A Review of the Science and Implications of the Green Revolution

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I. Abstract

Wheat has evolved since ancient times but crossbreeding in the past 100 years has allowed humanity to vastly change the genetics of wheat and develop a narrow selection of varieties. Japanese scientist Gonjiro Inazuka discovered the Norin 10 variety in the early 20th century. This became the parental genetic lineage for future crossbreeds by American scientists Orville Vogel and Norman Borlaug in the mid-20th century. This work led to the creation of rust-resistant, dwarf, high-yielding varieties which were quickly made commercially available by the late 1960s. Alongside a series of connected advancements in related fields, notably in the development of chemical fertilizers, an era of industrialization in agriculture began, now known as the 'Green Revolution'. These developments quickly led to vastly increased wheat yields in Mexico and other places, and also resulted in improved food security for some places around the world. The 'Green Revolution' also caused a number of negative socioeconomic and environmental effects. This case study reviews the science behind some of the key advancements that drove the 'Green Revolution' and critiques its established standing among the scientific community and wider society.

II. Background on Science in General

Science, defined in its simplest form as "knowledge of the world of nature", originated in prehistoric times, and has progressed immensely over several millennia (Williams, 2022). In its mature form, the institution of science principally developed in the West, but often knowledge in other areas of the world, notably China, was far superior to Western science (Williams, 2022). The Renaissance, 'Scientific Revolution' and following institutionalization of science in the 19th and 20th centuries, gave rise to the established occidental epistemology understood today as the 'scientific method' (Hepburn & Andersen, 2021; Williams, 2022). The 'scientific method' has been defined as "a method of procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses" (Oxford English Dictionary). Fundamentally, the scientific method uses hypotheses as tools to gather data; many investigations are completed to explore hypotheses, and thus using the findings and data gathered, scientists can formulate broad explanations, or scientific theories to address misconceptions (Britannica, 2022). The scientific method is usually characterized as a linear process, but this notion should be challenged. Ryan & O'Callaghan categorize the scientific method into five steps:

“1. Make an observation
Gather and assimilate information about an event, phenomenon, process, or an exception to a previous observation, etc.
2. Define the problem
Ask questions about the observation that are relevant and testable. Define the null hypothesis to provide unbiased results.
3. Form the hypothesis
Create an explanation, or educated guess, for the observation that is testable and falsifiable.
4. Conduct the experiment
Devise and perform an experiment to test the hypothesis.
5. Derive a theory
Create a statement based in the outcome of the experiment that explains the observation(s) and predicts the likelihood of future observations.”
(Ryan & O’Callaghan, 2002)

Similarly, Wolfs identifies four steps to the scientific method:

“1. Observation and description of a phenomenon or group of phenomena.
2. Formulation of an hypothesis to explain the phenomena. In physics, the hypothesis often takes the form of a causal mechanism or a mathematical relation.
3. Use of the hypothesis to predict the existence of other phenomena, or to predict quantitatively the results of new observations.
4. Performance of experimental tests of the predictions by several independent experimenters and properly performed experiments.”
(Wolfs, 2013)

The view of the scientific method as a simple step-by-step and linear process is misguided and should be treated as a misconception. The process of science is complex and significantly more nuanced. Science is an ongoing process that may be cyclical and requires the input of others from both inside and outside the scientific community. Researchers at the University of California Museum of Paleontology, Berkeley, have framed a more comprehensive view of the scientific process, which they call the “Science flowchart” (Fig 1). This framework provides a holistic and authentic view of the process of science, and the work of scientists. In this case study, this process will be examined through a review of discoveries in wheat genetics, and advances in knowledge in chemistry and microbiology.

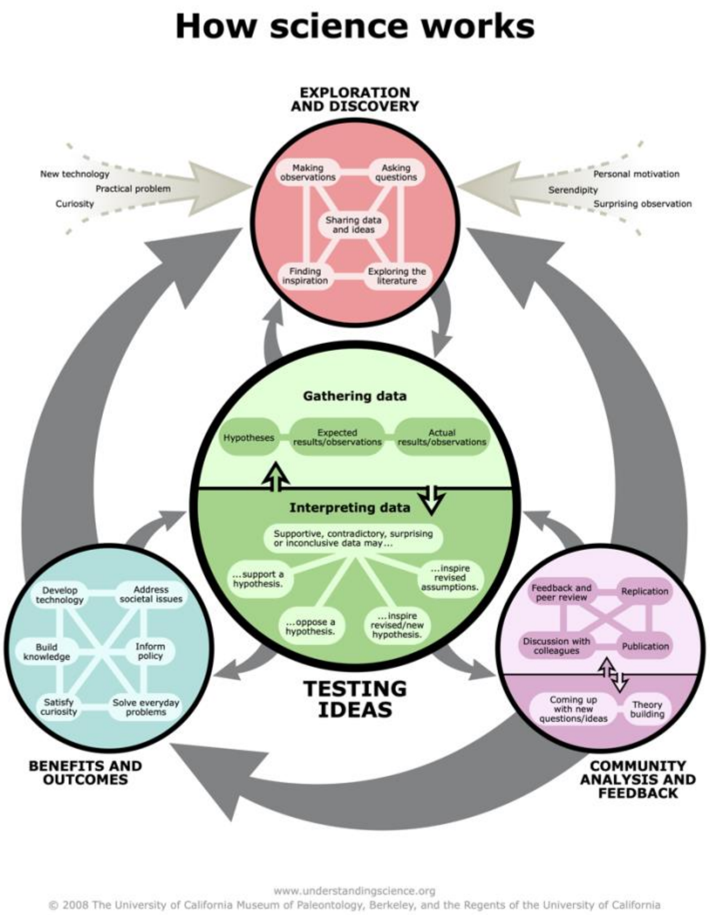

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Fig 1. Science flowchart
(UC Museum of Paleontology, 2022)

III. Historical Context

Over the course of Earth's history, thousands of flowering plants have existed, but very few have been domesticated (Vergauwen & De Smet, 2017, p.858). Of these, wheat, maize, and rice supply the majority of our calories. These species have genetically evolved over the past 10,000 years to the crops we use today, with large seeds, low toxicity, and reduced seed dispersal (Vergauwen & De Smet, 2017, p.858). Our ancestors ate ancient cereal varieties like emmer, einkorn, and kamut wheat, but we now consume two main types of allopolyploid wheat (with chromosomes derived from different species) – hexaploid common wheat (*Triticum aestivum ssp. aestivum*), and tetraploid durum wheat (*Triticum turgidum ssp. durum*) (Vergauwen & De Smet, 2017, p.858). The hexaploid ancestor of today's bread wheat originated from a polyploidization event around 8,000 years ago in the Middle East, while the tetraploid ancestor of today’s durum wheat developed around 500,000 years ago (Vergauwen & De Smet, 2017, p.858). Advances in cereal-driven farming began in the Middle East around 12,000 years ago, and opened new avenues for the invention of tools, such as the ability to process grains into flour (Vergauwen & De Smet, 2017, p.859).

Two major improvements to wheat production were made by the 1960s. The Industrial Revolution brought huge advancements in grain milling, with the invention of the modern steel roller miller, replacing stone mills (Vergauwen & De Smet, 2017, p.861). The steel mills allowed for the production of low-cost white flour; they were fast, efficient, and gave precise control over each part of the kernel (Vergauwen & De Smet, 2017, p.861). Although semi-dwarf wheat varieties may have originated in Korea in the third or fourth century, these varieties were only exploited in the 20th century (Lumpkin, 2015, p.14). Profound changes were made to the genetics of wheat, with Norman Borlaug leading the charge to introduce dwarf wheat varieties which have shorter stems and a greater yield (Vergauwen & De Smet, 2017, p.861). In 1924, Japanese scientist Gonjiro Inazuka cross bred a semi-dwarf Japanese landrace with two American varieties, and this resulted in a vastly improved semi-dwarf variety, named ‘Norin 10’ (Lumpkin, 2015, p.13). Samuel Cecil Salmon, a wheat breeding researcher with the United States Department of Agriculture (USDA), served as an advisor to the occupation army in Japan, and visited the Marioka Agriculture Research Station on Honshu (Borojevic & Borojevic, 2005, p.456). On his return to the United States, Salmon brought some samples which he received from Japanese scientists at the lab and sent them to the Joint USDA/Washington State University project at Pullman (Borojevic & Borojevic, 2005, p.457). An American scientist at the university, Orville Vogel, used Norin 10 to produce high-yielding, semi-dwarf winter wheat varieties (Lumpkin, 2015, p.13). This cross breeding led to a new variety called ‘Gaines’, and this dominated wheat production in the Pacific Northwest in the late 1960s (Borojevic & Borojevic, 2005, p.457). Borlaug wrote to Vogel in 1952 to inquire about his successes in incorporating the semi-dwarf genes from the Norin 10 variety with winter wheat and asked if the genetic material containing the Norin 10 genes could be used as parental lines for his own wheat breeding work in Mexico (Lumpkin, 2015, p.14). In 1953, Borlaug successfully crossed Vogel’s variety with local Mexican rust-resistant varieties (Mohanta, 2009, p.56). Borlaug named two of the most effective varieties Sonora 64 and Lerma Rojo 64 (Lumpkin, 2015, p.13). These varieties began to be distributed nationally, and average wheat yields doubled within 7 years in Mexico (Lumpkin, 2015, p.13). They quickly spread around the world and kicked off the ‘Green Revolution’ in India, Pakistan, and other countries (Lumpkin, 2015, p.13). Thomas Lumpkin notes how this simple exchange of information and germplasm between scientists from different parts of the world led to “one of the most extraordinary agricultural revolutions in history” (Lumpkin, 2015, p.14).

IV. Conceptual & Content Background

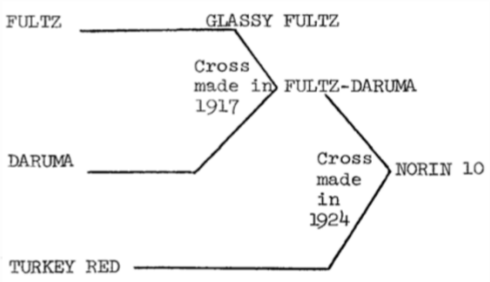

Fig 2. Genetic crossbreeding of Norin 10 (Lumpkin, 2015, p.14)

This quick succession of discoveries, which exploited dwarf genes and resulted in the creation of so-called ‘high-yield’ cereal varieties, was the result of decades of accumulation of knowledge in genetics, microbiology, chemistry, and ecology. Key to the development of these varieties is a group of genes known as ‘reduced height genes’ (*Rht*), and the Japanese Norin 10 variety contained two of these important *Rht*: *Rht1* (*Rht-B1b*) and *Rht2* (*Rht-D1b*) (Borojevic & Borojevic, 2005, p.455). The genetic lineage of Norin 10 is composed of three distinct wheat varieties: ‘Daruma’, ‘Fultz’, and ‘Turkey Red’ (Lumpkin, 2015, p.14). ‘Fultz’ is a soft wheat variety (low-gluten) that was introduced to Japan from the United States in around 1892, and ‘Turkey Red’ is a hard wheat variety (high-gluten) also from the United States and introduced during this time period (exact year is unknown) (Lumpkin, 2015, p.15). ‘Daruma’ is a native Japanese short-straw variety that contained *Rht*, and this was first artificially cross bred in 1917 by Inazuka with an isolated variety of ‘Fultz’ called ‘Glassy Fultz’, creating the ‘Fultz-Daruma’ variety (Lumpkin, 2015, p.15). In 1924, Inazuka crossed ‘Fultz-Daruma’ with ‘Turkey Red’, and the final lineage selection, named Norin 10, was then released in 1935 (Lumpkin, 2015, p.15). The stems of prior tall wheat varieties were not strong enough to support existing high-yielding varieties and the plants would fall over (known as ‘lodging’), leading to large yield losses (Vergauwen & De Smet, 2017, p.862). The genetic cause of tall wheat growth is the phytohormone (plant hormone) gibberellic acid, and *Rht* genes are key to solving this problem (Vergauwen & De Smet, 2017, p.862). *Rht* encode a GRAS (gibberellic acid insensitive repressor) family transcriptional regulator, similar to the gibberellic acid-insensitive gene found in *Arabidopsis* (a small flowering plant, also called ‘rockcress’), a DELLA protein (a subgroup of GRAS regulators known as ‘aspartic acid–glutamic acid–leucine–leucine–alanine’), that negatively regulates and interferes with gibberellic acid signaling, i.e. controlling plant growth (Vergauwen & De Smet, 2017, p.862). The substitutions in *Rht-B1b* and *Rht-D1b* alleles create stop codons and make proteins that function as gibberellic acid-insensitive repressors of growth (Vergauwen & De Smet, 2017, p.862). These genes reduce plant height and internode length, and crucially, resist lodging (Lumpkin, 2015, p.15). The Norin 10 *Rht* dwarfing genes are now found in more than 70% of commercial wheat cultivars (Vergauwen & De Smet, 2017, p.862).

Rust diseases have posed a consistent and persistent challenge to high-yield wheat varieties and the broader monoculturalization of agriculture. There are three main rust disease types: leaf rust caused by *Puccinia triticina* Eriks (Pt), stem rust caused by *Puccinia graminis* f. sp*. tritici* West. (Pgt), and stripe rust caused by *Puccinia striiformis* f. *tritici* Eriks (Pst) (Aktar-Uz-Zaman, 2017, p.431). Rust fungi (*Puccinia spp*.) are obligate plant parasites which include over 7,000 species (Babu et al., 2020, p.3). Wheat rusts have complicated life cycles that include two hosts (wheat as the primary host, and an alternate host), with each type having its own ideal temperature and moisture conditions (Salgado et al., 2016). *Berberis* species and *Mahonia* species are alternate hosts of Pgt and Pst, while *Thalictrum*, *Anchusa*, *Isopyrum*, and *Clematis* are the alternate hosts of Pt (Babu et al., 2020, p.3). The *Puccinia spp.* causing rusts on wheat are obligate parasites with five spore stages: spermatia, aeciospores, urediniospores, teliospores, and basidiospores (Babu et al., 2020, p.3). The pathogens are specialized into distinct physiologic races that are identified by their reactions on a set of differential wheat varieties (Salgado et al., 2016). Tackling rust epidemics is challenging as any wheat variety may be immune, resistant, or susceptible to a race of rust, but no variety is resistant to all races of any of the three rusts (Salgado et al., 2016). Adding to this difficulty, every few years new races of rust arise, making previously resistant varieties susceptible to infection (Salgado et al., 2016). In severe rust epidemics, stem rust and stripe rust can cause 100% loss, while leaf rust can lead to 50% loss (Babu et al., 2020, p.2). To minimize crop loss by rust pathogens, agribusinesses use two main approaches: chemical control using fungicidal spray, and genetic control by breeding for rust resistance (Babu et al., 2020, p.2). Plant pathologists and breeders pyramid effective resistance genes, known as *Lr* genes, with durable resistance, to prioritize the development of disease-resistant varieties with high-yield capacity (Aktar-Uz-Zaman, 2017, p.432). Also called multigenic resistance, this gene pyramiding has enhanced the durability of resistance (Aktar-Uz-Zaman, 2017, p.431). To ensure the continued genetic resistance of wheat to rust diseases, the identification of new or effective resistance genes in different germplasms of global wheat species, or relative species, is crucial.

The ‘Green Revolution’ also led to a large-scale increase in the use of chemical fertilizers, and this is because agribusinesses sought to increase grain yield and achieve sufficient plant growth quickly, including in wheat. Plants began to be supplemented with three main macronutrients: nitrogen (N), phosphorus (P), and potassium (K) (Melillo, 2012, p.1034). In 1909, German chemist, Franz Haber, discovered a way to transform nitrogen in the air into fertilizer, a method now known as the ‘Haber-Bosch process’ (Harford, 2017). Nitrogen is the foundation of nucleic acids, proteins, chlorophyll, and enzymes, and the Earth’s atmosphere is made up of approximately 79% triple-bonded nitrogen gas (N_2), while the remaining 21% is oxygen (Melillo, 2012, p.1034). Even though gaseous nitrogen is abundant, only a small amount of the atmospheric supply is readily available to terrestrial organisms, because atmospheric nitrogen (N_2) is highly unreactive, meaning most plants cannot use it (Melillo, 2012, p.1034). N_2 needs to be transformed into reactive forms (N_r), including ammonium (NH_4) and nitrate (NO_3), and this can be done through biofixation (Melillo, 2012, p.1034). This is the conversion of inert N_2 into organic compounds, like amino acids, which are further transformed by microbes to create NH_4 and NO_3 (Melillo, 2012, p.1034). Biofixation can be completed by *Rhizobium* bacteria joined to the roots of leguminous plants, or by other free-living microbes, like cyanobacteria (Melillo, 2012, p.1034). High temperature events such as lightning, volcanic activity, and forest fires, as well as artificial processes, such as the combustion of fossil fuels, can also achieve the fixation of nitrogen (Melillo, 2012, p.1034). Processes such as the recycling of crop residues, manures, or human waste, i.e. composting, can help to preserve existing amounts of reactive nitrogen within an ecosystem (Melillo, 2012, p.1034). The Haber-Bosch process achieved this biofixation by using natural gas as a source of hydrogen, a necessary element to which nitrogen binds to create ammonia (NH_3) (Harford, 2017). Haber then used high temperatures between 450°C and 600°C, high pressures of 200 to 400 standard atmospheres, and an enriched iron catalyst to produce a reaction of nitrogen and hydrogen that created ammonia (NH_3) (Melillo, 2012, p.1054). This reaction breaks the bonds between the nitrogen atoms and induces them to bond with hydrogen instead (Harford, 2017). Motivated by the promise of a lucrative contract from the chemical company BASF (*Badische Anilin und Soda Fabrik*), Haber informed the company's engineer, Carl Bosch, of the discovery, who then replicated Haber's process on an industrial scale (Harford, 2017). The Haber-Bosch process can be summarized by this exothermic reaction: $N_2 + 3H_2 \rightarrow 2NH_3$

V. Implications of the Case Discovery

The discoveries of high-yielding cereal varieties and the broader 'Green Revolution' led to a series of negative economic impacts, exemplified by the consolidation of the global neoliberal and neocolonial order. The 'Green Revolution' and resulting rise of industrial agricultural systems was motivated by profitability, not efficiency or productivity (Azzopardi, 2022, p.10). This is most especially observed with the monoculturalization (using high-yielding varieties) of farming, itself a legacy of colonialism whereby imperial countries seized land, established monoculture plantations, and engaged in the slave trade (Azzopardi, 2022, p.8). The globalization of industrial agriculture and monopolization of agricultural markets has led to Western methods of using monocultures, pesticides, herbicides, and chemical fertilizers being imposed on and replacing small-scale agricultural methods suited to local climate and conditions (Azzopardi, 2022 p.8). This is essentially a form of neocolonialism, as large agribusinesses continue to consolidate their power and expand their imposition of occidental industrial methods. The adoption of high-yielding varieties in the 1970s and early 1980s displaced farmers and increased inequalities, as smallholders could not afford the high cost of purchased inputs (such as fertilizers and pesticides) that were required to cultivate these new crops, further concentrating land and resources in a minority of economically privileged, large farm business owners (Chhetri & Chaudhary, 2011, p.488). Free trade agreements and the World Trade Organization's 1995 'Agreement on Agriculture' further reduced protections for peasants, and prioritized countries' capacity to import and export food (Azzopardi, 2022, p.12). The high cost of required inputs for high-yielding monocultures, along with these policies, greatly expanded the power of transnational agribusinesses, as peasants did not produce enough of one crop to export to distant countries and thus could not compete (Azzopardi, 2022, p.12). Oligopolies are now visible in various agricultural markets, with a handful of companies, namely Bayer-Monsanto, BASF, DuPont/Dow, and Syngenta, now controlling 60% of the global seed market and 75% of the global pesticide market (Azzopardi, 2022, p.13). The harmonization of trade policies also allowed for the ‘dumping’ of surplus produce at cheap prices by large agribusinesses, outcompeting local peasants and further monopolizing agricultural markets (Azzopardi, 2022, p.12). For example, Mexico’s signing of the North American Free Trade Agreement (NAFTA) led to half of the country’s peasants becoming unable to afford enough to eat, and between 1978 and 2000, half of farms disappeared in France and Germany (Azzopardi, 2022, p.12). Stemming from the discoveries and introduction of high-yield varieties and chemical fertilizers, neoliberal policymaking in the agriculture sector and the oligopolistic behavior of agribusinesses had a direct and indirect adverse impact on local farmers. Perhaps most concerning was the steep rise of farmer suicides in India during the mid-1990s, which sparked a debate on the socioeconomic failures of the ‘Green Revolution’ in a country that was one of the first to both adopt new technologies and import Borlaug’s high-yielding dwarf wheat varieties (Chhetri & Chaudhary, 2011, p.489).

The adoption of ‘Green Revolution’ methods and technologies also had damaging, long-term effects on the Earth’s ecological systems, and have thus created a highly inefficient and destructive global agricultural market that fails to address persistent food insecurity. The motive of profitability, brought about by the imposition of Western industrial methods and the globalization of neoliberal economics, has resulted in wide inequalities in food distribution and accessibility (Azzopardi, 2022, p.5). This is exemplified by persistent food insecurity in many parts of the Global South and poor nourishment in some parts of the Global North, with an estimated 925 million people worldwide who still struggle to access food (Azzopardi, 2022, p.5; Chhetri & Chaudhary, 2011, p.487). Pielke and Linnér have criticized the title and narrative surrounding the so-called ‘Green Revolution’ and characterized it as a “political myth of averted famine”, shaped by Cold War politics in the United States and a community of neo-Malthusian scientists who sought greater political influence (2019, p.266, p.271). Chhetri and Chaudhary note that the ‘Green Revolution’ failed to end hunger in countries where these new varieties and technologies were first introduced and most heavily used, most especially in South Asia (2011, p.487). 224 million people, or 16.3% of India’s population, remains undernourished, and 72 million people, or 32.6% of the Pakistan’s population, are moderately or severely food insecure (FAO et al., 2022, p.141, p.154). Simultaneously, the ‘Green Revolution’ relied on (and continues to) a devastating rise and depletion of water resources. Between 1900 and 2005, water use for agriculture increased fivefold, and agriculture now accounts for approximately 70% of water consumption worldwide, with the total use for agriculture still increasing (Chhetri & Chaudhary, 2011, p.492). Water availability in most South Asian countries has decreased after the introduction of ‘Green Revolution’ technologies and methods. For example, per capita water availability in Pakistan decreased from 5,650 m^3 in 1951 to 1000m^3 in 2001, and in Punjab (a northwestern region of India and Pakistan), the so-called “home of the Green Revolution”, nearly

80% of groundwater is now “overexploited or critical” (Chhetri & Chaudhary, 2011, p.492). This rapid extraction of water may have irreversible effects on the surrounding land, people, and ecosystems in Punjab, with rivers and streams already severely depleted (Chhetri & Chaudhary, 2011, p.492). Chhetri and Chaudhary observe that this region and birthplace of the ‘Green Revolution’ is now in “deep ecological distress” (2011, p.489). India’s exportation of grain and integration with the neoliberal global grain trade have resulted in lasting hydrological damage and the sacrifice of the country’s ancient aquifers (Chhetri & Chaudhary, 2011, p.492).

Concurrently, the use of high-yielding monocultures and agrochemicals has exhausted soil systems and degraded the environment, having ripple effects on agrobiodiversity and compounding the inefficiency of industrial methods. Traditional agricultural practices using polycultures of cereals, legumes, and oilseed crops, were replaced by monocultures of rice or wheat in the 1960s as part of the ‘Green Revolution’ (Chhetri & Chaudhary, 2011, p.491). Monoculturalization not only reduces agrobiodiversity but also leads to decreased soil fertility by reducing the amounts of nutrients in the soil over time, as bacteria attached to legume roots no longer achieve biofixation naturally and chemical nitrogen fertilizers have to be supplemented. Additionally, the intensive cultivation of crops using high-yielding varieties exacerbated this problem, requiring further use of chemical fertilizers, leading to degradation of soils and a gradual deterioration in the productive capacity of the land (Chhetri & Chaudhary, 2011, p.489, p.490). Even though agricultural systems that encourage biodiversity and naturally replenish soil nutrients have higher total yields, agribusinesses and proponents of industrial systems mask this by measuring yields per acre instead of the totals (Azzopardi, 2022, p.10). More traditional polycultures produce fewer yields of a single crop but compensate by growing multiple, diverse crops and by ensuring the sustained fertility of the soil (Azzopardi, 2022, p.10). However, the introduction of high-yielding varieties itself reduced agrobiodiversity. High-yield wheat varieties were bred and introduced from an extremely narrow and alien genetic base, and these few high-yield varieties have replaced almost all other species (Chhetri & Chaudhary, 2011, p.491). From the nearly 10,000 wheat varieties grown in China in 1894, only around 1,000 remained by the 1970s after new varieties were introduced (Chhetri & Chaudhary, 2011, p.491). This phenomenon is observed on a broader scale too, with about 75% of the worldwide genetic diversity of agricultural crops lost in the past 50 years and continuing with an annual decrease rate of 1-2% (Chhetri & Chaudhary, 2011, p.491). An estimated 300,000 species of plants exist today, of which about 7,000 are cultivated for food, and only 12 species currently supply 80% of the world’s food (Chhetri & Chaudhary, 2011, p.491). Monoculturalization and the increasingly reduced genetic base of high-yielding varieties have resulted in vastly greater vulnerability to insects, pests, and diseases (Chhetri & Chaudhary, 2011, p.491; Azzopardi, 2022, p.11). Even high-yielding varieties bred for disease resistance, like the ones developed by Borlaug, breakdown to diseases and insects rapidly, requiring continuous replacement (Chhetri & Chaudhary, 2011, p.491). Stripe rust continues to threaten over 10 million hectares of land in Northern India, and remains a potential threat for Kennya, Ethiopia, Yemen, the Middle East, and South Asia (Babu et al., 2020, p.4). Imported, high-yielding varieties, have replaced indigenous seeds that are more diverse and adapted to local conditions (Azzopardi, 2022, p.10). As global food demand continues to rise and as the effects of climate change worsen, it is essential that genetic diversity is protected in order to avoid vulnerability to increased pests and diseases expected in the future (Chhetri & Chaudhary, 2011, p.491). Worldwide crop losses from Pgt (stem rust) alone are estimated to cost approximately USD 53.7 billion per annum, and this is expected to continue rising (Babu et al., 2020, p.4). Chhetri and Chaudhary have termed this shrink in agrobiodiversity “gradual genetic erosion”, and they comment on the challenges humanity faces as a result of the ‘Green Revolution’, especially in developing new varieties that would be adaptive to a changing climate (2011, p.491). Some academics have characterized the ‘Green Revolution’ to be a key culprit of the “environmental disaster of modern times” (Chhetri & Chaudhary, 2011, p.88).

VI. Scientist of Focus

Fig 3. Norman Borlaug, 1970 (Britannica, 2022)

Norman Borlaug was a key driver of the ‘Green Revolution’, and his work in breeding high-yield, disease resistant, dwarf wheat varieties, kicked off an era of industrialization in agriculture. Borlaug was born on 25 March 1914, and learned about agriculture from a young age, as he grew up on a farm in Iowa (Swaminathan, 2009, p.894). In 1942, Borlaug earned a Ph.D. in plant pathology, studying biology and forestry at the University of Minnesota, before briefly working for the chemical giant DuPont Company (Britannica, 2022). Borlaug worked as a microbiologist for the company’s foundation, Nemours, and was responsible for research on industrial and agricultural bactericides, fungicides, and preservatives (Haberman, 1972). In 1944, he joined the Rockefeller Foundation’s cooperative agricultural program in Mexico, which later became known as the International Maize and Wheat Improvement Center (CIMMYT) (Swaminathan, 2009, p.894). This program was a joint project by the Mexican government and the Rockefeller Foundation, and involved research in genetics, breeding, plant pathology, agronomy, cereal cultivation, among other agriculture-related areas of knowledge (Haberman, 1972). Borlaug focused on controlling rust diseases, and initiated a multi-faceted approach, developing composite varieties of wheat characterized by phenotypic identity but genotypic diversity in resisting different species of pathogen (Swaminathan, 2009, p.894). Utilizing dwarfing genes made available from the Norin 10 variety, Borlaug experimented by breeding semi-dwarf, high-yielding varieties, that responded well to irrigation and application of fertilizers, with disease resistant genes (Swaminathan, 2009, p.894). He then adopted a ‘shuttle’ program which involved growing different generations under two distinct soil and weather conditions: a summer crop in the cooler highlands nearby Mexico City, and a winter crop in the warmer conditions of Sonora in northwest Mexico (Swaminathan, 2009, p.894). This approach led to the successful breeding of semi-dwarf, disease resistant wheat varieties with broad applications, and potential for vastly increased yields per hectare (Swaminathan, 2009, p.894). The Indian and Pakistani governments quickly requested his expertise, and both nations began importing several of Borlaug's Mexican dwarf wheat varieties (Britannica, 2022). Both countries experienced food shortages as a result of rapid population growth, but by the mid-1960s, the importation of these seeds led to a 60% increase in harvests in the region (Britannica, 2022). This is when the 'Green Revolution' started to take off. Borlaug helped both countries to become agriculturally self-sufficient, and his work is supposedly estimated to have saved as many as one billion people from starvation and death (Britannica, 2022). For this work, Borlaug earned the Nobel Peace Prize in 1970 (Haberman, 1972). In later life, Borlaug served as an advisor to numerous organizations, committees, and governments worldwide, and taught a graduate course in international agriculture at Texas A&M University (Swaminathan, 2009, p.894). Borlaug also founded an organization at the same university in 2006, to promote science-based solutions for the challenges facing global agriculture, known as the Norman Borlaug Institute for International Agriculture (Swaminathan, 2009, p.894).

Borlaug dedicated his life to scientific research and serving others, even if the overall worthiness of his work is contested. Borlaug's findings undisputedly had negative impacts on the environment and gave rise to high-input industrial agricultural systems that are now commonplace around the world, but it is unlikely that Borlaug knew or foresaw the scale of environmental damage his crossbreeding discoveries would lead to. Notwithstanding, depictions of Borlaug as an apparent 'savior' should still be challenged, as much of the scientific foundation of his work was completed before Borlaug's own successful crossbreeding; most notably, the discovery of the Norin 10 wheat variety by Japanese scientist Gonjiro Inazuka.

VII. Connections to Today

The advancements in wheat genetics, and the various other scientific developments involved in the industrialization of agriculture, provide several potential avenues for further research and inquiry. Genetic analysis of common wheat varieties in China, and a comparison of the present genes with other varieties from around the world, could be a fascinating yet complex project to undertake. This investigation would require a multi-context approach, and inquiry into preexisting research in other countries along with work conducted locally. Further research could then be made on the susceptibility of local varieties to different strains of rust diseases. Additionally, inquiry into the use of chemical fertilizers and viability of natural alternatives would also pose a relevant and interesting investigation. Composting has gained prominence in recent years as a natural and sustainable alternative to chemically produced fertilizers, like nitrogen fertilizers created by the industrial Haber-Borsch process. Research into the processes and history of composting, as well as its development locally for smallholders and industrial agricultural firms alike, would make a comprehensive and exciting project.

VIII. Final Argument

The quick succession of advances in the breeding and genetics of wheat during the early to mid-20th century transformed agricultural practices, processes, and systems around the world, and greatly expanded scientific knowledge. The successful breeding of the Norin 10 variety by Inazuka, and later the crosses with rust-resistant varieties in Mexico by Borlaug, kicked off the so-called ‘Green Revolution’. This term has come to encapsulate the package of advancements in genetics and new technologies, which allowed for the rapid industrialization of agriculture with the stated aim of reducing global food insecurity. More than 60 years later, the ‘Green Revolution’ was largely unsuccessful in achieving this goal, with hundreds of millions of people, mostly in places where these new technologies were intended to end food insecurity (i.e. the Global South), still struggling to access and afford enough food. Although the ‘Green Revolution’ should not be characterized as a complete failure, the mainstream consensus that it averted catastrophe and solved world hunger for the foreseeable future should be strongly challenged and critiqued. Likewise, Borlaug’s role in the advancements made is also likely overstated and should be questioned. The ‘Green Revolution’ unleashed an attack on diverse ecosystems around the world, particularly water and soil systems, and they will become increasingly vulnerable with the advent of climate change. The effects on these systems are gradually becoming clearer, as widespread water shortages and soil exhaustion, along with a precipitous decline in agrobiodiversity, pose unique challenges to humanity this century. The industrialization of agriculture, encouraged by neoliberal governments and institutions, also caused the forming of oligopolies in agricultural markets around the world, leading to the impoverishment of smallholder farmers and a rise in farmer suicides. Multinational corporations have engaged in forms of neo-colonialism, by imposing Western industrial methods and eliminating traditional and indigenous agricultural approaches. Further research can be conducted to analyze the success of the ‘Green Revolution’ locally, and explore more sustainable alternatives to these technologies.

IX. Works Cited

Aktar-Uz-Zaman, Md, et al. "Genetic Analysis of Rust Resistance Genes in Global Wheat Cultivars: An Overview." *Biotechnology & Biotechnological Equipment*, vol. 31, no. 3, 21 Mar. 2017, pp. 431-45, https://doi.org/10.1080/13102818.2017.1304180. Accessed 4 Oct. 2022.

Azzopardi, Miguel. *Rethinking Food Systems: A Case for and Analysis of Alternatives to Industrial Agriculture, with a Focus on Permaculture*. 2022. U of Edinburgh, MS thesis.

Babu, Prashanth, et al. "Application of Genomics Tools in Wheat Breeding to Attain Durable Rust Resistance." *Frontiers in Plant Science*, vol. 11, 11 Sept. 2020, https://doi.org/10.3389/fpls.2020.567147. Accessed 4 Oct. 2022.

Borojevic, Katarina, and Ksenija Borojevic. "The Transfer and History of 'Reduced Height Genes' (Rht) in Wheat from Japan to Europe." *Journal of Heredity*, vol. 96, no. 4, 13 Apr. 2005, pp. 455-59, https://doi.org/10.1093/jhered/esi060. Accessed 4 Oct. 2022.

Britannica, The Editors of Encyclopaedia. "scientific method." *Encyclopedia Britannica*, 22 Aug. 2022, www.britannica.com/science/scientific-method. Accessed 4 Oct. 2022.

Britannica, The Editors of Encyclopaedia. "Norman Ernest Borlaug." *Encyclopedia Britannica*, 8 Sept. 2022, www.britannica.com/biography/Norman-Borlaug. Accessed 4 Oct. 2022.

Chhetri, Netra, and Pashupati Chaudhary. "Green Revolution: Pathways to Food Security in an Era of Climate Variability and Change?" *Journal of Disaster Research*, vol. 6, no. 5, 1 Oct. 2011, pp. 486-97, https://doi.org/10.20965/jdr.2011.p0486. Accessed 4 Oct. 2022.

FAO, et al. *The State of Food Security and Nutrition in the World: 2022 : Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable*. Rome, FAO, 6 July 2022, https://doi.org/10.4060/cc0639en. Accessed 4 Oct. 2022.

Haberman, Frederick W., editor. "Norman Borlaug." *The Nobel Prize*, Elsevier, 1972, www.nobelprize.org/prizes/peace/1970/borlaug/biographical/. Accessed 4 Oct. 2022.

Harford, Tim. "How fertiliser helped feed the world." *BBC*, 2 Jan. 2017, www.bbc.com/news/business-38305504. Accessed 4 Oct. 2022.

Hepburn, Brian, and Hanne Andersen. "Scientific Method." *Stanford Encyclopedia of Philosophy*, 1 June 2021, plato.stanford.edu/entries/scientific-method/. Accessed 4 Oct. 2022.

Lumpkin, Thomas A. "How a Gene from Japan Revolutionized the World of Wheat: CIMMYT's Quest for Combining Genes to Mitigate Threats to Global Food Security." *Advances in Wheat Genetics: From Genome to Field*, 2015, pp. 13-20, https://doi.org/10.1007/978-4-431-55675-6_2. Accessed 4 Oct. 2022.

Melillo, Edward D. "The First Green Revolution: Debt Peonage and the Making of the Nitrogen Fertilizer Trade, 1840–1930." *The American Historical Review*, vol. 117, no. 4, 21 Sept. 2012, pp. 1028-60, https://doi.org/10.1093/ahr/117.4.1028. Accessed 4 Oct. 2022.

Mohanta, Ranjan Kumar. "Norman Borlaug and Green Revolution." *Agriculture Today*, Dec. 2009, pp. 56-57, www.researchgate.net/publication/275019368_Norman_Borlaug_and_Green_Revolution. Accessed 4 Oct. 2022.

Pielke, Roger, and Björn-ola Linnér. "From Green Revolution to Green Evolution: A Critique of the Political Myth of Averted Famine." *Minerva*, vol. 57, no. 3, 26 Mar. 2019, pp. 265-91, https://doi.org/10.1007/s11024-019-09372-7. Accessed 4 Oct. 2022.

Ryan, M., and Angela O'Callaghan. "The Scientific Method." *University of Nevada, Reno*, 2002, extension.unr.edu/publication.aspx?PubID=4239. Accessed 4 Oct. 2022.

Salgado, Jorge David, et al. "Rust Diseases of Wheat." *Ohioline*, Ohio State University, 12 Apr. 2016, ohioline.osu.edu/factsheet/plpath-cer-12. Accessed 4 Oct. 2022.

"Science flowchart." *Understanding Science*, UC Museum of Paleontology, 2022, undsci.berkeley.edu/science-flowchart/. Accessed 4 Oct. 2022.

"scientific method." *Oxford English Dictionary*. *Oxford English Dictionary Online*. Accessed 4 Oct. 2022.

Swaminathan, M. S. "Norman E. Borlaug (1914–2009)." *Nature*, vol. 461, no. 7266, 15 Oct. 2009, p. 894, https://doi.org/10.1038/461894a. Accessed 4 Oct. 2022.

Vergauwen, David, and Ive De Smet. "From Early Farmers to Norman Borlaug — the Making of Modern Wheat." *Current Biology*, vol. 27, no. 17, Sept. 2017, pp. R858-R862, https://doi.org/10.1016/j.cub.2017.06.061. Accessed 4 Oct. 2022.

Williams, L. Pearce. "history of science." *Encyclopedia Britannica*, 7 Feb. 2022, www.britannica.com/science/history-of-science. Accessed 4 Oct. 2022.

Wolfs, Frank L. H. "Introduction to the Scientific Method." *Prof. Frank L. H. Wolfs*, 2013, teacher.pas.rochester.edu/phy_labs/appendixe/appendixe.html. Accessed 4 Oct. 2022.

Zimmerer, Karl, et al. "RETHINKING THE GREEN REVOLUTION." *Issues in Science and Technology*, vol. 36, no. 4, 2020, pp. 10-11, www.jstor.org/stable/26949152. Accessed 4 Oct. 2022.