? Modelers make many assumptions, like whether people will react the same way as they did to earlier climate disasters. Although models are improving, predicting how high seas will rise and how long droughts could last involves many unknowns. "There's still a lot of work to do in this field, and I think we're just scratching the surface," says Bryan Jones of Baruch College, one of the report's authors.

Modelers are trying to get more accurate numbers with new information from satellite images or mobile-phone data. But there are "constraints in using that technology," says Valerie Mueller, an economist at Arizona State University and author of a number of studies on climate-change-induced migration. For example, satellite imagery can be used to count populations, but changes in population could result from births and deaths, not just migration. SIM cards in mobile phones can show where the phone went, but not why; and more than one person might use any given phone.

The examples at right focus on migration within rather than between countries, because that's what most of the existing models focus on. Why? Because when people move, they don't usually go far—people forced into migrating typically don't have a lot of money, and if people in a neighboring country speak a different language, that's yet another disincentive to leaving the home country. And in some cases a potential destination country has physical or legal barriers that can compel people to stay close to home.

Improving these models is crucial, because if governments know where people might go, they can prepare for what's coming. For example, a city with great economic opportunities is likely to draw more migrants if a climate shock happens. If policymakers can get a better sense of how many people might arrive and when, they can prepare by directing investment to that area for affordable housing, hospitals, and schools.

"We're never going to get exact numbers," says Alex de Sherbinin of Columbia University, another of the report's coauthors, "but if people understand what the model is doing, they can get very useful information out of it."

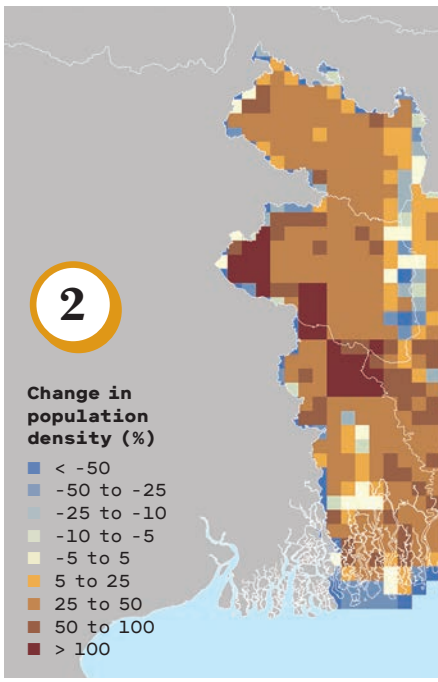
Migration predictions

Mexico

1 By 2050, climate change is expected to turn 1.7 million Mexicans into migrants. The arid north and low-lying southern regions of Mexico will be more prone to drought, wildfires, and flooding than the central plateau around Mexico City, so migration into urban areas will increase. Port workers and farmers from Veracruz and Tabasco will likely need to retrain for the urban economy of Mexico City.

Bangladesh

2 Researchers expect that 13.3 million Bangladeshis could be climate migrants in 2050. That's close to 8% of the projected population. The most likely migrant is a rural rice farmer moving into the Ganges River

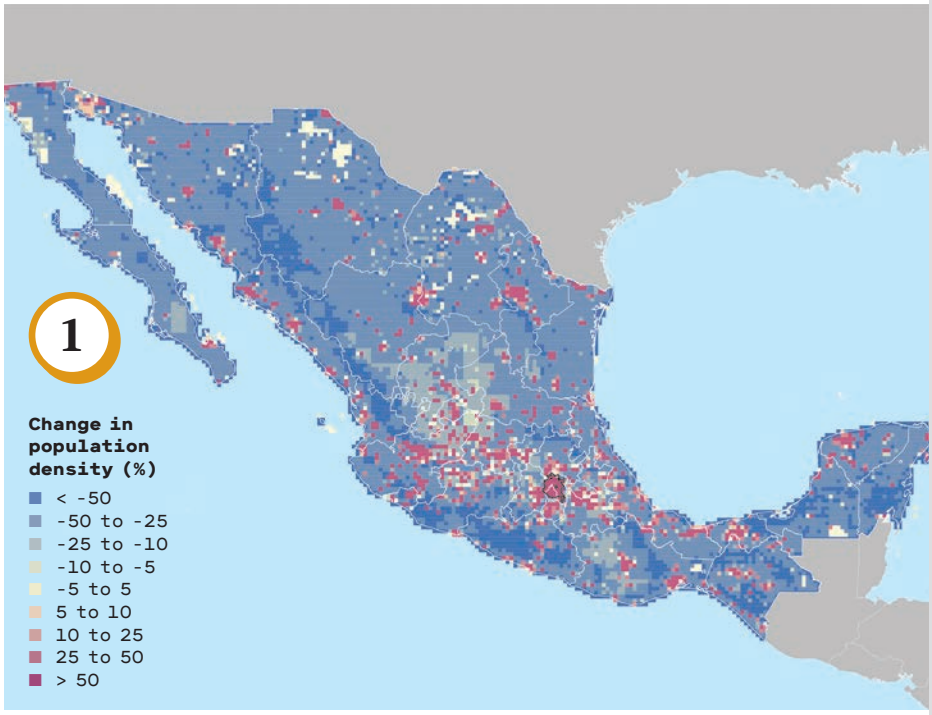


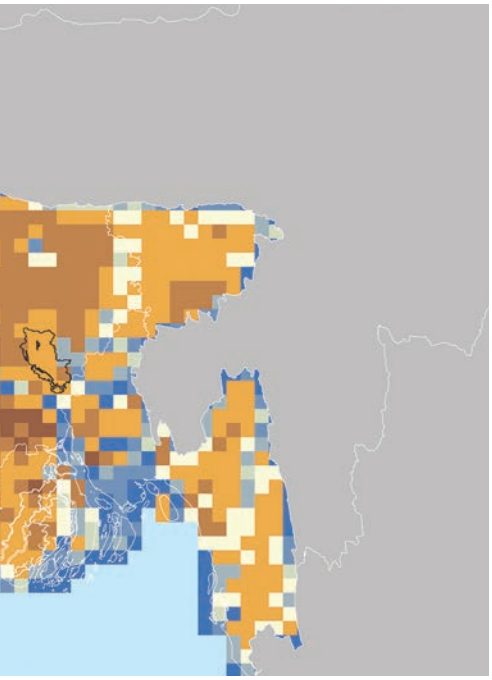
THE WORLD BANK GROUNDSWELL REPORT

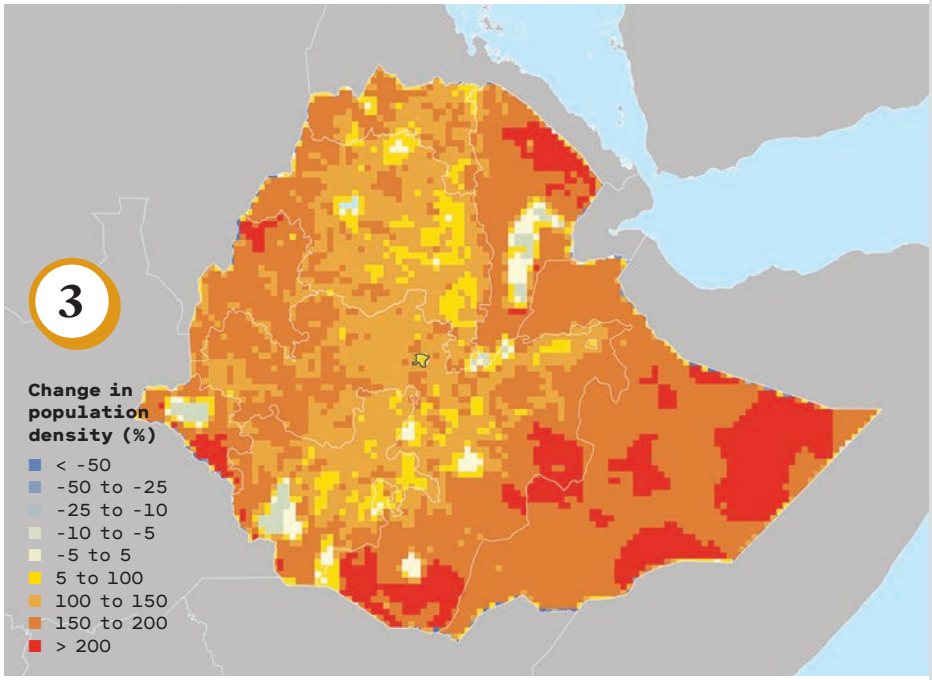
Basin—but since that region is already overcrowded, the migrants are likely to have a hard time finding work and shelter.

Ethiopia

3 As climate change worsens even moderately, it could cause water shortages in Ethiopia severe enough to prompt 1.5 million Ethiopians to migrate by 2050. They'll most likely move out of the northern highlands and Addis Ababa into the southern highlands and Ahmar Mountains. Addis Ababa lies at the center of Ethiopia's agricultural region, and lower crop yields will result in movement out of the urban center, which is currently the hub of the country's economic development.







PIPED

By **James Temple**
Photographs by **Saumya Khandelwal**

CLIMATE CHANGE IS GOING TO TIP INDIA INTO A WATER CRISIS. FOR MANY INDIANS, IT'S ALREADY HERE.

R E A M S


TATA

Severe droughts have drained rivers, reservoirs, and aquifers across vast parts of India in recent years, pushing the nation's leaky, polluted water systems to the brink.

More than 600 million Indians face "acute water shortages," according to a report last summer by NITI Aayog, a prominent government think tank. Seventy percent of the nation's water supply is contaminated, causing an estimated 200,000 deaths a year. Some 21 cities could run out of groundwater as early as next year, including Bangalore and New Delhi, the report found. Forty percent of the population, or more than 500 million people, will have "no access to drinking water" by 2030.

India gets more water than it needs in a given year. But the vast majority of rain falls during the summer monsoon season, generally a four-month window. The country's other major source is melting snow and glaciers from the Himalayan plateau, which feeds rivers in the north.

Capturing and delivering the water to the right places at the right times across thousands of miles, without wasting or contaminating tremendous amounts along the way, is an enormous engineering challenge. India captures and uses only a fraction of its rainfall, allowing most of it to run off into the ocean.

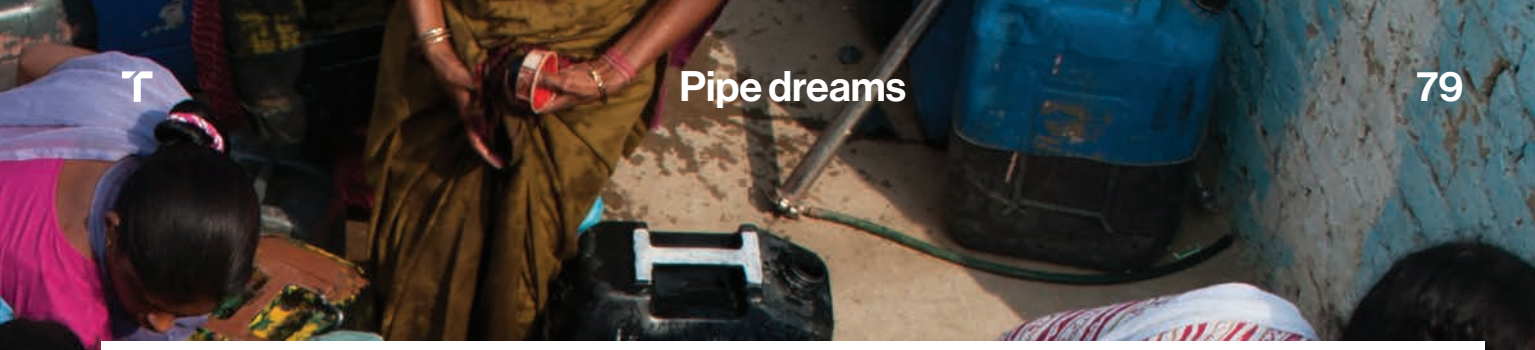
Meanwhile, farmers without efficient irrigation systems employ heavily subsidized electricity to suck up as much groundwater as possible. Agriculture is the single largest drain on India's water supplies, using more than 80% of the water despite accounting for only around 15% of the country's GDP.

"This is as alarming as any crisis you can imagine," says Pankaj Vir Gupta, a Delhi-based architect and professor at the University of Virginia, who helped launch a research effort in 2013 to identify ways to rehabilitate the highly polluted Yamuna River, the primary source of Delhi's drinking water.

FORCE MULTIPLIER

Climate change will surely make the problem worse. It's uncertain what role higher temperatures have played in recent droughts, as the climate models have mainly predicted increasingly intense

Saumya Khandelwal is a photojournalist based in New Delhi. These photographs of Indians living along the Yamuna River are from her larger body of work titled "The Dying Life Line," documenting life on the banks of the nation's highly polluted water bodies.



Indian monsoons. But the longer-term forecast is that the extremes will become more extreme, threatening more frequent flooding and longer droughts.

Most climate studies predict that India will get more rain on average in the decades to come, though regional and seasonal patterns will vary sharply. A paper published last year in Geophysical Research Letters found that flash flooding will significantly increase in 78 of the 89 urban areas evaluated if global temperatures rise to 2 °C above preindustrial levels. The resulting catastrophes will disproportionately harm India's poor, who frequently settle along the low-lying floodplains of major cities.

Sea-level rise threatens to deluge villages and megacities, and poison the water tables, along the subcontinent's 7,500 kilometers (4,660 miles) of coastline between the Arabian Sea and the Bay of Bengal.

Finally, climbing temperatures and shrinking snowfall will accelerate the melting of the Himalayan glaciers, the wellspring of major Asian waterways including the Ganges, Indus, Yangtze and Yellow rivers. In some regions, under high emissions scenarios, glaciers could shrink by as much as half by midcentury and 95% by 2100.

Initially the increased runoff will swell rivers, raising the risks of downstream flooding but sending Indians more water. That trend is likely to shift into reverse in the second half of the century, however, shrinking the flow to around 1.9 billion people who live along those rivers. The Ganges basin alone supports 600 million people, provides 12% of the country's surface water, and accounts for 33% of GDP.

"There are already a lot of stressors on India," says Navroz Dubash, a professor at the Centre for Policy Research in New Delhi. "But climate change is going to be a force multiplier."

Whether shoddy infrastructure or climate change is to blame for India's water sources running dry or turning toxic won't, in the end, much matter in the minds of the victims. And either way, India will need to grapple with present-day disasters and fortify infrastructure for worse dangers to come—all with fewer resources than rich nations and without derailing its economic growth.

THE RIVER GODDESS

The Yamuna River originates in the ice of the Yamunotri Glacier, a suspended body of water slipping under its own weight down the cirques and gullies of the Lower Himalayas.

Trickles become tributaries that steadily merge, widening and deepening as they descend the range, and snake through the foothills toward the vast fertile plains of northern India.

In the Yamuna Nagar district of Haryana, the river runs into a giant concrete wall. The dam, the Hathnikund Barrage, forces it into a sharp right turn, diverting 97% of the Yamuna's flow down the western canal. It feeds 1,200 kilometers of waterways that irrigate the alluvial soils of the so-called grain bowl state, Gupta and his coauthor, Tulane's Iñaki Alday, write in *Yamuna River Project: New Delhi Urban Ecology*.

The Wasirabad Barrage north of Delhi, about 250 kilometers downstream, seizes nearly everything that's left. That water is filtered through water treatment systems and piped to households and businesses across a metropolitan area of more than 25 million people.

It would be nearly enough water to supply the whole city if it actually reached people. But the aging system of pipes is leaking and corroded, is subject to illegal tapping, and simply doesn't extend to nearly 20% of households. Around 40% of the water is lost.

The gap between what's needed and what's supplied is largely filled by hundreds of thousands of illegal, community-dug borewells around the city—and by what's known as the "water mafia." Depending on whom you ask, these are entrepreneurs filling the market void by tapping wells and delivering the resource in tankers to homes, apartment buildings, and businesses—or a cartel that sets exorbitant prices and occasionally resorts to strong-arm tactics to ensure demand.

What's left of the Yamuna, after the Wasirabad has siphoned off most of its remaining water, runs through Delhi in a 22-kilometer stretch that is more of a sewage line than a river, the catchment for thousands of drainage basins that wind through the city, channeling the toxic runoff from homes, slums, businesses, and factories.

TOXIC SLUDGE

On an early afternoon in late February, Gupta drives me to one of New Delhi's drains near the sprawling, manicured grounds of the Sunder Nursery, a historic park in the center of the city. He weaves between concrete barriers and noses into a pull-off at the edge of an overpass.

There's a sharp smell of sulfur in the air. Gupta steps out, walks up to a low wall, and points down into the Barapullah drain.

It's a body of black muck that traces the curve of the overpass. A cluster of wire-haired boars root through trash that climbs the embankment, where they feed on sewage and garbage.

"And somebody's going to slaughter and eat them," Gupta says.

A healthy drainage basin would carry rainwater throughout the city, recharging aquifers and feeding the river. But slums without pipes and businesses without scruples dump sewage, garbage, and chemicals that all funnel into these channels. The sludge and waste is so thick in places that it prevents water from percolating underground, or poisons the water table when it does.

"And that's what we're dealing with for hundreds of kilometers in Delhi," Gupta says.

The gap between what's needed and what's supplied is largely filled by hundreds of thousands of illegal, community-dug borewells around the city—and what's known as the "water mafia."

The growing population has placed enormous strains on groundwater both by sucking it up faster than it can be replenished and by polluting the water bodies that recharge it.

The Yamuna itself is largely disconnected from the city, partitioned by embankments and hidden under highways. But a vast number of the city's poor have taken up residence on the dangerous side of the berms and flood walls, squatting in the shadow world of the Yamuna's wide, forgotten floodplains.

The following afternoon, as a blue sky emerges from the brown-orange particulate haze for the first time in days, young boys play cricket in a column of dirt on the eastern bank of the inky-black river. Up a small hill, a group of young women and girls picks vegetables from a small patch of green rows, next to a jumble of tin and wooden shanties.

In a 30-minute walk along this low-lying district of Delhi, near the Yudhister Setu bridge, I spot six water pumps within 200 yards of either bank of the river, one some 10 feet from the shore. Four are metal handpumps that can reach only into the shallowest of the water tables.

These kind of wells, settlements, and crops are illegal, and hazardous. The water and soil are almost certainly contaminated by the river and drains.

Samples taken along the banks routinely show high levels of lead, mercury, and other heavy metals. Intense flash floods that seem to be increasingly common during the summer monsoons regularly inundate the plains, washing away shelters and people.

THE PROBLEM WITH LARGE-SCALE SOLUTIONS

India's states have created climate adaptation strategies that call for big changes in behavior. The southern state of Karnataka, for instance, developed a plan recommending increased use of rainwater harvesting structures, wider adoption of drip and sprinkler irrigation in agriculture, tighter restrictions on borewells, and improved sewage management to prevent water bodies and aquifers from being polluted.

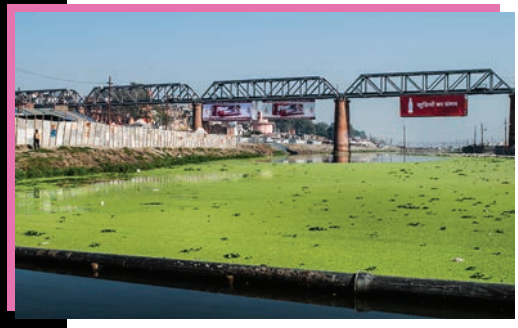
But experts say these plans would be incredibly difficult and expensive to implement, and inadequate even if they were realized.

India needs to overhaul the way it uses water. The dry parts of the country will have to create jobs in industries other than agriculture, which currently employs nearly half the workforce. Cities will need to build modern networks of water and sewage pipes, treatment facilities, and wetlands, and restrict development and

add flood protections along waterways.

But one of the most effective ways of dealing with an erratic water supply is to add storage, says Veena Srinivasan, a senior fellow at the Ashoka Trust for Research in Ecology and the Environment. That can mean everything from small-scale, private efforts like capturing rain on rooftops to centralized, large-scale dams, canals, and reservoirs.

The federal government generally prefers the latter. The most obvious and ambitious example is known as the Indian River Inter-link, a civil engineering project costing more than 5.5 trillion rupees ($80 billion) that would stitch together more than 60 of the nation's rivers into a network. The idea is that the government could smooth out imbalances across thousands of miles, sloshing water from a flooded area on one side of the country to a drought-gripped region on the other.



The concept dates back to the 19th century, but it's getting a boost from Prime Minister Narendra Modi, who pushed through approvals for the first phase. Critics say it's a boondoggle in the making, driven more by the political appeal of a silver-bullet solution than by any scientific evidence that it will work.

In a nation as large and spread out as India, any broadly workable strategy requires better water management at local levels, Srinivasan says. That means capturing and filtering rainwater in tanks; rehabilitating lakes, ponds, and rivers; and using both to recharge aquifers. "You've got to rely on groundwater, which means you've got to figure out ways to manage it," she says.

BANGALORE'S SEWAGE MIRACLE

On a morning in early March, Vishwanath Srikantaiah leads me on a tour around Jakkur Lake, a bowling-pin-shaped body of water in Bangalore.

Srikantaiah, a 55-year-old civil engineer turned water activist, is known as the "Zen Rain Man" of the swelling megacity, in the southwestern state of Karnataka. Standing a willowy 6′ 4″ (1.93 meters), with a full beard and long, wavy, graying hair, he looks the part.

Along the northeastern shore, he steps off the walking path around the lake and onto a thin trail leading into the surrounding wetland, a bright green thicket of cattails, water hyacinth, and alligator grass.

About a hundred yards down the trail, he gestures toward a channel at the edge of the grasses, where a stream of burbling water feeds into the lake. "You can see it's absolutely clear water coming in," he says.

Days earlier it was raw sewage.

Most of Bangalore's water is pumped up from the Cauvery River, around 100 kilometers south of the city. But about 40% of the residents rely on groundwater, largely drawn up from hundreds of thousands of borewells plunging into the ground throughout the city. The growing population has placed enormous strains on that resource both by sucking it up faster than it can be replenished and by polluting the water bodies that recharge it.

Srikantaiah helped form Bangalore's Rainwater Club in 1991 to help people install rooftop rainwater harvesting systems. They're little more than open pipes that collect water at the ebb of an angled roof and then run it through a filter into a tank. But the water can be stored and consumed or sent down wells to replenish aquifers.

Srikantaiah and his wife, Chitra Vishwanath, an architect who focuses on ecological design, later formed a nonprofit that lobbied the city's utility to set up a water treatment plant at the edge of Jakkur Lake. The growing neighborhood had polluted the lake for years.

Now wastewater runs through the plant and then down canals into the wetlands for further filtering. By the time it works its way through the thick grasses, some three days later, the water is clean enough to support commercial fishing, irrigate nearby farming, and replenish groundwater tables. The district's residents eventually draw that water back up through borewells, run it through home reverse-osmosis machines, and use it to drink and cook.

It's not a perfect solution, Srikantaiah says, pointing to a channel of untreated sewage that bypasses the plant and runs straight into the constructed wetlands. But the lake is far healthier than it was a decade ago, and the rehabilitation effort is seen as a model for restoring other water bodies in the city.

Srikantaiah says these local projects make real differences in real lives, faster and more reliably than some long-studied, large-scale scheme. "It's just so important that you pick a lake, start working from the bottom up," he says. "Show something. Do something."

DEALING WITH DELHI

But there's no way to solve some of the nation's most vexing water problems without tackling the overlapping developmental, environmental, and economic challenges all together, Gupta says. His book lays out a richly illustrated vision for rejuvenating the Najafgarh drain, a more than 50-kilometer stretch of water that winds through the western side of Delhi before flowing into the Yamuna. It and its subdrains contribute more than 60% of the pollution that pours into the river.

The proposed project would create continuous parklands along these basins, with bike paths, transit lines, markets, public space, and low-income housing alongside lush wetlands. The long green grasses would filter sewage, in conjunction with new sewer pipes and treatment plants, cleaning the water that recharges aquifers and feeds the river. It's a grand proposal, if one that ultimately seems farfetched. The Delhi Jal Board, the body in charge of supplying water to citizens, is struggling with far more rudimentary tasks. Instead of installing water pipes to unconnected neighborhoods, it's often delivering water by tanker from its own borewells north of the city. The board launched an effort to restore dozens of city drains and water bodies three years ago, including many along the Najafgarh, but has completed only one pilot project to date.

A major, multi-department effort to clean up the Yamuna starting in the 1990s failed to measurably cut pollution, despite costing billions of dollars. Many of the planned sewage plants weren't built or didn't work, an outcome variously blamed on poor coordination, corruption, or the inability to halt mushrooming development along the drains.

In the next three years, the city must finalize the "Master Plan for Delhi 2041," creating a legally binding document that will guide development and planning for the coming decades. Rehabilitating the Yamuna will be one of the highest water priorities in the plan, says Jagan Shah, director of the National Institute for Urban Affairs, the agency overseeing the effort.

"But it's not an easy exercise to pull off," he acknowledges, nodding to the many earlier failures. "The scenario is not encouraging."

As Gupta drives past the slums of the Nizamuddin neighborhood, a collection of tents and shacks that dump waste directly into the Barapullah drain, I ask if, in his most honest moments, he really believes that Delhi will clean up the Yamuna.

"As an architect I have to be optimistic," says Gupta, who is 48. "But don't ask me for a time line. Because sometimes I don't think it will be in my lifetime."

James Temple is MIT Technology Review's senior energy editor.

How bad will it be?

One of the biggest sources of climate uncertainty is how clouds will behave. Tapio Schneider's powerful new model should give us some answers.

By Mallory Pickett
Portrait by Ryan Young

The severity and speed of climate change will depend on the quantity of greenhouse gases we emit into the sky, but also on how sensitive the climate is to those gases.

One uncertainty is how clouds will respond as the atmosphere heats up. Tapio Schneider, a climate scientist at Caltech, and his colleagues from Caltech, Princeton, JPL, and MIT are building a climate model that will use machine learning, powerful computing, and petabytes of data to help resolve some of the unknowns around how, why, and where clouds form, produce precipitation, or dissipate. The goal: to cut the uncertainty in current predictions of carbon dioxide's impact on the planet in half.

Science journalist Mallory Pickett sat down with Schneider to find out how his research will do this, and why it matters.

How much uncertainty is there in current climate models?
There is a measurement called "climate sensitivity." It's the global mean surface-temperature increase that you get after doubling CO_2 concentrations and letting the system equilibrate. With current climate models, the climate sensitivity for doubling CO_2 ranges somewhere between two degrees [Celsius] warming up to five degrees warming.

What are the implications?
Take the two-degree target of the Paris agreement. We've had about one degree of warming already, so it's one more degree to go. How much more CO_2 can we put into the atmosphere before we have warmed Earth another degree?

For a model that has a climate sensitivity of around two degrees, you can get to CO_2 concentrations of close to 600 parts per million. We're at 410 parts per million, so even if we continue emitting a lot, we won't reach 600 before 2060 or so. In a model that has a climate sensitivity closer to five degrees, [one more degree requires] about 480 ppm, so that's only about 70 to go. That's something we'll reach in the next two decades or so.

Why the uncertainty?
The single biggest contributor is uncertainties about clouds, and specifically about low clouds in the tropics. Low clouds over tropical oceans reflect sunlight because they are white, and this cools the Earth. We don't know if we'll get more or fewer of them as it warms, and that's the key uncertainty in climate predictions.

One other important piece is how much carbon is being taken out by the biosphere. Right now only about half the carbon that humans emit ends up in the atmosphere. The rest is taken up by oceans and the land biosphere, and we don't quite know where it goes.

If there's so much uncertainty, do we really even know that things will get bad with a lot of CO_2?
When you put more CO_2 or other greenhouse gases in the atmosphere, they absorb thermal radiation. What happens if you put more of these greenhouse gases in the atmosphere is that everything else being equal, you ought to warm the surface. The physics of that's completely clear, undisputed by any serious scientist.

Where the uncertainties come in is to say, well, how much warmer will it get? What happens to these little clouds? They reflect a lot of sunlight. If we get more of them and more sunlight will be reflected, it will be less warming. If you get fewer of them, you have an amplifying feedback effect where you get more warming.

Are things worse than predicted?
I think the evidence in recent years—for example, from studies looking at cloud variations over the past decades—points more toward higher climate sensitivity.

The goal is to cut some of these uncertainties in half. How will you do that?
We want to use the data we have available: terabytes per day coming down from satellites. We want to assimilate those data into the model. That's a computationally challenging task, but it's just doable now and will give you a model that simulates a present climate better.

If climate sensitivity is on the high side, how worried should we be?
I would be very worried. It would mean higher heat extremes, especially in summer. It means more extreme precipitation in places like the [US] Northeast. It is possible the climate sensitivity is on the high end of what models predict, and if that's right then we'll experience severe impact in our lifetime, certainly in our children's lifetimes. Simply put, the higher the climate sensitivity, the more worried we should be.

By Paolo Bacigalupi

A full life

By the time Rue reached 15 she had begun to measure her life by her many moves, the parchment of her life torn into fragments, each one reducing the integrity of the whole. Each small leaf then folded. Folded and shaped until it became surreal origami. Tear here. Fold there. This part became a house, burning down. Tear here, fold again. This shred became a rusty diesel truck, driving south. Tear again. Fold. This bit became an apartment building, without a roof.

Tear here. Tear again. Make a casket.

Keep tearing.

Rue's first move came when she was eight, her mother and father selling the small-acreage farm they'd cultivated in a Colorado valley. They'd been part of a late-millennial wave of hipster farmers, fleeing the cities' meaningless consumerism for something more natural. They'd grown organic microgreens for farm-to-table restaurants in nearby ski towns.

"We live like people are supposed to live," her father said. "Slower. More connected. Focused on the land."

Then the Maroon-Treasury Fire burned Aspen. When the smoke cleared, trees stood barestick black against hot blue sky and the air reeked of char. Ski slopes drifted with ash moguls, then slumped with mudslides.

In the aftermath, Rue collected trophies from amongst the blackened Anasazi-like ruins of billionaire mansions, picking her way through concrete foundation outlines. Aluminum puddled in silver castings, rivulets of melt. Glass globs sparkled, treasure gems, the remnants of picture windows.

At first, Rue's mother and father had laughed, seeing people who had complained about dirt specks in their radish greens fleeing an inferno that cared not for their wealth. A certain schadenfreude was inevitable. But other mountain towns were dying as well, drought whittling away their picturesque scenery, thinning their snowpack, and choking their summer skies with smoke.

Rue's parents might have held on, but failing snows meant inadequate irrigation water, and soon their domestic water failed too, the aquifer below their home unable to recharge. Old-timers laughed that they'd bought land with bad irrigation rights and a crummy well.

"My dad says you should have seen it coming," Rue's friend Hunter said. "Everyone knows how water rights work. 'Course your water got cut off."

"It never happened before," Rue retorted.

"My dad says you should have known."

They stopped talking because of that. Soon after, Rue moved.

Later, Rue heard that Hunter's family went dry too—a family that had ranched and farmed the same land for six generations. Rue wrote a text asking if Hunter's dad should have seen it coming. But she deleted it before sending.

Rue was sad about that first move, leaving her small familiar town. She remembered the moving truck belching diesel

DAVID MCNEW / GETTY

SCOTT OLSON / GETTY

smoke, reeking and clanking unlike the electric pickup they'd used for the farm. Her mother told her they couldn't take her big clothes dresser with them.

"We can't fit it in the Austin apartment, sweetheart."

Her mother gave her a new phone, to console her. Rue couldn't take big furniture, but she could have her first phone. That, at least, was portable.

On the drive south, Rue called her grandmother.

"Oh, sweetpea," Nona consoled. "I know you're sad. But there's a silver lining to this. There's a big world to learn about. Plus, you'll get to see the bats."

"The bats?" Despite herself, Rue was intrigued.

"There are bats in Austin. Lots of them."

Seeing more of the world meant you were less ignorant than if you just lived in one small place all your life, and that was a good thing.

That's what Nona said.

Nona never really approved of college kids being farmers, so she was glad they were moving.

That's what Dad said.

In Austin, Rue's mother played ukulele in a band and her father drove an electric delivery truck. Some nights they'd walk along the Colorado River, watching bats stream out from under the Congress Avenue Bridge to catch insects. The city skyline glowed in the sunset, the buildings newly covered with perovskite solar skins, all of them a little shiny because of it.

Some people said things weren't the same as before. Some of the bats were invasive—bloodsuckers instead of insect eaters—but they were still bats, and Rue liked them.

Rue's new school was big, with way more friends than just Hunter. Also, there was a ballet class, and a tae kwon do class. Plus an old lady with purple hair who taught rock drumming.

"You see?" Nona said. "Things work out."

But then came a summer night when the electric grid went down. A hundred and ten degrees at 3 a.m. Everyone already on water restrictions. Pitch-dark in the middle of a city. Everyone out on the streets, desperate to catch a breeze. Everyone complaining. Blaming environmentalists, battery companies, natural-gas companies, Austin Energy, federal regulations, Texas's love

affair with low taxes. Rue's dad said Texas hadn't anticipated how record heat would stress their grid.

Rue got heatstroke; her parents decided to move. Rue's mother already had a job working remotely for a Miami-based mortgage company. She could get a promotion if she moved in-house.

In Miami, Rue's father drove a three-wheeled short-range electric hauler, delivering iced fish to restaurants. Rue swam sometimes in the ocean, when jellyfish and algae weren't choking up the coast. It was okay.

During their weekly phone chats, Nona told her about cubanos.

"You see?" Nona said, when Rue tried one. "It's better when the sugar brews into the coffee. I first tried one when I vacationed in Cuba. But Italian espresso is the best."

"How do you know all these things?" Rue asked.

Nona laughed. "Well, I lived a full life. And it was much cheaper to fly back then. It's harder now with all the aero-taxes."

"I wish I could fly places."

"Well, maybe we'll save our money and go to Italy."

Then Annaleen hit. The hurricane wasn't serious by Florida standards but it seemed big to Rue: Cat 4 on the New Meteorological Scale.

"It's nothing," her father told her as rain lashed their apartment windows. "The new scale goes to 11."

Her mother laughed and made an air-guitar motion. Rue didn't get the reference, so they showed her *Spinal Tap* on YouTube.

Rue laughed with her parents—because they were laughing at the idiot guitarist and his amp—but the clip didn't make her feel safe so much as make her wonder what a hurricane that went to 11 might feel like.

A month later, Carrie hit. Carrie accelerated from NMS Cat 3 to Cat 9 during two phenomenal days. The governor declared a state of emergency. Florida huddled down, unable to flee. Water boiled up out of storm drains and filled the streets long before the worst winds hit. Miami's brand-new seawalls disappeared, swamped on both sides. The sheer volume of water overwhelmed the city's new pumping stations. They shorted and shut down.

Rue huddled with her parents and members of her mother's new band in their apartment. The Blue Palms was the safest apartment complex in the neighborhood, built to endure the New Meteorological Scale.

"The Blue Palms are rock solid," her father said. "When we moved here, I thought this through."

Down on the street, the band's van floated away. Literally floated.

Rue watched people float away, too.

Before Miami could recover from Carrie, Delia hit. Just bad luck, everyone said. But to Rue, it was starting to feel like God was bowling against them. There wasn't enough time to recover, to breathe, to restock supplies. God just kept bowling. Delia ripped the roof off the Blue Palms. Popped it off like a can opener.

By the time sunny skies returned, their windows were gone and one wall had crumbled. Something big and heavy had blasted into the masonry and then flown away. A car? A tree? A bus? No one could say.

They used bedspreads and sheets to cover the windows, makeshift shelter while they waited for maintenance to fix things. Then word came down that the apartment company was abandoning the building. Its insurance company was going bankrupt from too many claims, so the apartment company was walking away too, leaving everyone squatting in the ruins.

"Well, on the bright side, at least we're not paying rent," Rue's mother joked.

A dark bright side, because the mortgage company that employed Rue's mother was going bankrupt too. With insurance failing, people were walking away from wrecked homes, leaving mortgages unpaid, sending ripples through the financial system. Why pay mortgage on a house that would never be fixed?

"Where's FEMA?" her father complained as he pumped brown water through a handmade filter of charcoal and sand and paper towels. "There should be some kind of backup for this." Sweating and dripping with the work. Shirtless. He was skinny, Rue realized. Not as big and strong as he'd seemed when she was younger. Just a scared skinny man, with new streaks of white in his bushy beard. "There were supposed to be emergency funds for this."

"They're doing what they can with what they've got," Rue's mother soothed. "There are other places that need help too. They're overwhelmed."

That was the crux of the problem. God had gone bowling all across the South. Fort Lauderdale, Tampa, and Mobile, Alabama, all had been hit hard. Over in Texas, Houston had gone under again. Corpus Christi, too. And that was just the big cities—the places people could name. All the small towns? Maybe they were there. Maybe they were drowned and gone. Who could say? No one could get there to find out.

As for Miami, it was finally draining. The streets reeked of ancient motor oil and fish and shit and garbage that had boiled out of sewers and dumpsters and basements. Flies and mosquitoes and orphaned dogs swarmed over it. But at least the city was draining.

Some people said Miami had enough money to survive. Boosters were already imagining a future hurricane-hardened version of the city. Now that they'd drowned, they could visualize the armored Venice-like Miami they should have built the first time. They'd make their buildings float, goddamnit.

Money liked Miami, Rue's mom said, so maybe the city really would make it.

New Orleans, on the other hand? New Orleans was a bathtub. And money didn't give a damn about New Orleans.

Money was racist—that's also what Rue's mom said.

Unlike money, mosquitoes didn't discriminate. They loved all the cities on the coast equally, and all the people too. Mosquitoes

snuck through the broken windows, the high whine of their wings always in Rue's ears, the welts of their bites always on her skin. Screening was sold out. FEMA mosquito nets had been hoarded. Walmart kept saying delivery trucks would come soon, for sure. Everyone got covered with bites.

They all got fever from it.

Nona said it was a new malaria strain, something the CDC had warned about, but it hadn't been faced because the damn Republicans kept cutting funding. Now here the disease was, just like epidemiologists had predicted. For some reason, kids and old people survived better. Middle-aged people often died.

That's what Rue's dad did.

Nona cried when Rue and her mother Skyped the news.

"Why was Dad so mad at Nona?" Rue asked later. "Why didn't he want to live around her?"

Her mother made a reluctant face. Finally she said, "Nona was always complaining about problems, but she never lived like she needed to do anything about them. And she hated that we tried to farm. I think she felt like we were insulting her. Judging how she lived her own life."

"But you were, right?"

"It bothered Dad a lot that Nona made certain choices. Especially after you were born."

"Like flying in airplanes?"

"And cars. And eating meat." She shook her head. "Anyway, that's all a long time ago. Everybody did it, and they all made it worse for everyone. Not just Nona."

Later, Rue asked Nona about it. "Mom says Dad was mad at you because he didn't like how you lived."

"Oh, sweetpea. This is the world we live in. We have to take at least a little joy in it." Her eyes were wet. "Life's short. We have to enjoy something. You should enjoy something too. I wish you had something you could enjoy."

She sent Rue some money on her phone, to buy something nice, but Rue didn't know what that would be. Their apartment was a wreck and they were about to move again. Rue didn't want more things. Except maybe a mosquito net.

Rue wondered what it would have been like to fly to the far side of the world. To go to someplace like Italy to drink espresso. Or fly to Japan and see the temples of Kyoto, where Nona had once gone to meditate. Nona hadn't sent enough money for either of those things.

Nona wanted them to join her in Boston, but Rue's mom preferred New York. They went to live with her brother, Armando.

Uncle Armando said the people in Florida deserved what they got.

"Those lame-ass seawalls! Some political appointee just made up the standards! That's why Manhattan used the European standards. Say what you want about the taxes here, at least we don't fuck around with our science." He shook his head at the stupidity of Miami as he cut into his steak. "Of course they were fucked," he said, gesturing with his fork as he chewed. "They were fucked from the moment they used those shitty American standards."

"Please don't say it that way," her mother said, rubbing her temples. She hadn't touched the meat on her plate.

"Say what? Fucked?"

"You know I don't like it."

"Five cities are underwater, and you're worried about my fucking language?" He laughed in disbelief. "The *language* is what bothers you?" He shook his head, gestured at her plate. "Try the steak," he said. "It's Kobe Rainforest."

"I'm not hungry."

"Carbon-free? Cruelty-free? It's right up your alley. You can't even tell it's vat meat. Zero methane, zero deforestation. Your husband would have loved this sh— this stuff. Give it a try."

"Maybe later."

"Suit yourself." He cut another chunk for himself. "You like the steak, Rue?"

"Yeah. It's good."

"Damn right it is." He forked another bite. Returned to his previous point, talking around the mouthful. "Some jackass lobbyist for some oil company wrote that shitty standard. Just like lobbyists did with mercury and methane and all the other crap. And then dumb-ass Miami just went ahead and used the sea-rise estimates. Fucked themselves, is what they did."

"Armando," Rue's mother said. "There are real people involved. It's not just one of your investment spreadsheets."

"You know I shorted Miami, right?"

Her mother glared. Armando subsided. But the word lingered in Rue's mind.

Fucked.

She was more than old enough to know the word. She knew how to say it in six different languages, thanks to the kids she'd met in her different moves. They used it all the time: who fucked who; how fucked-up the vocab test was; fuck you; fuck me; FUCK PRINCIPAL VASQUEZ—that was a Snapchat group. But the word had been casual, and they'd used it casually. They hadn't felt it. They hadn't understood it.

Miami was fucked, and now the word finally sounded right.

Fucked.

Hard and nasty and mean.

It described the world Rue experienced every day. The one the grownups in her life seemed bent on pretending didn't exist. Like if they pretended really, really hard, they'd be okay. Like they'd pretended the Miami seawalls were big enough. Like Nona had pretended that flying on airplanes was fine. They'd closed their eyes and pretended.

And now everyone was fucked.

It was almost a relief to have Armando say it. To have that word squat on the dinner table with the organic kale and the arsenic-free brown rice. It gave shape to an unformed feeling that had been lurking in Rue's mind for some time. Something

RALPH FRESO / GETTY IMAGES

she'd been unable to name or describe because all the grownups around her hadn't been honest enough to speak it clearly.

It felt like a door being kicked open.

As soon as Armando said it, it felt blazingly obvious. And now that Rue could see it, she could see it everywhere. In the cost of bread and cheese and vegetables and chicken. In the kids begging on the streets. In the storm warnings as winter hurricanes made their way up the coast, dropping rain and jamming rivers with ice floes and slamming against Manhattan's own seawall barriers.

Rue's mom had promised New York would be good for them. It was where she'd grown up. But Old New York was different from Fucked New York. Armando was the only one with a job, and things were changing, even for him.

All over the country, people's homes were being destroyed by sea-level rise, forest fires, droughts, storms, and floods. People were going reffee, and leaving behind ruined houses. And mountains of debt. So now, along with mortgage companies and insurance companies, banks started failing. Armando's shorting of Miami—he'd explained to Rue that "shorting" meant "betting a place was going to get fucked"—only worked if there was a safe place to stash his winnings.

Six months after Rue and her mother moved to New York, the FDIC collapsed, and the dollar fell off a cliff. Bank after bank went down. Traders all over Manhattan went bankrupt. Whole hedge funds. Wall Street ground to a halt. Checking accounts froze. People lost their savings, lost 401(k)s, 529s, IRAs—

It was like all the money in the world evaporated.

Rue's mom decided to send Rue to Boston.

"I don't want to live with Nona. I want to live with you," Rue begged as she hugged her mother goodbye at the bus station.

"As soon as I have a job, you'll be back with me," her mother said, wiping her eyes.

Another bit of pretend. The grownups were all playing pretend. Everyone except Armando, who hugged her and shoved a small sweaty wad of cash into her hand.

"Good luck, kiddo. Keep this for an emergency. Got it? An emergency."

"I will. I'm sorry about your job."

SEAN RAYFORD / GETTY

"Yeah, well, I knew I should have bought yuan." He sucked his teeth, irritated. "I got into this work because I swore I was never going to dig ditches. Now I'm not even sure they'll let me do seawall construction. Too many reffees competing for that shit."

He looked completely different now that his investment company was gone.

The bus to Boston passed through three Mass Pike checkpoints. They scanned her FamilyPass bar code again and again. Kids with fake documents got pulled off the bus and sent back. Each time State Patrol scanned her pass, she expected it would be her.

"I wish you'd come here sooner," Nona said as she hugged Rue in South Station. "I have room. I always had room for you." She hugged Rue tighter, and for a minute, in the middle of the bustling terminal, Rue felt safe.

The T was sardine-packed, even at noon. Despite the migration controls, refugees swamped Boston. "Everyone's trying to get in," Nona said as they sweated up the line. "I've been renting my spare rooms on Airbnb. Rents are crazy. It helps with the food prices, though. I don't know how other people are affording food with all the droughts."

Nona cleared out a whole family from Alabama to give Rue a room.

"I have to get back to the hospital," Nona said as she changed the bedsheets. "If you go out, watch out for muggers. There's not enough work for people."

Nona was a psychiatrist who specialized in trauma. The state paid her to prescribe antidepressants and anti-anxiety meds to refugees. "Benzos are cheap," she joked. "Hospital beds are expensive. And the heat makes everyone crazy."

Nona also said not to get too comfortable. Her single-family house was being torn down for a density project. She was moving to a high-rise. "They've got plans for this old place."

Boston definitely seemed to have plans. Billboards called Greater Boston a "City of the Future." They'd banned cars from Alewife all the way to the ocean. Only electric trams and occasional emergency vehicles used the narrowed main roads. Remaining streets were being converted into e-bike paths and gardens. Climbing vines shaded walking paths for summer. Enclosed skyways leapt from high-rise to high-rise for the winter. Not a drop of gasoline anywhere.

Rue could see how pleasant the city was supposed to be, but it was groaning under the weight of reffees from all the places that hadn't planned. The school Rue was supposed to attend—which Nona said was excellent—was overflowing. Kids were being given disposable tablets and asked to do Khan Academy instead of assignments from living teachers. They sat cheek by jowl, cross-legged on the floors, with security proctors watching over them.

Rue started ditching, killing time down by the Charles River with some other reffee kids. Jiyu—a girl from coastal North Carolina—and Josh, a kid from Iowa who'd never lived in a city before but who Rue had taken under her wing when she found him making origami out of trashed McDonald's wrappers.

Most days, they'd perch atop the new Charles River levees and skip rocks across warm algae-choked waters, occasionally trading hits on Josh's asthma inhaler. Up in Canada, whole beetle-killed forests were burning, and the smoke kept blowing south. Burnt Canadians, they called it. They rated the Boston weather by how thick the Canadians were, and how many asthma hits they needed.

A pair of joggers wearing fluorescent athletic gear and Nike particulate masks pounded past, giving them dirty looks.

"How do they know we're not from here?" Josh asked, taking another inhaler hit. "What do they see?"

Rue had wondered about that too. She'd been chased by local Boston kids multiple times, gangs of them intent on schooling the newcomers. She wondered if maybe she and her friends held their bodies differently. Like dogs that had been kicked too many times. Instinctually cowering.

"Kinda makes you hope one of these levees breaks," Josh said.

Rue could imagine it happening. Could imagine Boston—despite its attempts to harden and adapt—drowning just like all the other places she'd been. She wondered if it would happen, or if Boston would somehow manage to do better, not play pretend, maybe do something right.

On Rue's way home, a crew of Boston kids jumped her, bursting out of a humid alley. She curled in a ball on the pavement as they beat and kicked her. They left her bruised and crying with final gobs of spit and warnings to go back where she'd come from.

By the time she finally limped home, it was dark. Inside, she found Nona peacefully asleep in her easy chair, the TV streaming Netflix.

Rue stood in the flickering darkness, tasting the blood in her mouth and clutching her bruised ribs. Her grandmother shifted in her sleep. The air conditioner droned, fighting the October heat. Even with the doors and windows closed, Rue could smell the Canadians burning. The world that had existed before, for thousands of years, going up in smoke.

Rue tried to remember a time when something in her life hadn't been on fire, or underwater, or falling apart, and realized she couldn't. She tried to remember a time when she had slept as peacefully as Nona.

Nona said she loved Rue, but all Rue felt was empty distance between them—the shredded gap between the life her grandmother had enjoyed and the tatters that Rue had inherited. Her grandmother had drunk espresso in Italy and meditated in the temples of Kyoto. She'd lived a full life.

Rue imagined strangling her.

Paolo Bacigalupi is a novelist who often focuses on the environment and sustainability. His latest novel about climate change was The Water Knife, a thriller about drought and water conflicts in the southwestern US.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Must do better

A planetary health report card. By Rachel Cernansky

If we are going to cope with a changing climate and exploding global population, nearly everything about life needs to shift—including how people grow and eat food. That's the conclusion of the EAT-Lancet Commission, a group of scientists recommending a new approach for "planetary health." We rated human progress to see how things are shaping up.

Increase crop diversity

D

Today three quarters of the world's food comes from just 12 plant and five animal species—even though there are more than 300,000 known edible plants. This leaves the food supply vulnerable to climate change. Seed banks around the world store hundreds of thousands of species, but not enough are being planted. Fabrice DeClerck, coauthor of the EAT-Lancet Commission report, says markets, policies, and technologies to address the situation are all missing.

Boost underused crops

D+

Corn, soy, wheat, and rice dominate global agriculture—and research. We need more development and production of underused crops like fruits and nuts, with a focus on improved varieties that have higher yields and resistance to disease and pests. Brent Loken, the commission's director of science translation, says we must increase production of legumes by 200%, nuts and seeds by 150%, and fruits by up to 75%.

Change fertilizer use

F

Bard College environmental physics professor Gidon Eshel says, "We are as far from where we need to be as we can possibly be." US farms, especially, need to drastically reduce fertilizer use, while farms in many other areas around the world—where yields are a fraction of what they could be—need to use more. Precision agriculture technologies under development can help farmers pinpoint the right amounts, but it's still too expensive for many.

Optimize land use

D+

Growing more food is crucial, but much of the world's land is difficult to farm today. Research could focus on improving these tough environments. For example, large-scale mapping of soil characteristics could uncover areas that hold more promise for food production and spot those better suited to conservation. Optimizing where we grow is an "absolute necessity," says Loken: "You've got to select the right crop, plant it at the right time, in the right place."

Increase seafood production

C

Wild catches are exhausted, but the world needs more supply—particularly of farmed oysters and other bivalves. Norway has been making progress on sustainable salmon farming, but new aquaculture technologies are still in their infancy. What happens when antibiotic use is increased? Where does feed come from? What happens if genetically modified fish escape into wild populations? Nobody is quite sure.

Use less water in agriculture

D

Farmers need to make the most out of every drop. Out go the massive and inefficient crop sprinklers in favor of micro-irrigation systems that reduce water use by, for example, dripping directly into the roots of plants. After that, we need to get smarter about what crops are grown where. "Better crop-environment matching would make big gains here," says DeClerck.

Eat less meat

C

A more plant-based diet will set the baseline for some of these other changes, and reduce greenhouse-gas emissions at the same time. But while companies like Impossible and Beyond Meat are expanding the appeal of plant foods, it's a shift that is constrained mainly by culture, political will, and personal preference rather than technology.

Cut food waste

C+

An estimated 50% of Canada's food gets discarded, typical of many Western countries. Systems to monitor food and tell consumers when it's safe or unsafe to eat could help. Restaurants could also reduce waste by identifying and responding to customer eating patterns.

Reduce food loss

D

Lots of food is destroyed in production or transportation, before it is sold or eaten. While little food is wasted by consumers in rural areas of the developing world, poor storage and infrastructure can cause produce to spoil or become infested with pests or mold.

Improve trade policy

F

Strong local food systems can be important, but if everybody grows their own food "we're in big trouble," says Loken, because that essentially guarantees an increase in destructive practices such as deforestation. The world will benefit from trade policies that encourage regions best suited for food production to supply areas where agriculture poses greater risks to ecosystems or the global environment.

SOURCE: FOOD IN THE ANTHROPOCENE: THE EAT-LANCET COMMISSION ON HEALTHY DIETS FROM SUSTAINABLE FOOD SYSTEMS, 2019

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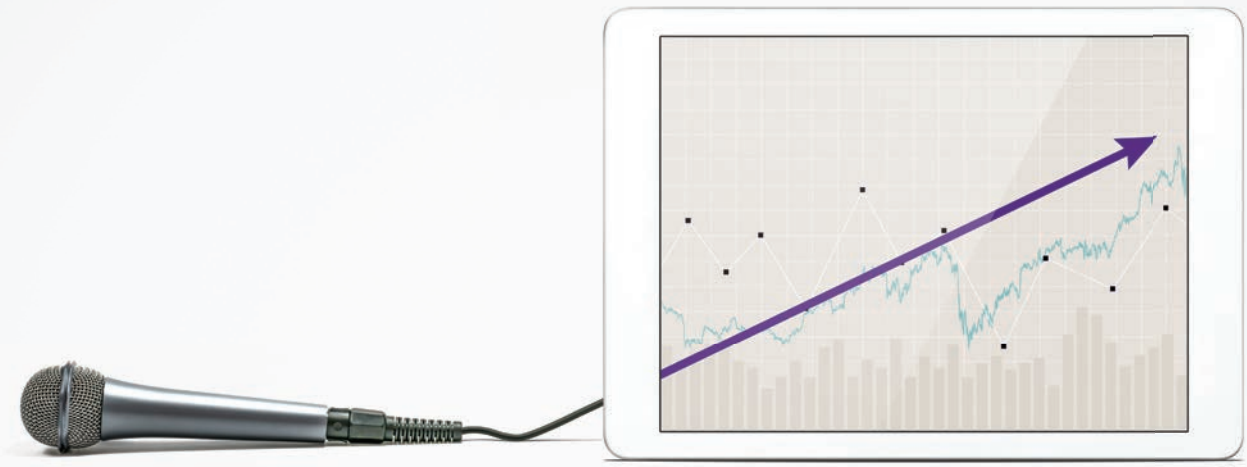

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