CHAPTER I

NARRATIVES AROUND WIDE ADAPTATION IN INTERNATIONAL WHEAT RESEARCH, 1960–1970

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In this book I trace Norman Borlaug's controversial ideas around adaptation from the 1950s and through several decades and countries. As such, a bit of background on the concept of adaptation is necessary. In the ecological and evolutionary sense, adaptation is a heritable process that contributes to a species' survival and fitness in its environment. The field of evolutionary biology considers adaptation a process, but in agricultural science, adaptation is more of a state or condition.[1] Historian Emily Pawley explained how the term *adaptation* sometimes describes human intervention into biological systems, such as a farmer *adapting* livestock to a particular environment through breeding and acclimatization; this concept is still present in the agricultural sciences.[2]

The adaptation of a plant includes its physiological tolerance and requirements of temperature, soil composition, moisture, disease, sunlight, wind, species competition, and so on. Through evolution and natural selection, as well as artificial selection (by farmers and plant breeders), it is commonly assumed that agricultural plants are specifically adapted to their region of origin—the place that they evolved in. Since at least the mid-1800s agriculturalists have used the term "wide adaptation" to describe the agroclimatic range of horticultural species in the United States—for example, the *Report of the Commissioner of Patents for the Year 1853* includes the observation that "the principal species [of the tobacco plant], *Nicotiana tabacum*, is sufficiently variable and sufficiently capable of a wide adaptation to permit Cuban varieties to be immediately transferred to Ohio or New York."[3] Adaptation is one of many possible plant characteristics, albeit a helpful one in terms of agricultural development. In the early twentieth century, wide adaptation was not often pursued as a strategy, however, as most plant breeders focused on developing crops for specific locations.[4]

In a plant-breeding context, adaptation means the relative performance (roughly, the yield and disease resistance) of a plant variety under different conditions. A widely, or broadly, adapted variety gives high yields under many different environments and locations. Wide adaptation can also be defined as phenotypic stability plus high yields. Specific, or narrow, adaptation refers to a variety that thrives only under a specific set of environmental conditions.[5] Scientists can measure how plant characteristics (such as plant height) vary to study the phenotypic responses of plants to different conditions, but adaptation is typically measured in yield (grain weight per area).

Wide adaptation existed in the lexicon of agricultural scientists in the 1960s, but only in the margins of agricultural science. The conventional wisdom of plant breeding in the early twentieth century was that crop selection should occur in the target environment, creating varieties with specific adaptation to the local conditions. Even a 1954 annual report from the Rockefeller Foundation (RF)'s Colombian Agricultural Program stated, "It is axiomatic in agricultural research that an improved crop variety, to be commercially successful in a given region, must be developed and tested in that region."[6] In other words, agriculture was a "site-specific science," and most cereal breeders viewed wide adaptation with little more than skepticism.[7]

Borlaug's wheat program changed the paradigm of international agricultural research. Borlaug introduced the promise of intentionally designing a crop that could be easily transposed between locations. For the US foundations that wanted to make their mark abroad through agricultural assistance, this was a huge boon. These foundations set up international research centers that followed Borlaug's research model and trained international scientists in his methods. Throughout the 1960s, the RF-sponsored international centers focused on developing a few widely adapted varieties of wheat, rice, and maize that could be grown in many countries.[8] While each program has continued up to the present, wheat most successfully proved itself as widely adapted.

Over the years wide adaptation has been "blackboxed": it has been packed with multiple, unfounded meanings and is only occasionally critically reviewed. In this chapter I unpack the black box of wide adaptation, starting with its role in Borlaug's wheat program. Through a series of incidental connections and rediscoveries in the 1950s and 1960s, Borlaug found that spring wheat varieties derived from Colombian and Mexican varieties had consistently high yields in widely dispersed trials. At that time, most agricultural scientists were skeptical that one variety could have consistent high performance over a variety of locations. Borlaug's international trials showed that a widely adapted variety could even outyield popular national varieties in their home countries. In just a few years, Borlaug took an unpopular idea and completely changed the paradigm of plant adaptation.

In this chapter I reveal the history of one of the most influential yet underexplored ideas in agricultural science. I explore how Borlaug came to focus his research program on wide adaptation and fertilizers; the work of his colleague, Charles Krull, in promoting wide adaptation and fertilizers; and Borlaug's correspondence with Keith Finlay, who supported Borlaug's mission but questioned his methods. We see the evolution of Borlaug's philosophy and program on wide adaptation and its acceptance in the international community as a valid scientific paradigm.

BORLAUG AND THE GLOBALIZATION OF SPRING WHEAT RESEARCH, 1950–1968

Borlaug found that wheat varieties from the United States and Canada were generally poorly adapted to Mexican conditions due to different lengths of daylight and seasons. The United States and Canada are major wheat-growing countries, but they grow winter wheat, which requires a period of cold to mature. For Mexican environments, he needed to use spring wheats in his plant-breeding experiments. Spring wheats are grown in tropical and subtropical areas and do not require a cold period. Under Borlaug's supervision, the Mexican Agricultural Program (MAP) released disease-resistant spring wheat varieties that were adapted to Mexican conditions in 1948, and by 1957 these new varieties constituted 90 percent of Mexican wheat acreage.[9]

Borlaug became interested in the idea of wide adaptation after participating in the US Department of Agriculture's (USDA) International Wheat Rust Nursery, which started in 1950.[10] In response to an epidemic of wheat stem rust in North America, the USDA set up the Wheat Rust Nursery to test their large collection of wheat seeds in different environments around North and Central America and to identify rust-resistant varieties.[11] By 1952 the nursery had expanded to Australia and various countries in Africa and Europe.[12] This nursery was possibly the first systematic global wheat test, and Borlaug was involved from its beginning.

Borlaug's mentor, Elvin Stakman, had written to the RF's president, Dean Rusk, back in 1953 that it would be useful to breed for "the best possible combination of genes for yielding ability, disease resistance, or any other universally useful character, without considering adaptability to particular areas."[13] These were not novel ideas in agricultural science, but Stakman's idea that "these lines could then be given to breeders in all interested countries for use in developing varieties adapted to their conditions" was prophetic of Borlaug's wheat program.[14] Stakman's ideas contrast with those of his colleague J. George Harrar, who as president of the RF in 1961, stated, "Unfortunately, most scientific advances most directly benefit the particular geographic area in which they originated. This is especially true in the agricultural sciences."[15] Borlaug's work on wheat proved this false.

Borlaug developed an interest in collecting basic data on the adaptation of wheat varieties after seeing how well some of the RF's wheat varieties, such as Lerma Rojo and Nariño 59, performed in the USDA nursery.[16] By 1959 Borlaug became convinced that wheat crosses between certain foreign strains produced varieties that could be grown over wide geographic areas. He stated at a 1960 meeting that "wheat is very different from corn in that it appears to be much more flexible in its adaptation to different soils and climatic conditions."[17] Borlaug's finding contradicted what many scientists presumed at that time, which was that agricultural assistance programs would always be constrained by geography.

Around 1959 Borlaug proposed a new international wheat nursery that would prove wheat's adaptation to diverse geographies. He wrote in a trip report, "In the past there has been a great deal of circumstantial evidence that certain types of wheat have great flexibility and adaptation; however, this has never been checked experimentally, and it seems that the time has now arrived for doing so."[18] He soon proposed a "uniform yield nursery" to collect "valuable information on varietal adaptation" in wheat.[19] In 1960 Borlaug started his first international nursery, called the Cooperative Inter-American Spring Wheat Test. Borlaug sent packets of twenty-four spring wheat varieties from the Americas and Australia to twenty different locations in the Americas, as well as in Egypt, Kenya, and Pakistan, where he had collaborators and former students.[20] In the first year of trials, the RF Colombian variety Nariño 59 had the highest average yield at the eighteen reporting locations, though it ranked first in only three of the trials.[21] This was surprising because it usually takes several years to adapt a foreign variety by crossing it with local varieties.

The Food and Agriculture Organization (FAO) soon invited Borlaug to tour the Middle East, where it had been working on wheat since 1952. In 1960 Borlaug examined some of the problems of wheat cultivation in that region.[22] Derek Byerlee has remarked on the importance of this

TABLE 1.1. Countries that participated in the First International Spring Wheat Yield Nursery and number of tests, 1964–1965

Country	Number of sites
Argentina	4
Australia	2
Chile	1
Colombia	1
Cyprus	1
Ecuador	1
Ethiopia	1
Guatemala	1
India	3
Iran	1
Iraq	1
Jordan	1
Lebanon	1
Libya	1
Mexico	2
Pakistan	3
Romania	1
Saudi Arabia	1
South Africa	1
Sudan	2
Syria	1
Turkey	1
United States	2

two-month journey, which was Borlaug's first trans-Atlantic tour.[23] Borlaug visited twelve countries, including Pakistan and India, and wrote an unusually long 198-page report on the trip.[24] While traveling, Borlaug observed varieties from the Rockefeller Foundation agriculture program planted in the nurseries and other experiments and was "amazed to see the wide adaptability of many of the wheat materials" from Mexico and Colombia.[25] He felt that the scientists running the nurseries did not recognize this amazing feat for what it was, owing to their lack of experience outside their own country. Based on these initial results, Borlaug wanted to expand his own wheat yield trials to the Middle East, India, and Australia.[26] He planned to use the international trials to evaluate "the relative adaptability of a uniform set of varieties of different origins by growing and observing them systematically under widely different conditions of climate, soil, and latitude" as well as the "possibility of developing wheat varieties with extremely wide patterns of adaptation."[27]

The RF and FAO together started the Cooperative Near East–American Spring Wheat Yield Nursery in 1962. Borlaug again packed seeds from twenty-five varieties of spring wheat into hundreds of envelopes, including commercial varieties from the Middle East, two varieties from Colombia, and seven varieties from Mexico. All varieties were grown under widely varied conditions, as Borlaug recommended planting seeds on uniform plots that represented average local conditions. In the first two years of trials, five Mexican varieties yielded, on average, the highest of all twenty-five varieties entered in the trials.[28] These varieties were among the highest yields even under unfertilized and rainfed conditions.

In 1964 Borlaug combined the Inter-American and Near East–American nurseries into the International Spring Wheat Yield Nursery. He sent 25 varieties to 34 locations in 23 wheat-growing countries (see table 1.1). Like the previous nursery, seeds were grown under both irrigated and rainfed, and fertilized and nonfertilized conditions.[29] And again, five Mexican varieties yielded the highest, on average. Draft RF reports casually noted the wide adaptation of the Mexican varieties, but as time went on the RF researchers made a stronger case that wide adaptation was not just achievable but desirable.

Bolstered by the results of his international trials, Borlaug spent little time pondering the theoretical aspects of wide adaptation and quickly moved to implementation. Borlaug and his colleagues saw wide adaptation as a method to share wheat varieties with countries with limited scientific resources.[30] He wrote to RF agricultural sciences director Albert Moseman in 1963 that materials from "one broadly based wheat breeding program" focused on wide adaptation can be "reselected for direct use in countries far distant from the location of the breeding programs."[31] This could radically speed up the time it would take to adapt varieties to a new location through crossbreeding. In 1965 Borlaug made a case for the moral imperative of wide adaptation, writing that "varieties and breeding lines with broad adaptation can be introduced rapidly and grown successfully in many areas of the world where expansion of food production is urgently needed. This is not possible with narrowly adapted varieties."[32] Borlaug realized that he could not only transmit scientific knowledge to other wheat breeding programs around the world but also directly transfer wheat seeds.

Borlaug's theoretical explanations for the wide adaptation of Mexican- and Colombian-derived wheats evolved over the years. Borlaug initially recognized that wide adaptation was the result of certain "germ plasm complexes" that were genetically inherited.[33] He surmised this because varieties he derived from the lines Mentana (from Italy), Marroqui/Florence-Aurore (from Tunisia), and Gabo (from Australia) tended to be more adaptable across locations.[34] Borlaug later attributed wide adaptation to his unique method of wheat breeding. Around 1945 Borlaug began growing wheat generations alternately between north and central Mexico to speed up the time needed to select and stabilize a new variety, which typically takes about ten years.[35] This was later called "shuttle breeding," and is one of Borlaug's best-known legacies.[36] In the winter, Borlaug planted wheat in the Sonora region of Mexico—a coastal, irrigated region near sea level and at 28°N latitude. Then he would select the best offspring from that season and plant them in Toluca (near Mexico City), which was at 18°N latitude and had a high altitude, heavy rainfall, and a higher prevalence of pathogens. Borlaug insisted that shuttle breeding would produce results. He stated in his 1967 oral history: "We were constantly, and very early, we were doing it consciously—discarding those things that fit in only one environment. We were interested because of the ease of multiplication of varieties of having things that were broadly adapted and consequently probably less vulnerable to the vagaries of climate, but also that if we found a variety that was well adapted and yielded well—it could be grown widely in Mexico."[37] Borlaug's insistence that wide adaptation was purposeful conflicts with other sources and my interviews with scientists who knew him, which described the finding as serendipitous.[38] Borlaug retroactively credited his shuttle breeding experiments with providing the proper selection pressures to favor widely adapted varieties.

Within a few years, however, Borlaug realized that the main genetic contributor to wide adaptation was photoperiod insensitivity, meaning a crop that is not sensitive to day length. Wheats from the United States and Canada were photoperiod sensitive, while photoperiod-insensitive wheats could be grown in a variety of latitudes, elevations, and seasons. Borlaug wrote that "in all probability one of the important factors in this lack of flexibility is their sensitivity to change in day length and date of planting."[39] Photoperiodism was discovered in 1918 by USDA researchers W. W. Garner and H. A. Allard, so by Borlaug's time it was well known.[40] Borlaug hypothesized that his shuttle breeding method had resulted in selection that favored photoperiod-insensitive varieties that thrived in both the Sonora and Toluca regions, which have different seasons and photoperiods.[41] Borlaug later wrote that due to the "day-length insensitivity and broad-based rust resistance" and high yields of the Mexican semidwarf wheats, countries could release "only a few varieties needed to serve commercial farmers—rather than a dozen or more that would have been necessary if narrowly adapted varieties would have been developed."[42] This would simplify "the work of newly formed national seed agencies."[43] Borlaug was correct that day-length insensitivity and rust resistance allowed countries to adapt foreign varieties to their conditions much more rapidly than in the past, because they did not require crossbreeding with local varieties. It should be noted, however, that the photoperiod insensitivity is not possible in all crops.

Although Borlaug clearly recognized photoperiod insensitivity as the main component of wide adaptation, his research program moved toward developing "even more widely adapted genetic types" of wheat and asked, "What is the maximum range of adaptation that can be incorporated into a variety?"[44] Borlaug seems to have thought that there were additional genetic factors of wide adaptation besides photoperiod insensitivity. And indeed, there was: Borlaug's varieties were bred to withstand high levels of fertilizer.

When Borlaug started working for the RF in Mexico in the 1940s, his task was to develop wheat varieties that had higher yields and greater disease resistance than the local varieties. He realized that more nitrogen-based fertilizer was required to improve yields. But when too much fertilizer was added to local wheat varieties, they would fall over because of the heavier grain at the end of the tall, thin stalks. This is called *lodging*, and it can also be caused by high winds or rain. A solution to the problem of lodging appeared when Borlaug learned about "dwarf" wheat through Orville Vogel, at Washington State University. Vogel had obtained the dwarf variety Norin 10 from Japan. Dwarf and semidwarf wheats have shorter and thicker stalks than traditional wheat varieties. Semidwarf wheats can withstand higher levels of fertilizers without lodging, which means semidwarfs typically have a higher yield potential than the traditional tall wheats. Borlaug began crossing Norin 10 with Mexican wheat varieties in the 1950s, which resulted in a semidwarf wheat variety adapted to Mexican conditions. By 1955 Borlaug had successfully crossed Norin 10 with Mexican varieties, and in 1962 he released the semidwarf wheats Pitic 62 and Penjamo 62 in Mexico.

Even before the semidwarf varieties, Borlaug was already adapting wheat varieties to higher-fertility conditions starting around 1945.[45] He assumed that fertilizers would soon become more easily available and affordable globally. Borlaug saw fertilizer inputs as key to reducing lost soil fertility from centuries of extractive farming. By the mid-1950s Borlaug tested new wheat varieties under high-fertility conditions exclusively. He believed that varieties must be adapted to higher-fertility conditions to increase overall food production. At Borlaug's suggestion, Argentina's varietal improvement program was "reoriented in 1962 in order to develop varieties which would be better adapted to higher levels of soil fertility should the use of chemical fertilizers become widespread."[46] Borlaug reasoned that "any breeding program which did not take into consideration a change in levels of soil fertility within the next five years, would be doomed to failure."[47]

Borlaug also believed that planting wheat under favorable environments (high fertility and optimum irrigation) allowed the scientist to observe a variety's "true genetic potential," because variation between varieties would be more obvious.[48] In a letter to a scientific advisor in West Pakistan in 1964, Borlaug argued that at high fertility levels, one can see problems with the wheat variety not evident on "tired soil."[49] Borlaug also emphasized that results from irrigated trials were more reliable than those from rainfed trials because the rainfed trials had more environmental variation that would eclipse genotypic differences.[50] He also noted that working under low-fertility conditions slowed down the plant-breeding process. He wrote in 1960 that RF scientists were "spending upwards of 70% of their time trying to unsnarl the problems relating to soil fertility, instead of devoting all or most of their efforts to the aspects relating to crop breeding and crop management."[51]

Finally, Borlaug believed that varieties adapted to higher levels of fertilizer would lead to social change among farmers and scientists and overall higher levels of wheat production. He wrote in 1966 that the government of West Pakistan "should realize that solving the fertilizer problem for wheat will be the start, not the end, of increased fertilizer demand. For once a farmer learns how to use fertilizer in large dosage on wheat, the practice will quickly spread to other crops. That was our Mexican experience."[52] In India, Borlaug argued, "the program should try to produce tremendous yield increases on the area where the dwarf varieties can be heavily fertilized and properly watered."[53] He continued, "By so doing a complete change in the psychology of wheat production—from one of survival to one of high yields—will shock both the farmer and the scientist."[54] Borlaug believed that complacency of local agricultural scientists was one of the biggest hurdles to modernizing agriculture, and that they needed a shock to wake up.

When Borlaug began focusing on wide adaptation around 1960, his wheat research program was solely focused on selection and testing under favorable conditions. Borlaug made wide adaptation a key part of his research when he became head of the RF's international wheat program. To Borlaug, wide adaptation was a symbol of his program's global reach and ability to cause radical agricultural change. Against the prevailing sentiment that "plant breeders must work in the place where their crop will be grown," Borlaug argued that wide adaptation was not only a tenable but also a desirable plant-breeding goal.[55] He influenced agricultural scientists around the world through his trainings, publications, correspondence, and lectures. Beyond this paradigm-shifting endeavor, however, Borlaug had a very mission-oriented reason to promote wide adaptation. He wanted to transform agriculture in developing countries from premodern to modern, and thought that widely adapted, fertilizer-responsive varieties were the most likely way to accomplish this.

While Borlaug was breeding and testing wheat under high levels of fertilizer, much of the developing world was relying only on natural soil fertility. For the international trials, the plant scientists in the Mexican locations applied 80 to 120 kilograms per hectare (kg/ha) of nitrogen (N) and sometimes more. A 1969 review of CIMMYT's research found that "one rate of fertilizer (160 pounds of nitrogen per acre) is used throughout the 140 acres of experimental plots devoted to wheat" (160 pounds per acre is about 179 kg/ha).[56] This rate was comparable to the highly fertilized Belgium, which between 1962 and 1966 used an average of 158 kg of N per arable hectare (including crops other than wheat).[57] India, on the other hand, barely registered at 3.3 kg N/ha (again, for all crops).[58] Pakistan, Iraq, Iran, Syria, and Turkey, as well as Africa's major wheat-producing countries, all consumed less than 10 kg N/ha during this period.[59] Despite the massive gap between fertilizer rates at CIMMYT and the collaborating countries, Borlaug soldiered on with his international wheat program.

When Borlaug started doing research in the Sonora region, the RF initially did not support him because this was outside of the program's mandate to help peasant farmers. Farmers in the Sonora were wealthier and had the benefit of irrigation, while the central Toluca region had smaller farms, poorer farmers, and more varied environmental conditions. Despite these differences, most Mexican farmers quickly adopted wheats derived from the RF program because of their high yields and disease resistance. RF-derived wheat varieties also spread fairly quickly in Colombia, Guatemala, Ecuador, Chile, and Bolivia.[60] The RF's maize program was not as successful, however, because maize was not as adaptable as wheat. The lack of fertilizers, irrigation, and government support also slowed down the spread of RF wheats in some Latin and South American countries.

Around 1965 Borlaug began promoting the idea that widely adapted varieties were adapted not only to different geographies but also across agroclimatic conditions such as irrigation and soil fertility. In response to those who might criticize his focus on favorable environments, Borlaug wrote that "even at low fertility and on dryland, they [semidwarf wheats] do surprisingly well, displaying their efficiency even though they were developed under irrigation."[61] Borlaug saw the success of his varieties in his international trials and used these results to support his claims. According to Borlaug, "because of this mass of information . . . we feel pretty confident also in moving aggressively in Pakistan and India or in Turkey."[62]

Farmers quickly adopted semidwarf, fertilizer-responsive, and photoperiod-insensitive wheat varieties in certain regions, but especially in the irrigated parts of India, Pakistan, and coastal Turkey. US Agency for International Development (USAID) administrator William Gaud declared the Green Revolution in 1968 and Borlaug was awarded the Nobel Peace Prize in 1970. In his Nobel lecture, Borlaug said that the Mexican wheat's "unusual breadth of adaption" along with other factors "made the Mexican dwarf varieties the powerful catalyst that they have become in launching the green revolution."[63] Thus, Borlaug canonized wide adaptation in his narrative of the Green Revolution.

Although Borlaug was modest about his award, by that time he had adopted a "missionary zeal" for increasing world food production and decreasing global population.[64] Scientists from the Middle East whom Borlaug trained became known as Borlaug's "wheat apostles."[65] And Borlaug's colleagues recalled him preaching, "What Mexico did, your country can also do, except that yours should do it in half the time."[66] Borlaug, though trained as a plant pathologist, gained a new status as one of the most respected wheat breeders in the world and used that platform to spread his gospel. Borlaug was not shy about making the link between widely adapted varieties and global food production. In an undated outline of a report titled "The Development of High Yielding, Broadly-Adapted Spring Wheat Varieties," Borlaug handwrote the rest of the title to be "*and its Significance for Increasing World Food Production*."[67] In the margins of the outline, he wrote "KF" and "CK" next to various sections. These were Keith Finlay and Charles Krull, Borlaug's two colleagues who were critical to promoting wide adaptation as a plant breeding ideal.

CHARLES F. KRULL AND THE ROCKEFELLER FOUNDATION'S COOPERATIVE PROGRAM IN THE MIDDLE EAST, 1965–1968

Charles F. Krull was a cereal breeder for the RF in Colombia from 1960 to 1965 and in Mexico from 1965 to 1968. Krull was a crucial advocate of Borlaug's concept of wide adaptation, especially with scientists in the Middle East. Krull also led the analysis of the first few International

Spring Wheat Yield Nurseries. While Borlaug was busy traveling, Krull served as Borlaug's program manager, editor, and proxy in Mexico. The records created by Krull in the late 1960s, including his correspondence, trip diaries, and an oral history, provide a unique insight to the RF's program, goals, and personalities.

Krull applied to work with the RF directly out of graduate school at Iowa State University, where he had worked with Kenneth J. Frey, a well-known oat breeder. The RF was looking for a cereal breeder to work in their Colombian Agricultural Sciences program, and Krull fit their requirements. Arriving in Bogotá, Colombia, in June 1960, Krull worked with the RF's wheat breeder John Gibler.[68] Krull and Gibler both became involved mainly in the wheat improvement program in Colombia, with oats and barley as secondary areas of focus.[69] After a few years, however, the RF considered phasing out the Colombia program due to successful training of several Colombian scientists.

In the mid-1960s Borlaug needed assistance with the Mexican wheat program as he took on a more international role. Borlaug also needed help analyzing results of the international wheat yield trials. For several years, only preliminary results had been sent to the international collaborators.[70] Borlaug needed someone with experience in both plant breeding and statistics to help him, and Krull was experienced in both from his dissertation work. In August 1965 Krull transferred to Mexico to coordinate the international wheat yield nursery and its analysis, as well as to cover many of Borlaug's duties in Mexico while Borlaug traveled. Krull was named resident coordinator of International Wheat Program in May 1967. Gibler, meanwhile, was transferred to Ecuador to continue working on wheat there.

Having Krull in Mexico was a boon to Borlaug's program on wide adaptation. With the analyzed results of the International Spring Wheat Yield Nursery, Borlaug now had empirical evidence to support wide adaptation: several of the Mexican varieties yielded, on average, the best of all varieties tested. Borlaug stated in his 1967 oral history: "We begin to understand some of the basic things that underlie this adaptation. This, to me, is a fundamental discovery that has long been overlooked. And it has been borne out now, and we have ample evidence, some of which has been reported in these recent bulletins that Dr. Krull has been getting out, that are backed up by large quantities of experimental data."[71] Krull's analysis of the international wheat nursery results bolstered Borlaug's confidence to expand the RF's wheat program into the eastern hemisphere.

Throughout his time with the RF in Mexico, Krull consistently stated that scientists should consider the importance of widely adapted wheat varieties, that countries should focus efforts on only one breeding and testing program for fertilized and irrigated environments, and that widely adapted varieties chosen under favorable environments could unequivocally outperform local varieties, regardless of environment. These views were not mainstream among wheat scientists, especially those from the FAO who were working in the Middle East.

Krull often argued that wide adaptation was an important and undervalued concept in wheat breeding. Speaking on the "elusive concept of breeding for adaptation," Krull addressed the Minnesota-based Crop Quality Council in 1967 about the "deeply ingrained philosophy that is held and taught by most of the North American graduate schools that such adaptation is probably neither possible nor desirable."[72] Krull had written earlier: "Plant breeders frequently feel that varieties must be well adapted to only very small areas. They feel that since variety × location interactions are frequently encountered the ideal variety must be narrowly adapted. Indeed, such varieties can be produced. *It is also possible, however, as is illustrated by these data, to produce varieties that are widely adapted*."[73] Krull obviously disagreed with mainstream plant breeders that varieties should be bred for local conditions. He even pondered the "possibility of producing spring wheat varieties with nearly universal adaptations."[74] Krull certainly did not lack Borlaug's missionary zeal.

Although Krull traveled to the Middle East only a few times, he frequently wrote to two FAO scientists working in the Middle East: Abdul Hafiz, a regional consultant for the FAO's Near East Wheat and Barley Improvement Project who was located in Egypt in the 1960s and 1970s, and C. L. Pan, a cereal breeder for the FAO in Iraq who, like Borlaug, had studied at the University of Minnesota.[75] Hafiz also helped coordinate the Near East–American Spring Wheat Yield Nursery with Borlaug.[76] The RF was interested in working in the Middle East and continuing their collaboration with the FAO, but scientists from the two organizations had different crop-breeding philosophies. The FAO team held the traditional position that crops needed specific adaptation to local conditions. Krull, on the other hand, attempted to influence wheat breeders in the Middle East to adopt breeding and testing practices more like Borlaug's methods.

Unlike the irrigated Sonora region of Mexico, where farmers clamored for semidwarf wheat, the Middle East had a diversity of wheat-farming practices. In the 1960s, plant breeders in the Middle East focused on low-fertility conditions that farmers were most likely to experience. Krull, like Borlaug, argued that wheat breeding should focus on only highly fertilized conditions. Krull made a trip to the Middle East in April and May 1966, where he recorded his detailed observations and opinions of the wheat programs there. Krull observed that in a dryland area of Jordan, "the yield nurseries showed a decided lack of fertilizer, and this tended to make all varieties look the same. The reasoning was that most of the farmers do not use fertilizers so varieties must be selected under these conditions."[77] He felt, however, that "this is a common fallacy among wheat breeders in under-developed countries, and there is actually little basis for it."[78] Krull reasoned that well-fertilized environments allow the breeder to see the variability between varieties to help them make their selections. In a letter to Hafiz in 1966, Krull wrote, "As suggested, I would like to see the nurseries more heavily fertilized. It is simply much easier to see yield differences at these high fertility levels. Putting on a good amount of fertilizer tends to iron out any soil differences that there might be, so that the differences in yields observed are mainly genetic."[79] Krull was consistent and persistent in his argument for high fertility and testing.

While visiting Iraq on the same trip, Krull wrote, "The experiments needed fertilizers badly and there were water logged spots that damaged parts of most experiments. . . . Pan had not fertilized the nursery on the basis that farmers do not fertilize."[80] After some discussion with Pan, Krull thought that he "finally seemed pretty well convinced" to use higher levels of fertilizer.[81] Pan indeed seemed convinced. He reported on the visit to his former advisor, the esteemed plant breeder Herbert K. Hayes. His experiments were conducted under the "local method of farm management with a brief that any promising varieties thus screened out will be adoptable to the local conditions. Dr. Krull's way of thinking in this respect, however, is quite different from mine. He thought that such a variety trial should be carried out in a field provided with the best conditions for the growth of the plant."[82] He continued, "This seems to me a more realistic way of approach, and I am prepared to follow such new approach when I design trials in the future. . . . I would become much more convinced if you also can endorse this new approach."[83] Unfortunately, Hayes's response is not included in the archives.

Krull also argued that scientists should breed and select plants under high fertility. He wrote to the FAO's Hafiz that "if the breeder is only working at the fertilizer level now used by the farmers, by the time the variety is actually selected and multiplied, it will already be obsolete with the better farmers."[84] Krull and Borlaug both felt that wheat breeders should anticipate higher fertilizer levels in the future and breed for responsive varieties. Hafiz echoed this, writing to Krull, "No doubt, the Cereal Breeders have now realized the great importance of breeding and testing varieties under high fertilization . . . the Breeders will have to cater for varieties suitable to be grown under high fertilization, which is the only answer to meet the food shortage."[85] Thus, it appears Krull influenced the thinking of both Hafiz and Pan around fertilizers.

Krull reflected on a trip to the Middle East in 1966 that, "there seems to be little basis for the widely spread belief that varieties selected under high fertility do not usually do as well under low fertility."[86] Krull drew from the results of the international nurseries to argue against this belief. In the *Results of the Fourth Inter-American Spring Wheat Yield Nursery*, published in 1967, Krull and his coauthors challenged the prevailing idea that "each environmental niche must ideally have its own set of varieties" with the finding that the Mexican varieties had the highest average yields around the world.[87] In his presentation to the Crop Quality Council, Krull argued:

> If we seed 10 Mexican and 10 Indian varieties without fertilizer in India, we find that they all yield about the same. If we then seed the same experiment at another site with 120 pounds per acre of nitrogen, we find that the group of Mexican varieties yields considerably more than the tall, weak-strawed Indian lines. . . . The varieties that yield well with fertilizer also tend to be the same ones that yield best with poor management. This is very nicely illustrated by . . . literally hundreds of smaller tests that were run last year throughout India and Pakistan, and to a lesser extent in other countries in the Near East and the Americas.[88]

He stated further, "My point is that the presence of variety × location interactions does not necessarily imply that the same varieties are not the highest yielding in all environments."[89] In other words, Krull argued that wheat could be widely adapted across not just locations but also diverse environmental conditions.

Krull also extended his argument to soil moisture, arguing that one variety could also be the best performer in both irrigated and rainfed environments. He said to the Crop Quality Council, "Evidence is accumulating that this same thing is true in irrigated versus dryland conditions. . . . Such a statement is considered to be rank heresy by most wheat breeders."[90] Finally, he argued "that varieties that show good adaptation in area are also better adapted over time," meaning they had consistently high yields year after year.[91] Krull wrote in 1965 that "the published results of our first five international yield trials have shown that it is possible to produce a series of varieties that are capable of outyielding local varieties from Chile to Canada and from Minnesota to the Near East."[92] He believed, like Borlaug, that high yield and wide adaptation made the Mexican semidwarf wheats superior to nearly all other wheats, no matter their environment.

Krull's thoughts on breeding for soil moisture echoed his opinions on soil fertility. Krull argued that varieties selected under irrigation could still be adapted to moisture-stressed environments, and that they were superior to local varieties. He wrote to Hafiz in 1966, "It appears that varieties that are adapted to intensive irrigation may also be adapted to very droughty conditions. Thus, it is not necessary to initiate a separate program for the irrigated and arid areas."[93] In a 1967 letter to Byrd C. Curtis, a plant breeder at Colorado State University, Krull wrote that the Mexican semidwarf wheats were "extremely productive under irrigation and high fertilization, but the results of our international nurseries indicate that they do as well as supposedly drought-resistant varieties under poor conditions."[94] He wrote further that "in other words, the dwarfs *respond* to but do not necessarily *require* irrigation and extremely heavy fertilization."[95] This argument implies that widely adapted varieties have an inherent (or genetic) high yield, that they can efficiently use moisture and nutrients under both surplus and scarcity.

While Hafiz and Pan were both amenable to Krull's fertilizer suggestions, they disagreed with his recommendations for dryland agriculture. Hafiz wrote to Krull that agronomic improvements ("agrotechniques") were necessary for dryland conditions, not just widely adapted varieties: "For dry farming areas we will try to follow your suggestions but still I feel these areas require at least one comprehensive programme for the Region not only from the point of view of developing drought resistant and higher yielding varieties but also for developing better agrotechniques for the efficient use of soil moisture and fertilizers. . . . It is really a very big and very difficult problem, but at the same time the most important and immediate one."[96] Krull responded: "I certainly do not disagree that it would be worthwhile to concentrate heavily in at least one place on drought resistance. My point was simply that I don't believe it would be wise to separate it from an irrigated program as it appears to be possible to produce drought resistance varieties that are also adapted to irrigated conditions."[97]

Pan also wrote to Krull about the problems of dryland farming. For the wheat-growing areas of Iraq, Pan wrote, "It seems that wheat breeding should concentrate on drought resistance in the north and salinity tolerance in the south."[98] A year later, Pan still insisted to Krull that a drought-resistance was critical in Iraq. He wrote, "As you know more than two thirds of the wheat crop in Iraq are grown in the north in the rainfed area. But rainfall varies very greatly from year to year. It seems that the most effective way to increase the yield level of wheat in the rainfed area is to use drought resistant variety."[99] Here, Pan touched on a decades-long scientific debate on the efficiency of selection environments, which will come up in the next few chapters.

During the mid-1960s the RF's wheat program decided to focus on irrigated areas because they could raise yields more easily there. This strategy was a clear contrast with the FAO program in the Middle East. The FAO breeders evidently held a different philosophy of agricultural development from the RF wheat scientists. While the FAO focused on improving agricultural production under all conditions, the RF was "betting on the strong" and emphasizing production gains in irrigated and fertilized areas. Krull wrote, "While there is interest in many countries in producing varieties that do not require fertilizer or water, *there is no such group of varieties*. The important thing in changing the production pattern in a country is to introduce varieties that will *respond* to good management and then change the management."[100] This statement reflects a belief, held by the RF administration and Borlaug, that technical change would inevitably lead to social change. Borlaug and Krull viewed "good" agronomy as maximizing yield under high-resource conditions, while others might define it as getting by with the resources at hand.

Krull left Mexico in 1968 owing to a divorce, but remained affiliated with the RF.[101] While Krull seems to have been very influenced by Borlaug, Krull left an impression on Borlaug as well. Borlaug used Krull's data analyses to support the spread of widely adapted, fertilizer-responsive wheats. Krull argued that the most productive way to improve a national plant-breeding program was to aim for widely adapted varieties selected under favorable environments. His evidence was the results of the International Spring Wheat Yield Nurseries. Around the same time, Keith Finlay used empirical analysis to take Borlaug and Krull's results a step further: to quantify adaptation across environments.

KEITH FINLAY'S CORRESPONDENCE ON ADAPTATION, 1963–1968

Agriculturalists had long regarded adaptation as a factor that could not be predicted or quantified, but only tested through trial and error by introducing plant varieties to new locations. Starting in the late 1930s, scientists began using analysis of variance models to analyze crop performance against independent variables.[102] These models could, for example, show that a variety's phenotype changed based on location or experimental treatment. Then in 1963 an Australian wheat breeder, Keith W. Finlay, and his colleague, statistician Graham N. Wilkinson, created an experimental design and mathematical model that measured the phenotypic stability—or adaptation—of plant varieties in different environments.[103] The model was a simple logarithmic plot of a variety's yield versus the mean yield at a location; in other words, performance versus an environmental index. The model became immediately popular among plant breeders and led to a variety of other "stability models" that are still employed today. As one of the first computational analyses of plant breeding, this model influenced plant breeders to study crop adaptation to environments.[104] The prominent crop physiologist Lloyd T. Evans called stability models "the plant breeder's icons, ubiquitous but with a variety of styles to support a variety of dogmas."[105]

Finlay was a professor of plant breeding at the Waite Agricultural Research Institute at the University of Adelaide, Australia. He provided an academic counterbalance to Borlaug, though he shared many of Borlaug's goals. Borlaug became aware of Finlay through Vogel, who considered Finlay a "first choice" hire to coordinate the RF's Indian wheat program.[106] Finlay visited Borlaug from October through November 1963, partly for an academic exchange and partly to express interest in an open wheat breeder position in Mexico. He presented his work on adaptation while touring Mexico and Colombia. Despite finding Finlay "a very capable theoretical research scientist," Borlaug found him too academically oriented for either the India or the Mexico position, where Borlaug wanted someone with an inclination toward fieldwork.[107]

A few months later Finlay wrote to Borlaug to apprise him that he had submitted a research proposal to study adaptation together with the RF's scientists in Mexico. Robert Osler, the assistant director of agricultural sciences for the RF, let Finlay know that the success of the proposal depended largely on how Borlaug prioritized it. The RF rejected the proposal in September 1964. As soon as 1965, however, Borlaug proposed bringing Finlay back to Mexico to help Krull set up to analyze the international trial results. It appears that Finlay was able to visit in 1966 and in 1967, and Borlaug or Krull provided him with data from the international trials to analyze for his own research.

Borlaug wrote to Finlay in 1964, "Since I last saw you we have learned considerably more about adaptation of the Mexican breeding material in far-away places. . . . The Mexican material was equally as well adapted in India as in Sonora."[108] Finlay responded, "There is certainly no doubt that the more recent Mexican varieties have a very wide adaptation," and he hoped they could continue working on adaptation together.[109] Finlay also included some preliminary analyses of the 1961–1962 and 1962–1963 Near East–American Spring Wheat Yield Nurseries, where he plotted the varieties' average stability by their average yield, clustering the varieties into groups. He found that the newer Mexican varieties were superior in terms of stability across locations and having a higher average yield, although there was not much difference between the varieties released in 1960, 1962, and 1964.[110] In other words, there was not much different between the tall and semidwarf varieties: both were widely adapted and high-yielding.

Borlaug wrote to Osler the same day he wrote back to Finlay. He wrote, "I feel that Dr. Finlay has developed some useful information to partially explain adaptation phenomena we have already uncovered in the FAO-Near East-American Spring Wheat Yield Tests, and the Inter-American Spring Wheat Yield Nurseries."[111] Meanwhile, Louis P. Reitz, who led the USDA's wheat research, also corresponded with Osler about Finlay. Reitz wrote that Finlay's analysis "surely would lead to wider use of the fine Mexican materials and the work might lead to improved pools and greater understanding of gene pools. Some benefits would come even if the work merely 'proved the obvious.'"[112] Finlay's analytical work appeared useful to "prove" the wide adaptation of Borlaug's wheats.

In late 1966 Finlay wrote a long, detailed letter to Borlaug about adaptation, the analysis of the international yield trial results, and the future directions of CIMMYT. Though excited about CIMMYT's expanded international programs, Finlay also had some reservations about Borlaug's research program. He wrote to Borlaug, "Although this wide adaptation is one of the strong points of your programme, it is also possibly the weakest!"[113] He suggested that Borlaug should collect more basic data to determine what causes wide adaptation, writing: "Your present wide adaptation is resulting from selection successively in a number of different environments, but the *type* and *degree* of adaptation is not known for any particular variety until it goes into the International Yield Trial."[114] Finlay thought that more testing throughout the breeding process would be helpful. He cautioned Borlaug to understand more about the mechanism of wide adaptation before advancing too quickly with his international wheat program.

Finlay also had some concerns about Borlaug's shuttle breeding method, writing, "The selection technique used at present certainly allows the selection of widely adapted genotypes but it also *automatically eliminates* genotypes with exceptional potential for yield given the correct specific environment."[115] Thus Borlaug's program might be weeding out varieties well adapted to conditions such as drought. Finlay suggested separating the breeding of rainfed and irrigated wheat varieties to "exploit both sets of environments much more efficiently by having varieties which are widely adapted to environments *within* each set."[116] Yet Finlay believed that with some experimental modifications, Borlaug's work could "revolutionise thinking in plant breeding circles."[117]

Finlay was meanwhile working with Australia's well-known plant breeder Otto H. Frankel to promote the conservation of plant biodiversity. They worked together on the International Biological Program project called Biology of Adaptation, which Finlay convened starting around 1966. The International Biological Program (IBP, 1964–1976) was an attempt at "big biology" to collect large-scale data sets, modeled after the International Geophysical Year.[118] The Biology of Adaptation project and another on "plant-germ-plasm pools," chaired by Frankel, fell within the IBP's subcommittee on "Use and Management of Biological Resources."[119] Finlay and Frankel were not unusual in their interest in plant biodiversity; plant biodiversity conservation became a major focus of plant breeders around the world, including India's famous M. S. Swaminathan, who was also involved in the IBP program on adaptation.

The original goal of the Biology of Adaptation project was an "analysis of the performance of a large number of varieties in certain standard, selected environments . . . and consequent analysis of productivity in genetic, physiological, and ecological terms" for four to six crops in an experiment like Borlaug's yield trials.[120] Although Borlaug and Finlay appeared to have a cordial relationship, Borlaug was initially unimpressed by the IBP's Biology of Adaptation project. On his copy of the "IBP Second Circular" from August 1966, Borlaug wrote in the margins of the planned experiments, "Being done by RF," "Charlie—this looks like our own ISWYN [International Spring Wheat Yield Nursery]," and, regarding Finlay as coordinator for temperate zone cereals, Borlaug wrote, "Competition?"[121] Borlaug wrote to the RF's director of agricultural sciences, Sterling Wortman, "Why should we set another organization up in competition with our own?"[122]

In fact, the resemblance of the projects was likely due to Frankel himself, who favored Finlay's analytic aspects of adaptation along with Borlaug's practical aspects.[123] But Borlaug, ever focused on expanding his wheat program, was offended rather than flattered. Frankel wrote to Borlaug, "We are mainly concerned with a broad adaptability study on the Finlay pattern; you are, I imagine, mainly concerned with the agricultural success."[124] Frankel became personally interested in recruiting Borlaug to the IBP adaptation program and invited him to the conference meetings in Rome. By January 1967 Borlaug appeared to be on board to support the IBP's adaptation program. CIMMYT collaborated with IBP to conduct adaptation experiments as part of CIMMYT's Sixth International Spring Wheat Yield Nursery of 1969–1970.[125] The IBP wheat adaptation program did not seem to progress much beyond that, however, and likely was simply subsumed by CIMMYT's existing international yield nurseries when Finlay started working there in late 1968.

Despite his earlier rejections by the RF and Borlaug, Finlay helped bring Borlaug's program on adaptation to international academy. He brought Borlaug to the Third International Wheat Genetics Symposium, held in Canberra, Australia, in early August 1968, to give a keynote titled "Wheat Breeding and Its Impact on World Food Supply."[126] This conference signaled Borlaug's wider acceptance by the wheat research community. Finlay also presented a paper titled "The Significance of Adaptation in Wheat Breeding."[127] He used the results of Borlaug's international trials to show that varieties could be bred with both high average yield and wide adaptation.

Though Borlaug had passed over Finlay for positions at CIMMYT several times already, after Krull's departure in 1968 Borlaug needed someone with a strong mathematical background to help with the international trials and general administration of the wheat program.[128] Gibler was promoted to associate director of the wheat program, and Finlay was recruited to assist him and Borlaug. Finlay was quickly hired as "Director, Basic Research and Training (International nurseries and data retrieval)" for the maize and wheat programs at CIMMYT and remained there until his death in 1980.[129]

Finlay's work on adaptation, both theoretically and programmatically, helped solidify it as a measurable object of study in the plant breeding community. Corresponding with Borlaug starting in 1963 and working at CIMMYT for a dozen years, Finlay "proved the obvious" of Borlaug's adaptation program—that certain varieties could be widely adapted across environments—through his analysis of adaptation.[130] The two scientists were not completely in sync in their views on wide adaptation, however. Finlay called for more understanding of the mechanisms of adaptation, while Borlaug focused on rapidly growing his wheat program. Finlay appeared more interested in how adaptation emerged and how it could be developed in a plant-breeding program, especially drawing on plant diversity. Borlaug, on the other hand, seemed more concerned with the practical and immediate uses of widely adapted varieties, and ignored empirical evidence at times. Despite their differences, Borlaug and Finlay depended on each other for theoretical models and experimental data, which they both used to promote wide adaptation internationally.

ADAPTATION WITHOUT CONTEXT

Borlaug, Krull, and Finlay were three influential figures in international wheat research in the 1960s. Borlaug undisputedly played the major role in elevating wide adaptation as a goal in agricultural science and establishing the narrative and meaning of wide adaptation. Krull and Finlay, however, have been rather overlooked in the history of agricultural science. Krull promoted wide adaptation and breeding for ideal environments in the Middle East. Finlay, on the other hand, corresponded with Borlaug about the more theoretical aspects of wide adaptation. He also promoted Borlaug's wide adaptation through international research forums. Finlay's theoretical and administrative work on adaptation helped solidify it as a measurable object of study in the plant sciences. Best known for his mathematical model of adaptation, Finlay started a revolution in quantitative plant breeding.

It is unquestionable that the Mexican semidwarf varieties combined several genetic qualities that allowed very rapid international adoption. The daylight insensitivity, dwarfing genes, and rust resistance of these varieties added to the intrinsic wide adaptation of wheat. These varieties had, on average, high yields regardless of the location and agronomic conditions. They also fit the RF's mission of helping countries that lacked a well-developed agricultural research system.

However, the international consequences of Borlaug's program are not all positive. Although Borlaug's wheat varieties garnered international interest, critics began pointing out that these varieties did not always perform well in rainfed or low-fertility environments. Borlaug more or less ignored these claims and focused on the dire consequences of traditional agriculture and overpopulation. He relied heavily on the averaged, decontextualized results of his international trials and brushed aside anecdotal evidence from field staff in the Middle East. The more he was criticized, the more he sank into his position that widely adapted wheats could outyield local varieties even under rainfed or low-fertility environments. Simultaneously, Borlaug's research program worked exclusively under high-fertility conditions to maximize the varieties' response to nitrogen fertilizer. Thus, while wide adaptation itself is not inherently problematic, Borlaug tied wide adaptation to the need for high fertility in a way that ignored the reality of many farmers around the world who lacked access to fertilizers.

Borlaug and Krull promoted wide adaptation to expand the RF's wheat programs and to increase global wheat production, but they did so under questionable scientific premises. The team promoted breeding and testing under only high-fertility and irrigated conditions but extended the meaning of wide adaptation from adaptation across location to adaptation across agronomic conditions. While the results of the international yield trials on average supported their assumptions, Borlaug did very little, if any, investigation into the performance of his wheat varieties under farmers' conditions outside of Mexico. This is important because yield trials are often biased as a consequence of more careful management, better soil conditions, and so on, and results from bad years (such as drought) are often thrown out. Borlaug and Krull also drew firm conclusions about the superiority of the semidwarf wheats while comparing these to only a few local varieties, including varieties that were photoperiod sensitive and thus would not yield well outside of their growing zone. Borlaug and Krull did not examine the possible biases of the international yield trials, even when confronted with alternative explanations.

Finlay's involvement with Borlaug and CIMMYT points to some problems with Borlaug and Krull's mission-driven approach to expanding the RF's wheat program. Namely, Borlaug and Krull focused on irrigated and fertilized conditions through controlled experiments while overlooking the genetic and physiological factors that contributed to wide adaptation. Borlaug downplayed the genetics of photoperiod insensitivity to emphasize how his method of shuttle breeding led to widely adapted varieties. This breeding technique is still employed by CIMMYT to select for wide adaptation.

We can say that Borlaug made a series of reductionist arguments for wide adaptation. Modern scholars have examined the phenomenon of "disembedded grain," and this descriptor seems apt.[131] Borlaug developed his international program on wide adaptation without much engagement with farmers outside of Mexico; even in Mexico, he worked with wealthier farmers who used irrigation and fertilizers. While there is nothing inherently problematic about introducing plant varieties to new locations, there is a problem when these varieties require a set of agronomic techniques vastly different from the local context.