The Famine Fighter's Last Battle

More than a half-century after the research that helped spark the green revolution, Norman Borlaug is again fighting a devastating fungus that threatens wheat around the world

ON A COLD, JANUARY MORNING IN 2005, A small plane landed outside the town of Njoro, Kenya, where a handful of scientists waited eagerly as the plane taxied. After the propellers stopped, an old man slowly climbed out and walked across the grassy airstrip. Norman Borlaug, then 91, had come from Nairobi to examine for himself the impact of a highly virulent race of stem rust, called Ug99, a plant pathogen that had recently crossed the border from Uganda and was now threatening wheat farmers around the world.

Few living people—scientists or farmers—had had any experience with outbreaks of stem rust. To Borlaug, however, it was a familiar enemy. After epidemics had devastated wheat fields in Mexico in the 1940s, Borlaug, who was working at an agricultural experiment station in Mexico, bred new varieties of wheat that could resist the disease. These varieties were a key component of the green revolution of the 1960s, helping to boost wheat yields in Mexico and avert famine in India, Pakistan, and elsewhere. Ever since, the world had seemed safe from stem rust. Now, the energetic, tenacious, Nobel Peace Prize–winner is trying once more to defeat the threat.

Persistent. Norman Borlaug surveying research fields.

At the airstrip, researchers from the Kenya Agricultural Research Institute (KARI) hustled Borlaug into a car and drove him 50 kilometers to the experimental plots they had planted in the village of Mau Narok. These small fields contained more than 100 varieties of wheat that had been sent to KARI from around the world to see how they would fare against Ug99.

The situation looked bad. As Borlaug combed every inch of the field, bent over in the chilling wind, his alarm grew. Almost all of the varieties were infected, their stems covered with a rash of red, spore-filled pustules of *Puccinia graminis*. Finally, Borlaug found a few varieties that showed some resistance, but he remained pensive. The world was ill-prepared to fight this reemerging threat, he thought.

Back in his office at the International Maize and Wheat Improvement Center (CIMMYT) in El Batan, Mexico, Borlaug kicked into high gear. With his characteristic passion and impatience with bureaucracy, he wrote a blunt memo to CIMMYT's director general calling for more funding and threatening to sever his ties with the institution if it didn't happen immediately. Soon the Rockefeller Foundation, which had supported Borlaug's early work on stem rust, contributed as well. Borlaug and others formed the Global Rust Initiative (GRI) to coordinate international activities, key among them testing more wheat varieties and breeding resistance. Relentless, Borlaug has kept using his connections and reputation to highlight the danger of Ug99 and extract more funding from governments.

Since then, CIMMYT has created 15 varieties of high-yielding Ug99-resistant wheat. Seed is being grown to send to countries infected with, or in the path of, Ug99. The fungus is already endemic in Kenya and Ethiopia, it has been found as far east as Iran, and it is threatening the breadbaskets of South Asia. Meanwhile, three new, dangerous

variants have appeared in South Africa and Kenya. "There is no room for complacency," Borlaug exhorted more than 300 wheat breeders and pathologists at a March conference in Ciudad Obregón, Mexico. "So let's get on with the job."

Hunger pangs

Born and raised on a farm near Cresco, Iowa, Borlaug initially wanted to be a high school science teacher. When he enrolled at the University of Minnesota in 1933, at the height of the Great Depression, he was sickened by the number of homeless people he encountered camped out in parks, hungry and begging for food—a sight he never forgot. In the fall of 1937, Borlaug heard a lecture by Elvin Stakman, a renowned plant pathologist who studied stem rust, a poorly understood disease that periodically decimated wheat production around the world. "Rust is a shifty, changing, constantly evolving enemy," Stakman said in his lecture. "We can never lower our guard." Inspired by Stakman's weaving together of microbial evolution and human hunger, Borlaug switched to plant pathology and earned his Ph.D. with Stakman in 1942.

Borlaug took a wartime job with DuPont, working on fungicides and bactericides. At that time, the Rockefeller Foundation was starting to work with Mexico to improve its agriculture. The foundation hired Stakman, and Borlaug joined the team in 1944. It was a rude awakening coming from the laboratories of DuPont. When Borlaug arrived at the fields donated by the Mexican government 30 kilometers outside of Mexico City, there wasn't much to work with: one adobe shed and no equipment.

Once again, Borlaug was shocked by poverty and hunger; on top of other problems, 3 years of stem rust had slashed wheat yields in half. "I've seen the misery that comes from rust epidemics," he says. Borlaug began to train Mexican technicians and made thousands of crosses of wheat varieties from around the world, trying to improve resistance to stem rust, boost production, and adapt varieties to local conditions. Counter to the culture of the time, Borlaug insisted that scientists work alongside technicians in the fields. Yields began to improve.

But the progress wasn't fast enough for Borlaug. When he learned about an abandoned experiment station 2000 kilometers to the north in the Yaqui Valley of Sonora, he decided to visit. Stem rust had caused massive problems for wheat farmers there as well, but apparently one variety was somewhat resistant. It took 2 days to fly there in an old Fokker Tri-Motor.

The station was in shambles, Borlaug recalls. "There was nothing except a few goats running around." But Borlaug saw an opportunity and had a crucial—if unorthodox—insight: He realized that because of the difference in climate between the two stations, his team could grow two generations of wheat a year. First, they could plant summer wheat in the cooler highlands near Mexico City, then harvest that seed and plant it in the warmer fall weather in Sonora, which was only 40 meters above sea level.

His idea instantly met with opposition. At the time, most agronomists thought that seeds required a dormant phase after harvest. Another dogma was that breeders should plant their varieties and make selections in the same place that farmers were planting. His boss, who vetoed the idea, also balked at the cost of renovating a second experiment station, as well as the time involved in transporting researchers and seed across the country. Borlaug threatened to resign. Finally, Stakman intervened, and Borlaug got the green light.

This new approach, called shuttle breeding, cut breeding time in half; it also allowed Borlaug's team to produce more adaptable varieties that could grow in a range of latitudes, climates, and soils. By 1956, the team had introduced 40 varieties that could resist stem rust, and Mexico no longer needed to import wheat. Breeders at CIMMYT are still shuttling seeds between Mexico City and Ciudad Obregón.

Starting in 1953, they bred varieties with even greater yield potential, crossing their resistant wheat with short-stemmed wheat from Japan that produced more grain. Their short, sturdy stems prevented them from blowing over, which damages the plant. With these dwarf Mexican wheat varieties, first introduced in 1961, yield potential doubled to 9 metric tons per hectare.

In action. Borlaug evaluating wheat in Mexico in the early 1960s. He assessed damage from Ug99 in Kenya in 2005.

Worldwide impact

Impressed with the success in Mexico, the Rockefeller Foundation decided to take it global. Working with the United Nations' Food and Agriculture Organization, Borlaug helped create a network of about 15 testing nurseries around the world to test the disease-fighting, yield-boosting potential of these new varieties. These data proved crucial for helping deal with famines in South Asia in the mid-1960s. After some head-butting with bureaucrats to get the seed introduced, wheat yields rose by 60% in India and Pakistan by 1970. Pakistan became self-sufficient in 1968, and India 6 years later.

When CIMMYT was founded in 1966, Borlaug became director of the wheat-breeding program. On 20 October 1970, he had already left for the fields when his wife, Margaret, received a call at 4 a.m. announcing that Borlaug had won the Nobel Peace Prize. The citation noted that "more than any other single person of this age, he has helped to provide bread for a

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hungry world. We have made this choice in the hope that providing bread will also give the world peace."

The green revolution has been criticized for its reliance on synthetic fertilizers, irrigation that led to salinization of soils, and other problems; Borlaug acknowledges some of these shortcomings but says they pale in comparison to starvation and political unrest. Moving forward, he says, scientists will have to find a way to boost global grain production by 50% in 2 decades "in environmentally more sustainable ways."

After he officially retired from CIMMYT in 1979, Borlaug turned to Africa, co-leading the Sasakawa-Global 2000 Programme to bring relatively simple technology—fertilizer, improved irrigation techniques, and crop management—to poor farmers. By the 1990s, Borlaug was also teaching fall semester courses at Texas A&M University. He spent the rest of the year mainly in Mexico, where he consulted at CIMMYT, starting his workday, as usual, before 6 a.m. His family saw him for just a few months a year, at most, as had been the case since he first began fighting stem rust in the 1940s.

Test bed. Wheat varieties are being bred in many countries, including Ethiopia (*top*), for resistance to stem rust (*bottom*).

CREDITS (FROM TO BOTTOM): JENNY NELSON, DRRW PROJECT, CORNELL UNIVERSITY; USDA/CEREAL DISEASE LAB

Stem rust returns

Borlaug's resistant varieties protected the world's wheat against stem rust for decades. So it was a surprise to Ravi Singh, the chief bread wheat breeder for CIMMYT, when he heard about an infestation of stem rust at a research station in Uganda in 1998. "My first thought was it's a mistake. It can't be possible," Singh recalls. Wheat in Uganda had typically been afflicted with yellow rust, not stem rust.

But Borlaug says he was not surprised by the return of stem rust. "I used to tell the new people, 'Don't think this isn't a problem,'" he recounted to *Science* in a 2007 interview.

At first, the severity of the threat was hard to gauge, Singh says. After surfacing in 1998, the new race, dubbed Ug99, did not reappear at the Uganda research station's monitoring plots for several years. But in 2002, the fungus showed up at the research station in Njoro, Kenya. Initially, some 30% of the varieties tested at KARI appeared vulnerable. The wind-borne spores were clearly spreading.

"This is a time bomb," Borlaug told his colleagues at CIMMYT, recalls Christopher Doswell of the Consultative Group on International Agricultural Research (CGIAR), a longtime associate. Even if conditions are not wet enough for an outbreak, stem rust can lie in wait on alternative hosts, such as a shrub called barberry. Ug99 is "going to lie there, and then all of the sudden it's going to go boom," Borlaug warned colleagues.

In 2003, Ug99 was detected in Ethiopia, where it became established in the damp wheat fields of the highlands. Borlaug thought nations should start growing, or "multiplying," seed from the few known resistant varieties from Kenya. But agriculture departments in various nations that hadn't seen stem rust in decades underestimated it, thinking their own varieties would be resistant. Hit with a budget crisis, CIMMYT couldn't do the work alone.

Borlaug started a quiet campaign, requesting a private meeting in 2004 with then–U.S. Department of Agriculture Secretary Michael Johanns, who steered an initial $35,000 of emergency funds to testing efforts by scientists in Kenya and Ethiopia. Borlaug and Doswell also went to the U.S. Agency for International Development, which later provided $400,000.

Borlaug was even more alarmed when he returned from his visit to Kenya in January 2005. He railed against the bureaucracy and the shortage of funds at CGIAR, which hampered a rapid response. He was also mad at what he saw as the low priority national agricultural departments were giving to monitoring for rust.

Again, he appealed to the Rockefeller Foundation, which provided $80,000 to CIMMYT. It was enough to fund an expert panel to further assess the threat. Then CIMMYT and the International Center for Agricultural Research in the Dry Areas hosted an international meeting in Nairobi. Borlaug and Singh had urged breeders from 18 countries to send samples of commercially grown wheat to be planted by KARI. That way, they could see how they fared when infected with Ug99. During the field trip to the experimental plots, the visiting breeders were shocked at how many wheat varieties were stricken. "It was a mixture of embarrassment and desperation," says Miriam Kinyua, a wheat breeder who was head of KARI's Njoro station at the time.

Ug99 continued its march. The next year, it turned up in Yemen, continuing a global track predicted to take it across the fertile crescent and into Southern Asia (*Science*, 30 March 2007, p. 1786). By 2007, the fungus had been found in the main wheat-growing area of western Iran, where for now it has stalled due to drought.

Borlaug, too, has slowed down a bit after being diagnosed with lymphoma in 2006. But he still helped garner a 5-year, $27 million grant from the Gates Foundation that's being used to fund basic research, surveillance, and breeding.

The cancer is under control now, and Borlaug was full of vigor at a March meeting of the renamed Borlaug Global Rust Initiative in Ciudad Obregón. After visiting his old research plots, he says he's pleased with progress but insists much more needs to be done. "It has to be an international effort," he says, thumping his finger on the arm of his wheelchair. "So you can move the multiplication [of seed] and the replacement of the susceptible varieties before disaster strikes."

Ronnie Coffman of Cornell University, BGRI's vice chairperson, says that bringing researchers together to work on stem rust has become a second calling for Borlaug. "He's almost an evangelist now," he says. And the missionary work continues. When Coffman and Borlaug visited Washington, D.C., last year, Borlaug insisted on renewing his passport.

–ERIK STOKSTAD