Assessing the Impact of Public Research on Net Farm Income

Authors: Klieger, Michelle[1], McAdams, Callie[2], and Owens, Rachel[3]

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Introduction

The goal of this research was to assess which types of public research have the highest economic benefit to farmers. This project uses three case studies to show different factors that impact the benefits public research has on farmers. The three case studies explore public research on Huanglongbing, also known as citrus greening, value-added cattle production, and drought tolerant corn. Before identifying the case studies we investigated, we discussed different measures of farmers' well-being. There are multiple ways to assess the economic health of farm households and farming operations. Each provides a different lens to examine for farm operations and farmers. The most common are gross cash farm income, net farm income, balance sheet and solvency ratios, and farm household income. After reviewing literature on this topic and interviewing farmers and farm organizations, we chose to focus on net farm income (NFI).

Net Farm Income

NFI is farm gross cash income minus farm expenses. The result is the return to the operator. Many other studies look at farm gate prices, which do not consider the relative cost of inputs or expenses. Even if farmers are earning more money, that revenue may not be enough to cover the higher costs of inputs or new technologies. In these cases, they are benefiting from the new technology and innovations, but they are not in a better economic position. Farm revenue comes from cash receipts, government payments, and other farm-related income. Farm expenses include production expenses, government expenses, and other expenses (interest/debt servicing).

The USDA's Economic Research Service tracks farm income and wealth statistics and releases this data three times per year. Forecasts typically highlight changes in farm income and wealth from prior forecasts and from prior years. The forecasts highlight which components of farm income and wealth are having the largest impact on the overall farm income and wealth trends.

[1] Stratagerm Consulting
[2] Vibranteco
[3] RKO Consulting Group

Table 1: Types of Research that Impact Net Farm Income			
Revenue Component	**Research Impact**	**Expense Type**	**Research Impact**
Price – increase demand / increase value	New Uses / Higher Inclusion Higher Quality / Value Products	Labor	Automation, Higher Productivity
Price – world price, world output, energy policy	None – Outside of Agriculture	Livestock/Poultry	Better Efficiency Rates (Cost of Production)
Quantity Produced	Higher Yield / Output	Interest, Property Tax, Fees, Land Rent, Marketing Fees	None
Government Payments	None	Feed	Better Efficiency Rates
Farm-Related Income	None	Fertilizer, Pesticides	Best Management Practices, New Products
		Fuel, Oil	Increased Fuel Efficiency
		Transportation Costs	Many Drivers outside of Ag

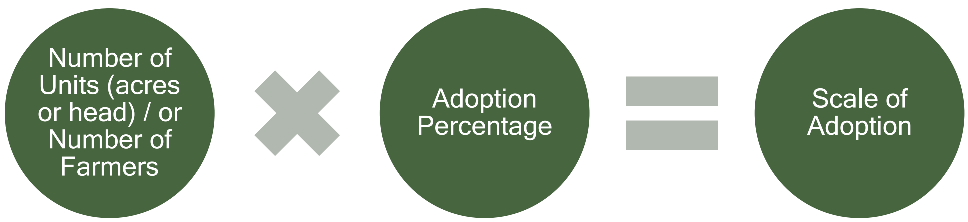
Research that increases revenue is likely, in the near term, to support increases in yield or commodity prices. Farmers get paid more either by charging a higher price per unit or selling more units. On the other hand, research that lowers expenses will decrease input costs, increase productivity, or improve efficiency. The farmer spends less or gets more value out of the money spent.

Measuring the Value of Research

Research is applied by individual farmers or businesses. The value of research can be measured in the economic benefit a farm receives after implementing the research. To understand the impact of research on the entire industry the economic benefit from each farm can be aggregated, giving an estimate of the industry total. Each farm decides based on their own circumstances and their benefit.

The total economic impact depends on the size of the industry that can adopt the technology, the size of the benefit, and the level of farmer adoption. To calculate, the first variable is the size of the industry, for example the number of acres or head. This can also be estimated by multiplying in the number of operations by the average size of that operation. Then the level of impact is based on the scale of adoption, or the percentage of acres or head that are impacted by a technology. Adoption scales overtime, and rarely if ever does adoption reach 100%.

Figure 1. Measuring Scale of Adoption

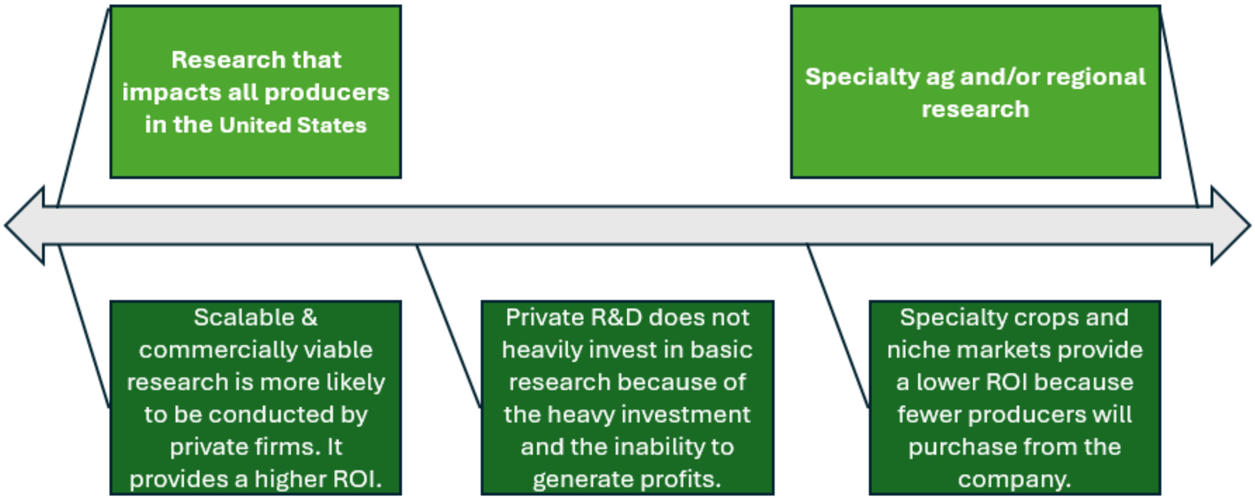


Each case study required specific proxies for farmer adoption. In the Huanglongbing disease case study, we considered the number of acres without the disease as successful adoption of disease solutions. For value-added cattle the proxy was the number of animals marketed as value-added, and for drought tolerant corn the proxy was acres of drought-tolerant seed planted. The producers that adopted the technology and innovations are the ones to see a higher net farm income compared to the farms that do not use the new technology. In the case studies, we also explore resistance to adoption, which could prevent farmers from earning a higher net farm income. Therefore, having conditions to where research is applied is necessary to maximize farmer returns of public research.

Scale of Adoption

There is a range of how general versus specific research is. Some research provides a little bit of benefit to a wide range of producers, while other research is very specific to a few operations, but may provide quite large benefits to those operations.

Figure 2. Scope and Scale of Research impacts Return on Investment



Characteristics of Private R&D Spending with High Impact on NFI

Public and private research funding and goals are interrelated but also distinct. Private research tends to be concentrated in places where there is a clear return on investment, defendable economic returns, with innovation that consumers will pay for, and when the innovations help a specific company- not the whole industry. A company will invest in research in sectors where the company has expertise. Private R&D is one way that companies can increase profitability for leadership and shareholders. However, just because technology or innovation could be economically viable to a company, it does not guarantee that farmers will adopt that technology quickly or at all.

Public R&D Spending with High Impact of NFI

Public research can have similar targets to private research, but it can also fill in less profitable gaps left by private research. A high economic return is not a requirement of public research spending. Therefore, research is not dependent on the size of the market. Public research can leverage multi-disciplinary teams within or across public research institutions. The research can be aimed at opening new markets or protecting against downside risk to keep current markets open and profitable. Hard science research can be coupled with auxiliary farm business research like marketing and economics to increase adoption.

Public researchers are evaluated on different metrics. They are not necessarily looking for a return on the research dollars. In general, their mission is to explore knowledge or solve specific problems for specific groups or stakeholders, which may include farmers. For this reason, farmers may trust the source of the research more, which can also increase adoption. Public research is also a way of training new scientists.

Case Studies Overview

The case studies represent different types of research, different target outcomes, and variance in the likelihood of adoption. The agricultural markets include commodities and specialty products, highly localized and national production, as well as livestock and crops.

Case Study 1 is on Huanglongbing (HLB), also known as citrus greening, which is a disease that has devasted Florida's citrus sector. The industry has received special funds to address diseases with limited success. The research is conducted in citrus-growing states, especially Florida and California. Over the past twenty years Florida production has fallen dramatically, and companies have looked outside the region for fruit or divested from the citrus sector. In contrast, California's citrus industry has largely managed the diseases and has not experienced the declines seen in Florida. However, a research solution to HLB could still revitalize Florida citrus and serve to continue to protect the California sector.

Case Study 2 is on value-added beef opportunities and the public research on genetics, genomics, and heredity that made it possible for private beef associations, like the American Angus Association (AAA), to breed cattle for desired traits and market the meat as a premium product. AAA created and marketed the Certified Angus Beef (CAB) brand. The association keeps detailed records on certified cattle and the premiums received for those cattle along the supply chain. The number of certified animals and farmer payments have also increased, which suggested a benefit to Angus producers nationwide.

Case Study 3 is on drought tolerant corn, which has been bred to withstand heat and lack of water-stress that inhibits plant growth and reduces grain output and quality. As a result, these plants outperform and increase the grain a producer can sell during drought conditions. Genetic research into drought resistance enabled companies to breed for corn that can survive in higher temperatures and with less water. This technology could impact 90 million acres of corn planted every year in the United States. While farmers normally invest in products that increase yield, drought resistance reduces the downside risk of crop damage. This mentality might impact farmer adoption, especially if farmers have not recently experienced crop loss due to drought.

Methodology

The research began with a focus on measuring farmer wellbeing and metrics that quantify wellbeing. Afterward we looked at places where public spending could have a high impact on farmers. Based on this research, we selected three case studies to explore the impact of public research spending on net farm income, with the goal of quantifying the public R&D investment and the return to farmers.

We used a mixed methodology research process, combining a literature review, data analysis, and expert interviews to investigate the case studies. One challenge that arose was disaggregating the value of public and private research spending. Research is widely interrelated and drawing divisions on where research on a particular subject starts and stops is subjective.

To estimate the amount of public funding spent in each sector, we used the USDA's National Institute of Food and Agriculture (NIFA) database of projects, USDA Budget Summary, and specific research centers when applicable. The NIFA data was coded and analyzed. Because Huanglongbing is a very specific term, that research was straightforward to identify. In contrast, value-added beef and drought tolerance data were more complex. Not all the research generated by researching these issues was specifically relevant to the case studies. In the latter cases, we analyzed the keywords and created clusters. Then, included and excluded projects by cluster and calculated the total funding for the projects in the included clusters. A detailed methodology is found in Appendix 1.

The method of quantifying the impact on farmers was different for each case study. For the Huanglongbing case study, the loss in sales and production was used to estimate the economic losses the farmers faced. If a cure was found, the industry could potentially recover to prior levels or even grow and increase in value. We also considered the size of the California market that is still insulated from the worst of this disease. For the value-added beef we looked at the economic premiums paid for CAB cattle. This includes premiums paid to feedlots and ranchers by the packer, and the economic premium paid to seedstock producers and cow-calf operations. Finally, for the drought resistant corn case study we looked at the price of corn in seasons with drought-induced losses, the limits of crop insurance in these areas, and the higher price paid for remaining corn.

Case Study 1: Huanglongbing

Highlights

Huanglongbing, or citrus greening, is a devastating citrus disease first discovered in Florida in 2005.

Background: Since its introduction, HLB has devastated the Florida citrus industry, decimating U.S. production of oranges for processing (for orange juice).

Relevance: The scale and severity of the disease has united researchers and brought collaboration in control efforts, and there is still hope that some of the most promising researched solutions will be able to revive Florida's citrus industry and protect citrus production in California, Texas, and Louisiana.

Conclusions: The degree of this cumulative impact of citrus greening on Florida oranges alone since the introduction of citrus greening is estimated to be at least $2.5-$5.0 billion when using Florida's reduced orange production value since 2005 (packinghouse-door equivalent). This estimate is likely conservative relative to the full scale of the impact. Research has the potential to reverse this industry decline and help facilitate a road to recovery for Florida citrus.

Huanglongbing (HLB), also known as citrus greening, is a destructive disease of citrus that damages fruit quality and kills citrus trees over time. Within the United States, citrus greening was first discovered in Florida in 2005.[4] The disease is caused by a bacterium, *Candidatus* Liberibacter asiaticus, and is spread by an insect, the Asian citrus psyllid.[5] USDA Animal and Plant Health Inspection Service (APHIS) calls citrus greening one of the most devastating citrus diseases in the world and emphasizes that while the disease poses no health threat to humans or animals, most infected trees die within a few years.[6]

This case study focuses on the research conducted to detect, fight, and cure HLB in U.S. citrus production. To date, researchers have not found a cure for the disease. Farmers have benefited from research into rapid detection of HLB, which prevents the disease's spread, and ways to mitigate its negative impact on the quality and quantity of fruit produced. This research is built on previous plant, citrus, bacteria, and disease research and tools.

By 2008, citrus greening had spread to most citrus-growing counties in Florida.[7] Although some attempts at disease eradication through tree removal were made in the early years of the disease introduction in Florida, by 2010 those efforts had all but stopped in the state.[8] Numerous strategies have been used to try to prevent the spread of the disease and/or eliminate its presence in Florida, but their effectiveness has been limited and the disease has resulted in large impacts for the citrus industry. Many trees have died, orchards have been devastated,

[4] ARS Citrus Rootstocks: A Success Story
[5] Citrus Greening, Hurricanes, and the Decline of the Florida Citrus Industry
[6] Citrus Greening and Asian Citrus Psyllid
[7] Citrus Greening Portal
[8] Moving Beyond Greening - Citrus Industry Magazine

and industry-wide impacts continue to unfold. Further, citrus greening is no longer only found in Florida, and it has now been reported in Louisiana, Texas, and California.[9]

Background on the Citrus Sector

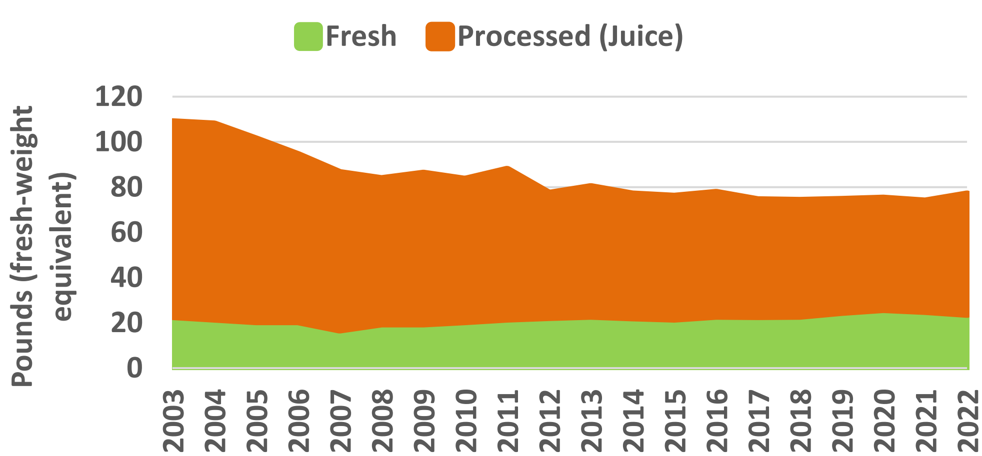
The U.S. citrus sector has weathered a series of challenging years, which has been reflected in both acres bearing fruit and in the value of production. From the 2021-22 to the 2023-24 seasons, bearing acreage fell almost 100,000 acres, from 625,700 acres to 532,500 acres. Nearly all that decline occurred in Florida's bearing area. Fifty percent of U.S. citrus bearing acres are in California, and 47% are in Florida, as of the 2023-24 season.[10]

In the most recent (2023-24) available USDA data on the U.S. citrus sector, two-thirds of the production in California is used fresh, while just 16% of production in Florida is used fresh, with the other 84% being processed. The difference in value of citrus used for processing relative to fresh carries through to the value of production for each state. Of the total $2.98 billion in U.S. production value (packinghouse-door equivalent), 86% comes from California, and just 10% from Florida.[11]

By type of citrus, oranges are about one-third of the 2023-24 U.S. value of production (packinghouse door equivalent) at $1.07 billion, and tangerines and mandarins are about another one-third of production at $1.03 billion. Lemons are about one-fourth of the total citrus value of production, with the remainder from grapefruit. U.S. lime production is minimal and is not tracked by the USDA.[12]

Over the last two decades, U.S. per capita citrus consumption (as proxied by per capita availability) sharply declined in the 2000's followed by a general leveling out through the 2010's, as shown in Figure 3.[13]

Figure 3. U.S. Citrus Availability per Capita



Source: USDA ERS, *Stratagerm*

[9] Citrus Greening: Is the End in Sight? : USDA ARS
[10] Citrus Fruits 2024 Summary, August 2024. USDA NASS.
[11] Citrus Fruits 2024 Summary, August 2024. USDA NASS.
[12] Citrus Fruits 2024 Summary, August 2024. USDA NASS.
[13] Food Availability (Per Capita) Data System - Food Availability Documentation

Imports of citrus most relevant to the U.S. citrus industry are commonly in the form of frozen concentrated orange juice. The U.S. has been able to import frozen concentrated orange juice primarily from Mexico and Brazil to somewhat make up for the reduced production of oranges for processing from Florida. However, overall orange juice consumption has been declining, meaning that the quantity of imports needed to meet consumer orange juice demand thus far has not fallen outside of historical ranges.[14] Brazil is by far the largest producer of orange juice in the world, producing around 1.0 million metric tons in 2024/25 and account for about 75% of global exports.[15]

Total U.S. imports of fresh oranges from the world were about 253,000 tons of fresh oranges in 2024, the equivalent of 9% of total U.S. orange production utilized that year.[16] While this quantity is sufficient to buffer some declines in U.S. production, it would be insufficient to ameliorate any possible future dramatic decreases in U.S. fresh orange production.

Scale of the HLB Challenge and Impact

HLB was first detected in the U.S. in Florida in 2005. Most recent data, using 5-year averages prior to the detection of HLB (2000-04) and up to 2024 (2020-24), suggest that during the presence of citrus greening, the volume of Florida orange production has decreased 83% and the nominal value of production has decreased 57%.[17]

Table 2. U.S. Citrus Availability per Capita

	FL Production, $ (nominal)	FL Production Utilized, Boxes
2000-2004 average	1,207,248,600	226,260,000
2020-2024 average	517,498,800	39,066,000
Change	-689,749,800	-187,194,000
Percentage Change	-57%	-83%

Source: USDA NASS, Stratagerm

While there are annual fluctuations in production and undoubtedly other challenges that have faced the Florida industry (particularly hurricanes in 2004, 2017, and 2022), the decline in the Florida citrus industry due to citrus greening is undeniable.

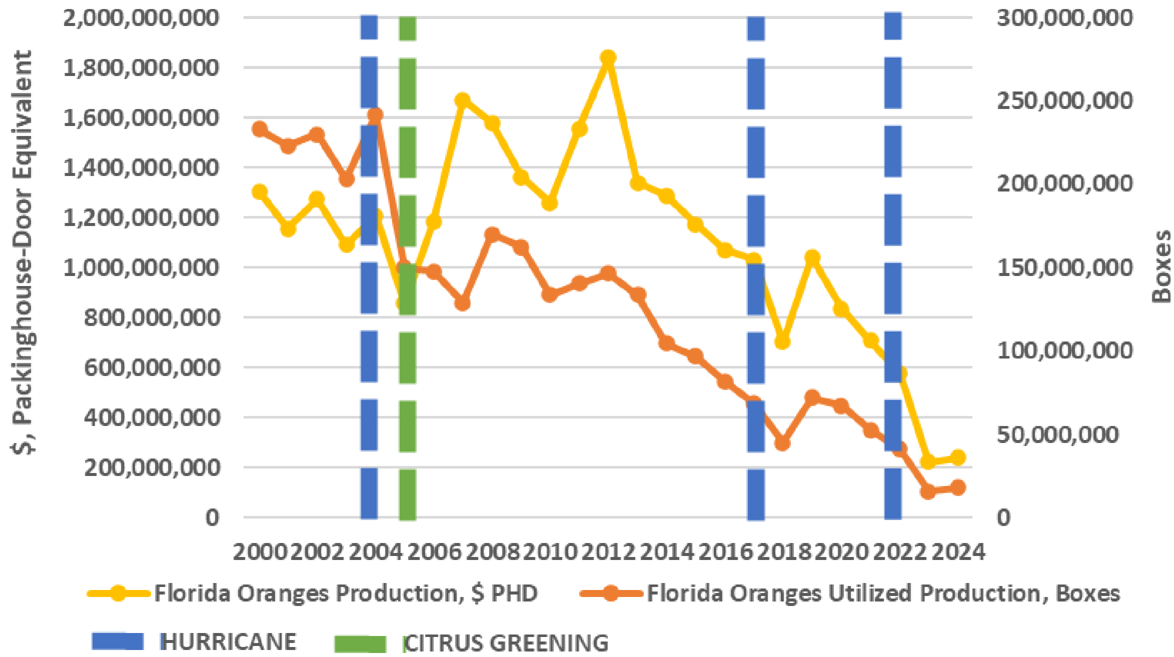
[14] USDA FAS GATS; Stratagerm

[15] USDA, FAS, PS&D Citrus

[16] USDA FAS GATS and USDA NASS; Stratagerm

[17] The decline in value is likely understated due to the impact of inflation, however nominal figures are presented because it is difficult to separate inflation from other factors such as changes in efficiency and trade patterns when focusing on a single product.

Figure 4. Florida Orange Production, 2000-24



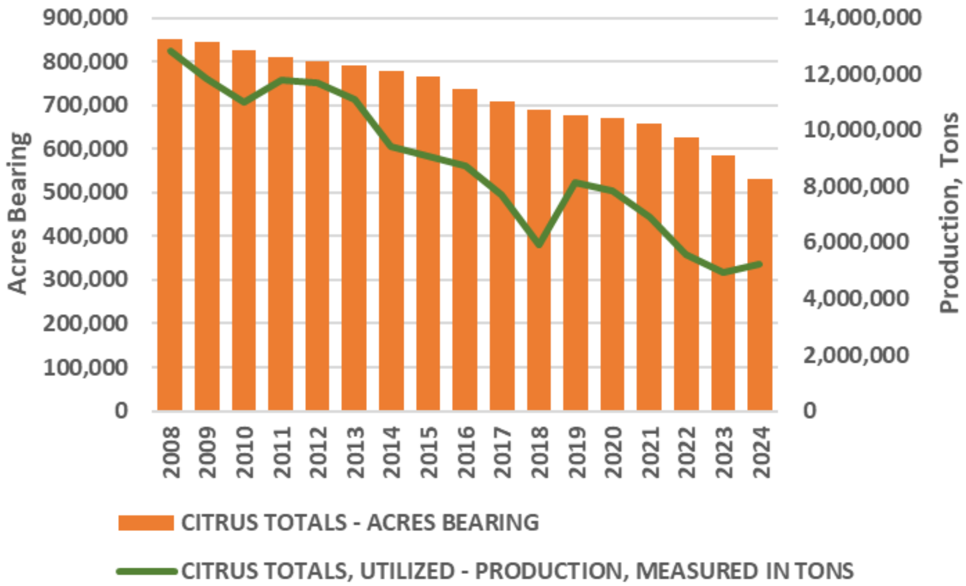
Source: USDA NASS, Stratagerm

The impacts of citrus greening to the citrus industry start in the citrus grove and extend far beyond. Besides the thousands of former citrus acres no longer in citrus groves, several orange processing plants and dozens of packinghouses have shuttered their doors.[18] One example of a potentially permanent impact of the disease in Florida is the announcement by one of the state's largest citrus growers that they would stop growing citrus. Alico was growing about 25,000 acres of citrus in Florida until 2025.[19] Florida shifts are also represented in national citrus industry measures and can be seen in Figure 5.

[18] Moving Beyond Greening

[19] Florida's citrus outlook remains bleak, but new science offers hope

Figure 5. U.S. Citrus Area and Production



Source: USDA NASS, Stratagerm

USDA ERS detailed the challenges the Florida citrus industry has faced over several decades.[20] Since 2000, those disasters have included impactful hurricane seasons in 2003/04, in 2017, and in 2022. The state also implemented a mandatory eradication program for citrus canker (a disease of citrus that's spread is encouraged by hurricanes) from 2000 to 2006, a factor that reduced willingness to implement further eradication programs in response to citrus greening when it arrived in the state.[21]

While hurricanes and freezes have impacted Florida for generations, the recent steep decline in the industry can be in large part attributed to the spread of HLB. Prior to HLB, the industry managed to thrive and rebound after setbacks caused by hurricanes. However, the spread of HLB in Florida marks a turning point for the strength and resilience of the Florida citrus industry that it has not yet been able to recover from. For example, a University of Florida collaboration with USDA National Agricultural Statistics Service and the Florida Department of Agriculture and Consumer Services found that during a survey period in 2007-08, nearly 1 million citrus trees were removed in Florida to prevent the spread of HLB.[22] There is no overarching tracking of the tree removal. Confidence in tree removal estimates are low because the orchards are mostly privately held, and trees were removed quickly to contain HLB. However, extensive review of available information suggests citrus greening has been the most prominent cause of the decline in the state's citrus industry.

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[20] Natural disasters, disease cut Florida orange production an estimated 92 percent since 2003/04

[21] Florida's citrus canker eradication program resulted in the loss of 5 million nursery trees and 11 million commercial and residential trees, and ended because in spite of the program, citrus canker spread widely throughout the state. Canker Update: Where is Canker now?

[22] USDA ARS Online Magazine Vol. 59, No. 7

As a result of HLB, major brands that once sourced citrus exclusively from Florida have begun to blend their orange juice with imports from Brazil and Mexico.[23] Globally, although Brazil and Mexico are filling some of the gap created in orange juice markets by the decline in Florida production, they have not been able to fully match Florida's prior production. For grapefruit, although grapefruit production in the U.S. has also decreased dramatically in the presence of citrus greening in Florida, other major global producers have been able to maintain production and export flows around the world.

The degree of this cumulative impact of citrus greening on Florida oranges alone since the introduction of citrus greening is estimated to be at least $2.5-$5.0 billion when using Florida's reduced orange production value since 2005 (packinghouse-door equivalent). This estimated decrease in production value is conservative and is likely an underestimate of the full impacts of HLB for several reasons:

- It does not account for increased production costs including increased costs for disease control, which directly impacts farmer net farm income.
- It does not account for the costs of broader industry shifts to distributors, retailers, and supply chains.
- It uses wholesale prices, which is what packinghouse-door equivalent prices reflect, and it does not attempt to translate the potential costs to a higher retail equivalent price.
- For context, a University of Florida study from 2012 estimated an impact of over $3.6 billion in lost revenue due to HLB from 2006-2012.[24] The disease impacts have extended an additional decade.
- The impacts of HLB are ongoing, so additional costs and lost production are accumulating daily.
- While the Florida citrus industry has been devastated by HLB, the disease has largely been kept out of commercial citrus groves in California via an aggressive quarantine and eradication program along with coordinated industry efforts. This effort is coordinated across many different stakeholders and is extensive in its visioning for how the disease and its primary vector can be managed.[25]
- This means that the ongoing research into the disease and its transmission have the potential to not only revive the Florida citrus industry, but also to protect the citrus production of California, the number one citrus producing state comprising 86% of the nearly $3 billion total U.S. annual production by value.[26] For context, since the data series for total citrus production (packinghouse-door equivalent) value started in 2008 until 2024, the U.S. total value of citrus production was $55.09 billion.[27]

What Research Is Being Done?

Intersecting efforts at the federal, state, and local level are targeted at understanding and limiting the harm caused by citrus greening and the Asian citrus psyllid. Citrus greening is also an excellent example of how a critical challenge facing a sector can drive creative collaborations and efforts to make research expedient, well-focused,

[23] Orange juice brands no longer making juice from 100% Florida-grown oranges.

[24] Citrus greening costs $3.63 billion in lost revenues and 6,611 jobs, new UF study shows - News - University of Florida

[25] California Statewide Action Plan for Asian Citrus Psyllid and Huanglongbing

[26] USDA Citrus Fruits 2024 Summary

[27] USDA NASS; Stratagerm.

and nonduplicative across many involved parties. There has also been a focus on the development of cost-effective approaches that can be the most widely implemented.

A wide range of research has gone into early detection of HLB, given the ongoing inability to cure the disease once trees are infected. In 2021, research summarized efforts to date for detection as having included "various technologies such as electron microscopy, serology, DNA probes, enzyme-linked immunosorbent assay, conventional PCR, quantitative PCR (qPCR), and canine olfactory detection" and further explored detection using CRISPR technology.[28]

Research into citrus greening has also covered numerous strategies to fight the disease and its impacts, including nutritional supplements, reflective mulch, heat treatments, insecticides, and bactericides.[29]

USDA NIFA's Emergency Citrus Disease Research & Extension (ECDRE) program fosters collaborative and efficient citrus greening research, previously the Citrus Disease Research and Extension Program. The *Agriculture Improvement Act of 2018* (2018 Farm Bill) established the Emergency Citrus Disease Research and Development Trust Fund and provided annual funding of $25 million for 5 years (FY19-23) in Emergency Citrus research funds.

USDA NIFA's research funding database includes over $282 million in research funding related to citrus greening (HLB). Approximately one-third of that funding is via Hatch Act funds, while approximately two-thirds of the funding is via "non-formula" funds.[30]

The funding included in the database (which may not include all projects) has project start dates spanning from 2005 to 2024 fiscal years and is concentrated on projects started from 2012 to 2020 (Figure 6).[31]

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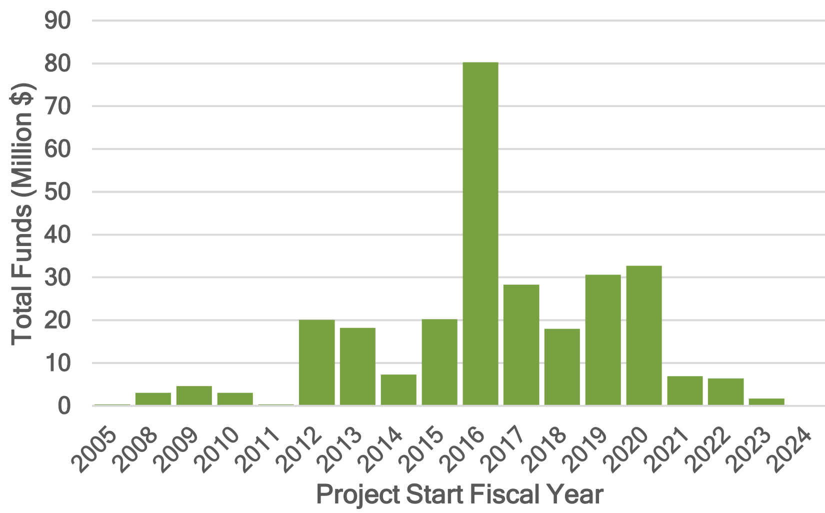
[28] Highly Sensitive and Rapid Detection of Citrus HLB Pathogen Using Cas12a-Based Methods

[29] Citrus Greening, Hurricanes, and the Decline of the Florida Citrus Industry

[30] Non-formula funds are research funds to land grant universities not allocated by formulas set in statute. Data through January 2025 NIFA Enterprise Search

[31] Note that project reporting may not be complete. Data for data prior to this period and data for most recent years may be incomplete.

Figure 6. Citrus Greening Funding in NIFA Database



Source: USDA NIFA, Stratagerm

A selection of example research efforts is described in additional detail here:

- In 2025, the University of Florida focused research on developing trees resistant to citrus greening. Some in the citrus industry consider the most promising research to date to be the results of tests with genetically modified trees that can produce a protein that is toxic to Asian citrus psyllids, the insects that transmit the disease from tree to tree. Consumers have consistently shown resistance to biotechnology/genetic engineering in food.[32] As such, this solution does have some concerns on consumer acceptance. It is yet to be seen if or how it might move forward.[33]
- Research at the University of Florida from 2020 to 2022 found that the antibiotic oxytetracycline (OTC) can be injected into tree trunks to minimize the impact of citrus greening on affected trees, improving fruit yield and quality. Results were particularly promising for young trees. This research was supported by the Citrus Research and Development Foundation and USDA NIFA. [34] Additional research funded by NIFA on this subject continued in 2023.[35] This research builds on the initial suggestion of the use of

Research In Depth Highlight

USDA Agricultural Research Service is conducting research related to HLB at these locations:

- Citrus and Other Subtropical Products Research Unit: Fort Pierce, FL
- Subtropical Plant Pathology Research Unit: Fort Pierce, FL
- Subtropical Insects and Horticulture Research Unit: Fort Pierce, FL
- Emerging Pests and Pathogens Research Unit: Ithaca, NY
- National Clonal Germplasm Repository for Citrus: Riverside, CA
- Molecular Plant Pathology Laboratory: Beltsville, MD

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32 Investigating consumer stated preferences for orange juice: The influence of behavioral traits

33 Researchers explore breakthrough approach to combat devastating citrus greening disease.

34 Research update on oxytetracycline injection for HLB management

35 Trunk Injection of Oxytetracycline for Huanglongbing Management in Mature Grapefruit and Sweet Orange Trees

antibiotics to treat HLB proposed in the 1970s. The injection of oxytetracycline has been found to be more effective than treatments studied of foliar applications and injections of the antibiotic streptomycin. [36]

- Some research in 2015 by University of California researchers, conducted in collaboration with USDA Agricultural Research Service's (ARS) U.S. Horticultural Research Laboratory, focused on methods to improve early detection of HLB. As the authors describe: "Improvements for detecting [the bacteria that causes HLB] infection are essential to combating the spread of HLB. Early detection of HLB allows for earlier intervention (tree removal and, perhaps eventually, treatment of the diseased tree), which will play a key role in preserving the citrus industry. Metabolomics offers a promising new strategy for the early detection of, defense against and resolution of HLB in the United States and the survival of the citrus industry."[37]
- Additional research at UC Davis has effectively mechanized the scent detection of a dog's nose, developing and commercializing technology to collect odors from around the citrus trees and conducting analysis to detect biomarkers related to citrus greening.[38]
- Plant pathologists at UC Davis are developing ways to test citrus trees for resistance to citrus greening at a very early stage, potentially speeding up efforts to breed resistant varieties.[39]
- Research has been promising into nutrient supplementation as a way to mitigate the impacts of citrus greening on infected trees. For example, USDA Hatch funds supported research that found increased growth and biomass accumulation with higher rates of manganese and iron applications on young HLB-affected trees.[40]
- Research into preventing or treating the bacterial cause of HLB has included collaborations between the private, public, and nonprofit sectors, including development of the development of a high-throughput screening system that enables an accelerated, targeted and more cost-effective screening of anti-microbial strains that can inhibit or kill the causal bacterium. Bayer and the Citrus Research and Development Foundation were awarded USDA NIFA research funding to screen for naturally occurring microbials to kill the bacteria that causes HLB, and to screen for synthetic compounds that can boost the plant's defenses against the disease.[41]

While much research continues, another wrinkle in the research journey has been that some of the remedies researched have been found to be more cost effective than others. Given that a remedy has to be sufficiently cost effective for private growers to choose to implement it in their groves, this is an ongoing layer to be considered as potential solutions to citrus greening are concerned and researched further.

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[36] Systemic Uptake of Oxytetracycline and Streptomycin in Huanglongbing-Affected Citrus Groves after Foliar Application and Trunk Injection

[37] Citrus and Other Subtropical Products Research: Fort Pierce, FL.

[38] Can Science Save Citrus? | UC Davis

[39] Can Science Save Citrus?

[40] Micronutrients Improve Growth and Development of HLB-Affected Citrus Trees in Florida.

[41] Conquering Citrus Greening: Research Collaboration Breeds New Hope

What is Being Done Beyond Research?

Tools for detection or eradication are not currently adequately effective or affordable to stop the spread of citrus greening in Florida; however, stakeholders have used available strategies to reestablish orchards and limit the spread of citrus greening and its impacts. For example, Florida's Natural Growers, a farmer-owned cooperative founded in 1933, created an incentive program to support replanting of trees. These interest free loans were able to support the replanting of 1.8 million orange trees and 50,000 lemon trees that have begun to come into production.[42] However, this approach does not appear to have been widely adopted beyond Florida's Natural Growers.

As another example, the California Department of Food and Agriculture developed, along with many stakeholders in the state, the Statewide Action Plan for Asian Citrus Psyllid (ACP) and HLB. The latest iteration, released in January 2025, continues to build on the Citrus Pest and Disease Prevention Program first established in 2009. Program elements include (quoting the plan)[43]:

- An ACP eradication program in areas where eradication is deemed feasible.
- An ACP suppression program using pesticide applications in areas where suppression is deemed feasible.
- An ACP population reduction program using biocontrol agents to slow ACP expansion from heavily infested areas.
- An HLB eradication program.
- An early detection program for both ACP and HLB.
- An ACP and HLB regulatory program.
- An ongoing dialogue with scientists from the ACP/HLB Ad Hoc Science Advisory Panel (SAP), University of California (UC), state and federal agencies, members of the citrus industry, and regulatory officials to ensure program design and elements consider the best available science and promote and protect the citrus industry.
- A grower education, outreach, and coordination program; and
- A public education and outreach program.

Conclusions

- Reviewing perspectives and evidence from across the U.S., citrus greening (Huanglongbing, HLB) remains the most pressing issue facing the U.S. citrus sector. Research is ongoing and is critical to the future of the U.S. citrus industry.
- Were it not for the combination of research investment, collaboration across the public and private sectors, and persistence in seeking a cost-effective solution to HLB, the impacts of citrus greening would likely have been even more devastating than what the industry has seen.
- U.S. citrus production is valued at $3 billion annually. Since the data series for total citrus production (packinghouse-door equivalent) value started in 2008 until 2024, the U.S. total value of citrus production

42 Moving Beyond Greening

43 California Statewide Action Plan for Asian Citrus Psyllid and Huanglongbing

was $55.09 billion.[44] Were citrus greening to have spread unchecked and untreated across U.S. citrus groves from the time it was first detected in the U.S., it is possible that the blow dealt to the U.S. citrus industry would have decimated nearly all of that value of production over decades. Whatever production remained would have been minimal, and impacts would have reached far beyond the citrus grove throughout the citrus supply chain and to consumers as well.

- Research efforts into control of citrus greening have delved extensively into methods to detect, prevent the spread of, and eradicate HLB, as well as efforts to minimize or eliminate the impact on citrus trees of the disease. USDA NIFA's database included $282 million in total research funding, likely a minimum value of research funding directed at citrus greening since projects not associated with USDA are not included and some projects may not have been entered into the database.

[44] USDA NASS; Stratagerm.

Case Study 2: Value-Added Beef

Highlights

Cattle producers operate in a competitive, commodity market and are looking for ways to compete in the protein marketplace.

Background: Beef consumption continues to fall in the United States, in part because of competition from lower cost protein sources. Cattle producers have increased efficiencies and output as well as developed value-added beef programs to maintain market share and improve their on-farm economics.

Relevance: Public sector research has created building blocks for private sector industry associations to build and maintain comprehensive genetic databases. These databases improve breeding efficiency and allow traceability for producers to earn a premium for high-value animals.

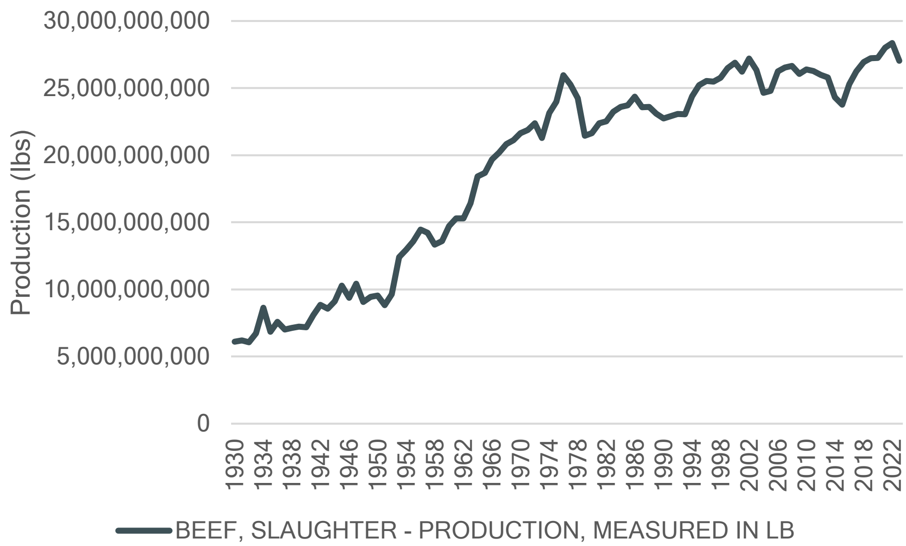
Conclusions: Research provided knowledge to increase efficiency and quality, but research alone did not create value-added beef. Several beef associations used the same genetic research to improve their herds, but Certified Angus Beef has been the most successful in creating increasing the value of and price paid for Angus cattle.

Introduction

Cattle production accounts for nearly a fifth of total cash receipts for U.S. agricultural commodities, valued at $88 billion in 2023. In addition to having the world's largest fed-cattle industry, the United States is also the world's largest consumer of beef—primarily high-value, grain-fed beef.[45] The USDA's 2025 beef production outlook estimated production after a peak of 28.4 billion pounds in 2023 (Figure 7). While beef production remains near all-time highs, the cattle herd, including beef and dairy cows as well as beef cattle, has fallen to 87 million head from a peak of 132 million head in 1975, meaning production per head has increased tremendously in that time.

[45] Cattle & Beef - Sector at a Glance | Economic Research Service

Figure 7. U.S. Beef Production in Pounds



Today's cattle herd is the same size, in head, as the herd in the 1950s. However, beef production has doubled over the same period. The improvements in productivity come from research in genetics, nutrition, management, and health. Genetic trend tables published by the USDA's Meat Animal Research Center in Clay Center, Nebraska, have shown an increase of 60 pounds in the yearling weight alone since the 1970s[46]. Average dressed carcass weights for steers increased by 150 pounds, over the same period. The increase is the result of improved genetics, herd management, nutrition, and health.[47]

U.S. beef consumption has fallen since the mid-1970s, facing strong competition from chicken. Chicken provided consumers with a low cost, low fat, protein source. The price of boneless chicken breast was $3.30 in January 2006 and fell to $3.00 per pound in February 2020. [48] The price of a pound of ground beef was $2.27 in January 2006 and reached $3.89 in February 2020.[49] To stay competitive, the cattle industry is looking for ways to lower consumer prices, which translates to lower prices paid to producers, which can create economic and viability concerns. The number of beef cattle operations was 622,000 in the 2022 USDA Census of Agriculture, down over 100,000 operations from the 2017 Census. Value-added beef offers an opportunity to improve farmer profitability.

Public and private researchers have conducted additional research on consumer preferences, producing cattle (through genetics and management) that meet those consumer preferences, and created branding to explain the high-quality beef available to consumers. The knowledge from this research is used by breed associations, like the American Angus Association (AAA), to breed and market more profitable animals. They also created a consumer-recognized brand, Certified Angus Beef (CAB), to explain these benefits to consumers. Now, consumers, beef

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[46] Since 1970, increasing cattle weights have fueled growth of U.S. beef production as cattle used have decreased | ERS

[47] U.S. Genetic Trends, Production Numbers and Discussion on How Breed Associations May Need to Adapt

[48] Average Price: Chicken Breast, Boneless (Cost per Pound) in U.S. City Average | FRED | St. Louis Fed. – Chicken data is only available from January 2006.

[49] Average Price: Ground Beef, 100% Beef (Cost per Pound) in U.S. City Average | FRED | St. Louis Fed.

processors, feedlots, and cow-calf operations all pay a premium for CAB products, which creates higher gross revenue for producers. This case study explores the link between public sector research and the creation of premium beef products.

Incentivizing Better Quality Meat

USDA is responsible for grading of beef in the U.S. and defines the terms Prime, Choice, Select, and Standard. This system helps consumers purchase a standardized product and is based on meat attributes. However, before the genetic links to meat quality were discovered, there was no way to know the quality of the meat before the animal was harvested. Knowing the genetic traits associated with meat quality and being able to test them while the animal is alive improved the rate of genetic improvements during breeding and enabled producers to get paid more for animals that would grade better.

Before the 1990s genetic testing was unavailable, and live animal sales prices paid by beef slaughterhouses were based on a pen-by-pen basis. The group pricing caused high-quality cattle to be penalized as they received only the average price per pound among all the cattle in their pen. Similarly, low-quality cattle were unjustly rewarded with the same average price per pound. This system encouraged seedstock producers, cow-calf operators, and feedlots to focus on producing cattle for weight gain instead of for quality, because heavy cattle were more valuable regardless of the meat quality.

To correct this market failure, in 1990, the Beef Industry Council and the Value Based Marketing Task Force of the National Livestock and Meat Board pushed for cattle sales based on individual carcass grade and carcass yield. The new pricing system was called “grid pricing”, which provides producers or feedlots with a base price and premiums or discounts for carcasses above or below the standard.[50] Since high-quality could earn higher payments ranchers invested in producing higher quality cattle. This system was supported by higher consumer prices for branded and high-quality beef and made possible with individual electronic animal ID tags combined with digitized sire and dam records regarding expected progeny differences (EPDs).

Paying Cattle Producers Premiums

Selection for superior genetics in bulls drives most genetic progress in commercial beef cattle herds. Operations that can identify bulls with superior genetics can produce calves with favorable phenotypic performance. However, the monetary benefit to these operations was limited because calves were sold based on weaning weight and could not capture value from better feedlot performance or carcass merit.

This changed with source verification and added-value marketing programs that help producers capture additional profit. Understanding a calf’s genetic potential for feedlot and carcass performance is valuable information for buyers. The industry created opportunities to capture additional feeder calf value based on the genetics of their sires or through genomic testing of commercial feeder calves. Breed associations offer marketing programs that help feeder calves sired by bulls from their registered populations.

Both types of programs provide buyers with more information about the calves’ genetics that can provide insight into future performance at feedlots or carcasses grading. Easily accessible genetic information allows buyers to

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[50] Livestock Mandatory Reporting - Live Cattle Dashboard | MMN

make decisions based on more technical information. Before, they made decisions based on average weights and coat colors. Source verification and add-value marketing programs have been excellent tools for helping producers capture value and return on investment.

Genetic Research

Livestock genetics research started with observing phenotypes and selectively breeding for desired traits. This research dates to the mid-1700s, when Robert Bakewell designed a livestock improvement program by setting breeding goals and using performance data from related animals. In 1924, the Fort Keogh Livestock and Range Research Laboratory (LARRL) was established and became a leader in developing tools for genetic improvement. LARRL's early research focused on the effects of inbreeding and selection, performance testing, and crossbreeding. Since 1986, the Laboratory has transitioned to a more specific focus on beef cattle, including research on cattle genetics, reproductive physiology, and nutrition.[51]

The Roman L. Hruska Meat Animal Research Center (USMARC) in Clay County, Nebraska, the Northern Montana Ag Experiment Station at Havre, Montana, and the FAMU-CAFS Brooksville Agricultural and Environmental Research Station (BAERS) in Brooksville, Florida all conduct cattle research with public funding. In 2015, the national eXtension program funded eBEEF.org, a website dedicated to sharing beef cattle genetics and genomics information from beef cattle specialists at land grant institutions including University of Kentucky, University of Missouri, University of Nebraska, University of California, Davis, Kansas State University, University of Tennessee, and Iowa State University.

NIFA Funding

From 1998 to 2024, there were 880 projects in the USDA's National Institute of Food and Agriculture (NIFA) program funding database with the label "Angus", worth $1.5 billion. These projects are not limited to genetics or breeding research. There were an additional 133 projects related to genetic research in the beef sector, worth $126 million. See Appendix 1 for a detailed description of the methodology used in this analysis.

Research Laboratories

In addition to the research conducted at universities, there are several research laboratories that are funded separately by state and federal programs.

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[51] USDA celebrates 100 years of agriculture innovation

The **USDA-ARS Fort Keogh Livestock and Range Research Laboratory (LARRL)** has operated and been publicly funded since 1924 in Miles City, Montana. In 1924, LARRL started its herd with 188 Hereford cows where they pioneered methods for genetic evaluation of beef cattle. The beef performance testing programs were built on this foundation. This long-term experiment demonstrates commitment to high-impact, long-term research.[52]

Today's producers continue to benefit from this work as they use expected progeny differences to select breeding stock, including some of the equations used by the American Angus Association to predict offspring values. This genetic research is directly responsible for the first estimates of heritability and genetic correlation for beef cattle. It led to the understanding of maternal genetics effects in beef cattle and crossing with other inbred lines provided early estimates of heterosis.

The Fort Keogh staff includes 20 USDA Agricultural Research Service (ARS) employees and 14 Montana Agricultural Experiment Station (MAES) employees plus 5-10 seasonal employees. ARS owns the land, facilities, and most of the equipment and MAES owns the livestock. The President's Budget Explanatory Notes for ARS includes salary for 24 full-time employees per year. No State of Montana funds are used at Fort Keogh other than those funds realized from the sale of livestock.[53]

The **Roman L. Hruska Meat Animal Research Center (USMARC)** is located on 35,000 acres in Clay County Nebraska. The center was established in 1964 to solve high priority problems for the beef, sheep, and swine industries. USMARC is recognized around the world for the comprehensive research and industry solutions produced over the last six decades and that legacy continues to this day. The facility has been conducting long-term research on cattle genetics for over 60 years. The University of Nebraska provides the operations staff responsible for animal care.

The **Northern Montana Ag Experiment Station at Havre** consists of 3,000 acres at the main facility with an additional 3,960 acres of grazing land located near the Bear Paw Mountains. The 3,000 acres on the main facility supports agricultural research activities. The research center, when fully staffed, consists of three faculty, two operations managers, a research scientist, master's level technician, and 12 permanent support personnel. A local advisory board made up of area producers and industry representatives from the five surrounding counties, provides guidance on NARC research priorities.

Building Blocks

Public researchers selectively bred livestock based on observed characteristics, determined the heritability of individual traits, located specific genes for traits important to industry, maintained pedigrees for decades to trace improvements in their herds over time, and had capacity to conduct genetic evaluations. Public research is often

[52] Fort Keogh Livestock and Ranch Research Laboratory's Historic Role in the Settlement of the West and Present Contributions to Range Ecology and Livestock Research

[53] Introduction: USDA ARS

achieved with a building-block approach, where new discoveries are based on earlier ones. In this case, beef breed associations used these building blocks to develop more advanced genetic tools created by breed associations.[54]

Budget cuts and faculty retirements reduced the capacity of land grant universities to conduct genetic evaluations. The breed associations and genetics companies moved their genetic testing in-house. The new, more private, system has created islands of data. This is inefficient, because there are multiple and disparate sets of data that are intended to represent the same or similar data.

Expected Progeny Differences (EPDs)

Breed associations have used public research data to create expected progeny differences (EPDs), which have significantly impacted cattle breeding by providing a powerful tool for genetic improvement in both commercial and seedstock operations.[55] EPDs are breeding tools to help breeders predict the phenotype of offspring based on the genetics of the parents and the known hereditability of traits. EPDs predict the expected performance of an animal's offspring for specific traits, allowing breeders to make more informed decisions when selecting breeding stock.[56] By knowing the genetic transmitting ability of a parent to its offspring, breeders can make selection decisions for traits desired in the herd. For a given trait, EPD values are calculated based on data submitted by producers to breed associations from an animal's actual performance, performance of progeny, performance of other relatives, and genomic data (DNA analysis, if available).[57] Breed associations collect genomic data on all the cattle they certify, giving them a lot of information about their specific breed. EPDs across breeds are less established because industry groups only maintain their own databases, not genetic information for cattle outside of their breed. The eBeef program maintains some of this information, but it is less well developed than the information maintained by industry groups for their own breed.

EPDs have

- **Improved Accuracy in Selection** because they are the best predictors of genetic performance for individual animals, offering more reliable selection criteria than traditional methods.[58]
- **Accelerated Genetic Improvement** in herds and breeds.
- **Allowed for Trait-Specific Breeding** for a wide variety of economically relevant traits, allowing breeders to focus on specific areas of improvement such as birth weight, weaning weight, yearling weight, and milk production.[59]
- **Allowed for Comparison Across Herds** of future progeny performance for bulls of the same breed, regardless of the environment or management conditions in which they were raised.[60]

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[54] U.S. Genetic Trends, Production Numbers and Discussion on How Breed Associations May Need to Adapt by Robert Williams, Ph.D. American-International Charolais Association Director of Breed Improvement and Foreign Marketing

[55] Expect Progeny Differences | Extension | West Virginia University

[56] Understanding EPDs and Genomic Testing in Beef Cattle

[57] Understanding EPDs and Genomic Testing in Beef Cattle

[58] Mississippi State University, Expected Progeny Differences and Selection Indices for Beef Cattle

[59] Understanding EPDs and Genomic Testing in Beef Cattle

[60] Understanding EPDs and Genomic Testing in Beef Cattle

- **Enhanced Accuracy with Genomics**: The introduction of genomic-enhanced EPDs (GE-EPDs) has further improved the reliability of genetic predictions, especially for younger animals and hard-to-measure traits like feed efficiency and carcass traits.[61]

By providing a standardized, quantitative measure of genetic merit, EPDs have revolutionized cattle breeding, allowing for more precise and effective selection decisions that drive continuous improvement in beef cattle populations. Initially, sire evaluation only used progeny information, which limited EPD calculation to older bulls. The introduction of animal models, incorporating data from the animal itself and its relatives to estimate genetic merit, made EPDs available for younger animals.

Evolution and Improvements in EPDs

1990s: Genomic testing led to advances in EPDs including the Genomic Enhanced (GE-EPDs). This era started with the Human Genome Project in 1990. From 1990 to 2003, the U.S. government budgeted $3 billion for the project, with funding coming from the U.S. Department of Energy (DOE) and the National Institute of Health (NIH). Investment continues even after the program has ended, with NIH granting approximately $29.5 million over five years (starting 2019) for advancing the reference sequence of the human genome.[62] While this research was not conducted specifically to advance agricultural genetics, the information gained eventually lead to sequencing the bovine genome, which allowed them to identify genetic variations linked to economically important traits.

Concurrently, Australian geneticists identified a marbling DNA marker. In the late 1990s, an Australia-based company, Genetic Solutions, offered a commercial DNA test for marbling and tenderness.[63] The genomic information was integrated into National Cattle Evaluation to create GE-EPDs, offering more accurate predictions earlier in life.

Modern: GE-EPDs are a selection tool for commercial and purebred cow-calf producers, enabling comparison within a breed. Commercial producers use EPDs in sire summaries and bull sale catalogs to make genetic changes in their herds. There are EPDs for important heritable traits like birth weight, maternal milk, mature weight, and marbling score. Some organizations are exploring region-specific EPDs to account for environmental stressors.

The Angus Breed

The American Aberdeen-Angus Breeders' Association was founded in 1883, with 60 members. Eventually, the group's name was changed to the American Angus Association and today it is the largest breed association in the world, representing 21,000 members in the United States and Canada. In 1975, the Association created Certified Angus Beef (CAB), a branded program to promote Angus beef among consumers, certified meat was available in 1978.

Angus refers to a breed of cattle known for its high-quality beef, specifically the Aberdeen Angus. This breed originated in Scotland and is characterized by its muscular build, naturally polled, and solid black or red

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[61] Expect Progeny Differences | Extension | West Virginia University

[62] Budget | Human Genome Project

[63] Genomic testing: The past, present and future | Ag Proud

coloration, preventing sunburned udders and eye cancers. Angus are known for their calving ease, marbling and growth rates. They have strong maternal instincts, superior milking capabilities, and high fertility rates.

History of Genetic Improvement

The Angus breed has a long history of public and private genetic improvement. Much of the early breed development was attributed to Hugh Watson in the mid-19th century, who sought to enhance the breed's characteristics for better meat quality.[64] In 1873, George Grant brought four Angus bulls to Kansas.[65] The Angus bulls crossed on Texas Longhorn cows, and the Angus cross cattle survived the winters better and were heavier the next spring.[66] The company, Jorgensen Land & Cattle, started its Angus line breeding program in the 1950s based on the beef cattle performance breeding concepts of the late Dr. Jay Lush from Iowa State University.

Dr. Lush's career focused on animal breeding and biometry (the application of statistical analysis to biological data). In January 1930, Dr. Lush joined the Department of Animal Husbandry at Iowa State University where he conducted research and taught animal breeding. His work focused on applying genetics more efficiently in improving animals, often using biometrical tools. During his career he published 200 research papers and a textbook, titled Animal Breeding Plans (1937). Over four decades of research, Dr. Lush greatly increased the scientific community's understanding of the potential usefulness of inbreeding and heterosis in animal improvement.[67] In 1933 his bulletin was published, which states the case for subdivision of breeds into many lines, each line bred to carefully selected ancestors, with continuous elimination of the poorer ones and recombining of better ones. The research that Dr. Lush and the scientists he trained led to an understanding of genetics and statistics that transformed genetics and paved the way for EPDs and breeding techniques that breed associations and seedstock companies use to breed animals with specific attributes and of high quality.

> *"Before about 1930, the primary statistical tools used in animal breeding were correlation and regression methods. R. A. Fisher lectured at Iowa State through the summers of 1931 and 1936. Fisher's work greatly advanced the knowledge and use of statistics. Dr. Lush was unique in combining the work of both Fisher and Wright to solve animal breeding problems. Many of Dr. Lush's papers from 1926 to 1930 could be described as developing and using more accurate ways to measure quantitative traits."*
>
> *Dr. A. E. Freeman*

Certified Angus Beef

The Certified Angus Beef (CAB) brand was created in 1975 to align consumer interests with the interests of Angus cattle owners. The American Angus Association worked with USDA's Agricultural Marketing Service to become the first USDA-certified brand. CAB has ten criteria for beef carcasses to qualify, adding value through marbling, maturity, rib eye area, weight, fat, muscling, and more. To qualify for CAB, animals must be 51% black hided or have documented Black Angus genetics. CAB premiums reward producers for hitting brand targets, transferring higher prices back to all upstream owners of the animal.

64 Angus Cattle | Oklahoma State University

65 History of the Black Angus Cattle - RFD-TV

66 Black Aberdeen Angus Cattle Came by way of Victoria, Kansas

67 Jay L. Lush | Department of Animal Science

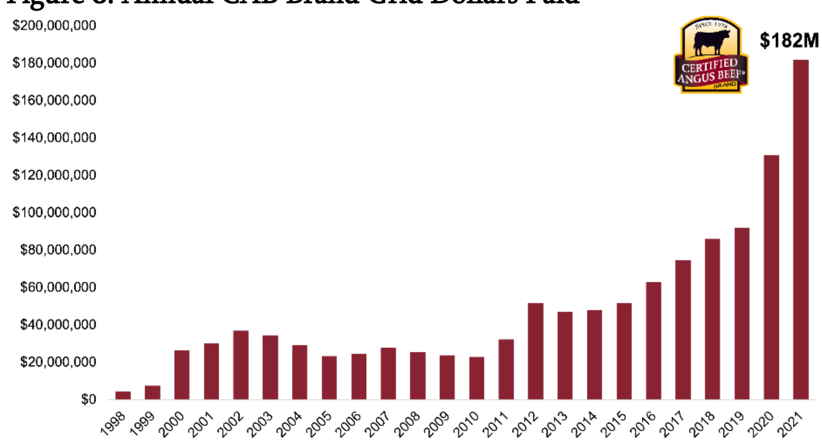
Certified Angus Beef® brand sales began in 1978. The brand promoted a new, high-quality product, which gained legitimacy after becoming a USDA-certified brand. CAB executive Mick Colvin worked with various levels of USDA and Congress to get final approval for Schedule G-1, CAB. Mick Colvin said, "[this was] the best thing that could have happened to Certified Angus Beef. Without a science-based approach and USDA approval, we would be just another Angus brand."

This model has been copied by American Wagyu Association and the American Hereford Association. They have USDA-certifications that are supported by genotypic, phenotypic, and pedigree data.

Industry Support

Angus industry associations support Angus genetic improvements. For example, the American Angus Association maintains the largest beef cattle registry and breed database, offering tools for producers to improve their herds. It is built on records submitted by Angus breeders since 1958.[68] The association publishes the National Cattle Evaluation weekly, based on records submitted by Angus breeders. Plus, the Angus Genetics Inc. (AGI), a subsidiary of the American Angus Association provides GE-EPDs to breeders, building on genetic evaluation tools maintained by the Association.

Figure 8: Annual CAB Brand Grid Dollars Paid



Source: CAB Cattle Article March 16, 2022

Genomic testing is available through breed associations who have partnered with two companies that provide genotyping services: Zoetis and Neogen/GeneSeek. There are different assays that test specific genetic markers. The tests are called chips, and they can look for the presence of 50,000-150,000 specific single nucleotide polymorphism markers on a single assay.[69] In 2014, AGI collaborated with Zoetis to produce GeneMax, a genetic test for commercial replacements that are more than 75% Angus. All these tools support ongoing Angus genetic improvements. Similar genetic tests exist for other breeds, like Hereford and Wagyu. Inter-breed genomic research is still conducted by public researchers.

Economic Impact

Research on Hereford cattle took place at LARRL for 75 years. Certified Hereford Breed was created in 1995, to promote breed and meat sales. Colorado State University conducted taste research, where consumers reported that Hereford meat had the best flavor and tenderness. However, Hereford does not report a higher consumer price for its products. The research alone was not enough to deliver an economic return to producers.

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68 ANGUS Information Advantage

69 Recent Developments in Genetic Evaluations and Genomic Testing

CAB Premium

CAB conducted an economic impact study of their brand from 1998 through 2021. During this time, they report that producers earned $1 billion in premiums, above commodity cattle prices. The economic impact is measured by:

1. Comparing the CAB carcass cutout (the price of individual cuts of beef) to the USDA cutout shows the premium paid to the packer for CAB branded meat. The aggregated premium earned by producers was $92 million in 2019 and $182 million in 2021. In 2024, CAB Choice accounted for 32% of eligible carcasses (72% of carcasses are USDA Choice), while CAB Prime accounted for 13% of total Prime carcasses (10% of carcasses are USDA Prime).[70]

Table 3: CAB Cut-Out Premiums over Non-CAB in dollars per hundredweight

Year	CAB Choice Cut-Out Premium	CAB Prime Cut-Out Premium[71]
Prior to 2019	$8-10/cwt	$20/cwt
2019	$10/cwt	$24/cwt
2021	$18/cwt	$19/cwt
2023	$17/cwt	$36/cwt
2024	$15/cwt	$32/cwt

Source: Urner Barry Market Data, USDA, Stratagerm

2. Calculating the packer premium based on the American Angus Association's AngusLink program. AngusLink assigns scores to cattle based on the three times they are sold. Scores range from 0-200, where 100 is the population's average.[72] In November 2024, National Beef Packers said that they will pay a $5 premium per head for cattle in AngusLink with a score of 100 or more. Scores over 150, earn a $10 premium.

There were 5.96 million head certified in 2024. In 1998, only 1.7 million carcasses were certified CAB.[73] This premium is paid directly to feedlots. Assuming all 5.96 million cattle earned at $5 premium at harvest offered by National Beef Packers, then processors paid an additional $29 million for the feedlots in 2024. No data is available on the scoring or payout of cattle enrolled in this program. We assumed at all CAB cattle earned a $5 premium and none earned a $10 premium, giving an average of $5 per head. AngusLink reports that over 40% of CAB cattle that score 105 points are considered low USDA choice and 15% are USDA Select, showing that even many low grades are earning the premium. On the upper end over 50% of cattle earning 155+ points are Premium Choice, 32% are Prime, and 15% are Low Choice.[74]

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[70] Prime Trends Up - CAB Cattle
[71] Prime Trends Up
[72] Beef Cattle Genetics Value-Added Programs
[73] CAB Market Report 2024, 1998
[74] Genetic Merit Scorecard

Prior to 2024 and this program, several university studies show a $4-5 premium for black calves (Angus) or Angus cattle.[75],[76],[77],[78] This price premium was paid by the feedlot operators to the cow-calf operators. This adds an additional $29 million in added return to cow-calf producers. This does not include the higher cutout price that the producers earn, or the premium paid to seedstock operations.

Conclusions

- By combining the public sector research with detailed information on the cattle herd, the industry created valuable, predictive breeding tools.
- Public researchers studied beef cattle genetics for 75 years, learning about genetics, heritability, and livestock breeding. This research had many applications, including increasing herd efficiency. The private sector created databases with this information about individual animals, or EPDs.
- To add value for Angus producers, the American Angus Association created CAB brand, held producers to its minimum standards, and marketed the quality of Angus beef to consumers. As a result, the CAB brand returns an economic benefit to producers. The database and the standards enable breeders and commercial producers to earn a premium for their improved herd.
- Starting in 2024, National Beef Packers paid feedlot operators a $5-10 per head Angus cattle premium. If all Angus cattle earn a $5 per head premium, feedlot operators would have earned an extra $30 million in 2024. Prior to 2024, USDA data show approximately a $5 per head premium for Angus cattle at cow-calf operations by feedlot operators. This was worth $30 million to cow-calf operators based on 2024 sales level. Since the cow-calf premium was paid before the packers announced this program, it is unclear how the payments will change moving forward. This does not include a premium paid to genetics providers or seedstock operations, which can be tracked in the database (but is proprietary), nor does it include the value earned by processors (large and small) for CAB beef.

[75] Beef Species: Beef Production
[76] Beef Species: Beef Cattle Production
[77] Some Facts on Sale Barn Premiums & Discounts
[78] AN278/AN278: Factors that Affect Calf Selling Price at Marketing

Case Study 3: Drought Resistant Corn

Highlights

Drought and heat-stress pose a serious threat to crop production and food security.

Background: High temperatures and drought conditions can devastate crop production as seen by the U.S. drought in the summer of 2012, which reduced corn output by a quarter and caused a major spike in U.S. and global corn prices.

Relevance: Public and private researchers have been improving corn seed for over 100 years. The result is a consistent increase in yield. Drought has always been a concern for farmers because it reduces their saleable crop and cause severe financial stress. Climate change is causing temperatures to rise and drought conditions to worsen, increasing the risk to farmers. Drought-tolerant seeds provide protection against this risk.

Conclusions: Drought and heat stress are complex biological responses that are controlled by the plant's physiology and morphology, and researchers are exploring many of these topics. This information is used by commercial seed companies to improve their varieties, commercializing both public and private research. Adoption of higher priced, drought tolerant seeds was low, until a severe drought when farmers saw the benefits. Overall, they experience more stable crop yields and better outcomes in adverse conditions.

Introduction

Corn is a staple crop that is more sensitive to constant water availability than most other major grain crops.[79] Drought stress limits crop production worldwide. Understanding drought-tolerance is critical to maintaining yield and production, which has led public and private researchers globally to research the topic.[80] Research on drought-tolerance in the U.S. is focused on corn because it is the most valuable crop in the agriculture sector. In 2023, U.S. corn farmers produced 15.3 billion bushels of corn, valued at $73.9 billion. The United States is the world's largest producer and exporter of corn, with a production volume of almost 350 million metric tons. Corn is an important source of livestock feed, fuel, and a major agricultural export.[81] Drought can severely reduce the volume and total value of corn produced in a growing season. The quick change in supply from drought can rapidly increase prices, disrupting these markets. Thus, identifying hybrids that can avoid or tolerate drought conditions is imperative.[82]

This case study focuses on the drought of 2012 and the subsequent adoption of drought tolerant (DT) corn. However, this is not the first time in the history of corn that public sector research advances were used by seed companies and adopted by farmers because of the benefits farmers experienced during a major drought. Hybrid corn became commercially available in 1919. Adoption was slow until a major drought in 1936 that devastated

[79] Mapping the Sensitivity of Agriculture to Drought and Estimating the Effect of Irrigation in the United States, 1950-2016 – Agriculture and Forest Meteorology

[80] A new integrated index for drought stress monitoring based on decomposed vegetation response factors - ScienceDirect

[81] Corn and Other Feed Grains - Feed Grains Sector at a Glance | Economic Research Service

[82] Unveiling Drought-Tolerant Corn Hybrids for Early-Season Drought Resilience Using Morpho-Physiological Traits

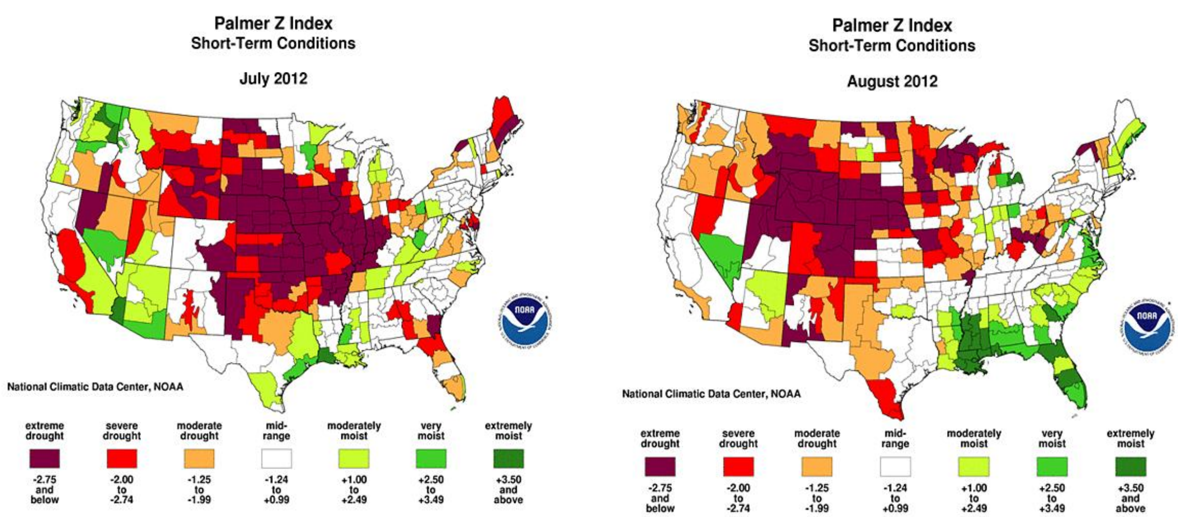
corn farmers. Then the hybrids outperformed open-pollinated varieties, adoption quickly followed. In 2011, new corn varieties were commercialized with increased drought resistance. Farmer adoption was low in 2011 and 2012 but took off after the 2012 drought reduced output by 25%. In both cases, the research existed, seed companies developed varieties, and adoption was slow. After a severe drought, adoption picked up quickly.

In the seed sector, public and private research are heavily interconnected. Public sector research is leveraged by seed companies and made available to farmers as new varieties. The seed companies profit from research by charging more for better seeds. Logically, adoption is linked to an improved economic return for farmers who use these seeds. Then the seed companies re-invest some of their profits into additional research and there are additional varietal improvements.

The 2012 Drought Overview

In the late spring of 2012, the weather was warmer and drier-than-normal. At the time, July 2012 was the second-hottest U.S. month on record, just behind July 1936. The result was a $30 billion agricultural disaster in the United States, according to the National Centers for Environmental Information (NCEI).[83]

Figure 9: Palmer Z Index Summer 2012



Source: NOAA, National Centers for Environmental Information, July and August 2012

The Primary Corn and Soybean agricultural belt, as defined by the National Oceanic and Atmospheric Administration, was especially hard hit by the drought. The extreme severity of the dryness and evapotranspiration demand over the growing season resulted in a rapid increase in the percentage area of this region experiencing moderate to extreme drought (as defined by the Palmer Drought Index). By the end of August, about 83% of the region was experiencing moderate to extreme drought.[84]

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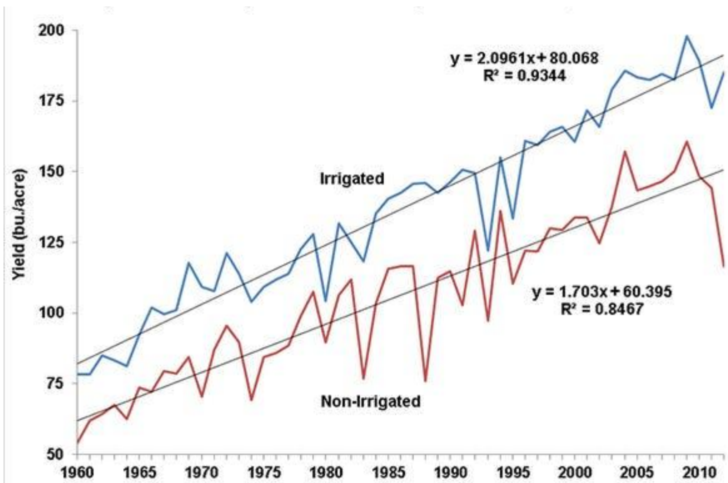
[83] The U.S. drought of 2012 - ScienceDirect

[84] Monthly Climate Reports | Drought Report | 2012 | National Centers for Environmental Information (NCEI)

Impact on Corn

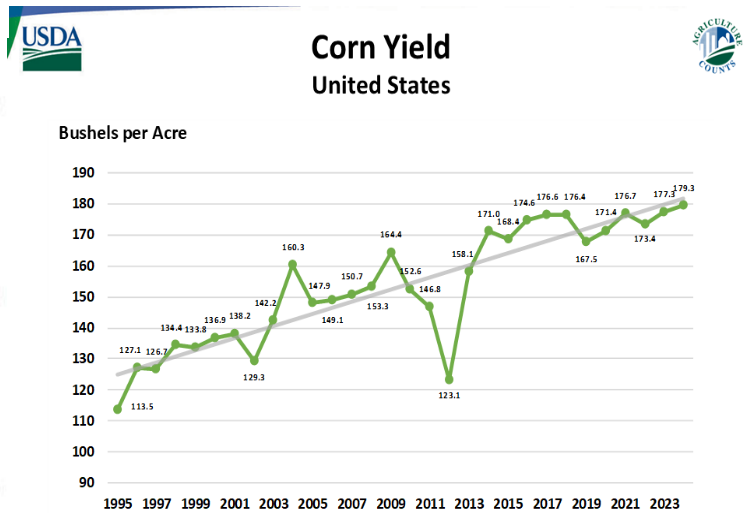
The impacts of this drought on corn were significant. The pre-drought estimates from the USDA indicated that U.S. corn yields would be 166.0 bushels per acre for 14.8 billion bushels of corn. In 2012, output was 10.8 billion bushels of corn, with a yield of 123.1 bushels per acre, more than a 25% reduction in output. This was the lowest yield since 1995. Field reports showed that corn ran out of soil moisture due to high evapotranspiration rates.[85]

Figure 10: U.S. Irrigated and Non-Irrigated Corn Yields, 1960-2012



Source: FarmProgress, with USDA NASS Data

Figure 11: U.S. Corn Yields



Source: USDA, NASS

Corn in the US is grown under irrigated and non-irrigated conditions, with irrigation more common in the western corn-belt states (Nebraska), and less common in the eastern corn belt (Iowa). Non-irrigated corn is more suspectable to drought conditions. The difference between the two production systems is exacerbated in drought years, like 1988 and 2012, where the yield in non-irrigated land falls much faster than on irrigated locations. There is a slight decrease in non-irrigated corn acres between 1995 to 2023.[86] The impact of DT corn in non-irrigated regions is more significant than irrigated acres, but yield declines in both areas shows the possible benefits of DT corn across the Corn Belt.

Drought conditions improved after 2012 and corn yields found new peaks, above 175 bushels per acre. Through 2024, the corn yield trendline remains positive.

[85] Crop Production Down in 2012 Due to Drought, USDA Reports Winter Wheat Seedings and Grain Stocks are also Reported

[86] USDA, ERS Corn Production Costs and Returns per Planted Acre

Corn Prices

Figure 12: 2011 -2013 Corn Prices (dollar per bushel)

A 25% reduction in U.S. output caused the price of corn to spike. Farmers impacted by the drought had lower quality and output. The drought hurt them financially. In contrast, farmers who had corn to sell benefited from a rapid rise in corn prices, fueled by a short supply. In June 2012, corn traded at roughly $5 per bushel. By late August, the price reached $8.44 per bushel and ended the year at about $7 per bushel.[87] U.S. export prices for corn went 128% above the 20-year historical average. From June to August, corn export prices rose 33%.[88]

Drought Tolerant (DT) Corn Supports Farmers

Corn is a water-intensive crop with major production under rainfed conditions. When faced with drought conditions, farmers can suffer catastrophic losses. Federal disaster programs and crop insurance provide relief but do not fully compensate farmers for their losses.

In 2012, total crop insurance indemnities reached $17.2 billion of which $11.7 billion was from of corn losses. This financial relief from crop insurance helped to stabilize farm income and prevent potential farm bankruptcies caused by drought.

Most producers face limited options to mitigate drought effects. Therefore, superior hybrids with drought resilience are important.[89] DT corn can increase yield stability, reduce input costs, serve as a risk management tool, and improve economic returns for farmers.

Increase Yield Stability

DT corn resistant corn varieties perform comparably under normal conditions and outperform non-DT corn hybrids during mild, moderate, and severe drought conditions. This means that in years with drought the farmers who plant DT corn outperform those who plant seeds without drought tolerance and in years that without drought the difference between the two varieties is minimal. Stable yields make it easier for a farmer to market their crop and be profitable. They can estimate their output and sell or hold the crop based on their estimated cost of production and yield.

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[87] December Corn Historical Prices Charts - Historical Commodity Futures Charts': CBOT
[88] Impact of the 2012 drought on export corn prices: The Economics Daily: U.S. Bureau of Labor Statistics
[89] Unveiling Drought-Tolerant Corn Hybrids for Early-Season Drought Resilience Using Morpho-Physiological Traits

Reduce Input Costs

Since 2006, harvested acres of irrigated corn production have exceeded 12 million acres.[90] On these acres, farmers have expenses associated with irrigation. Irrigation costs vary by location and water source. Texas A&M University crop budgets estimate that irrigation costs $284 per acre in Southwestern Texas.[91] Since DT corn can lower demand for irrigation, even when it is available, farmers can reduce irrigation expenses for the added cost of DT corn seed.

Risk Management

Planting DT corn can protect farmers from drought-induced yield losses, ensuring the farmer has a crop to sell. Moreover, the price of corn in drought years falls with the reduced supply. Therefore, farmers who have corn to sell at the end of the season are paid a higher price for their corn. As a result, farmers with corn to sell are generally more profitable than they would have been otherwise during drought years.

In 2005, the United States established the Renewable Fuel Standard (RFS) that dramatically increased demand for ethanol, which is primarily made from corn in the United States. Prior to RFS, corn returned an average of $250-$350 per acre gross and net return (minus operating costs) was $75 to $175 per acre. In 2007, RFS mandated 36 billion gallons of renewable fuel by 2015, with up to 15 billion coming from corn ethanol.[92] By 2010, the gross value of corn grain production exceeded $600 per acre and net of $275 to $325 per acre, in real terms.[93]

The high prices caused by tight supplies in 2012 increased the gross value of corn production above $800 per acre ($450 net), before returning to the $600 range.[94] The higher price benefited farmers that had corn to sell, but farmers who lost their crop to drought did not benefit from higher prices. Lower supply caused higher prices. Input prices increased slower than the price of corn, so average U.S. corn farm balance sheets during this period were relatively strong. In the subsequent years, crop prices fell back to the trend line, and input costs rose

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[90] Irrigated cropping patterns in the United States have evolved significantly since 1964 | Economic Research Service

[91] 2023 Estimated Costs and Returns per Acre Irrigated Corn

[92] Renewable Fuel Standard Factsheet

[93] USDA Corn Cost Return

[94] USDA Corn Cost Return

Figure 13: 2010-2013 Value and Cost of Corn Production

Improved Economic Returns

Farmers pay a premium of $8-10 per acre for DT corn above the same seeds without the DT traits. In 2012, the national average corn yield was 35 bushels below the 2013 yield. The average corn price in 2013 was $6 per bushel.[95] The 35 bushels were worth $210 per acre for a cost of $10 per acre. When farms are operating at a profit, the extra $10 can be an inexpensive insurance policy to protect against drought induced losses. However, if corn prices are below the cost of production, this added cost may be difficult to justify. Without a recent disaster people are resistant to purchase insurance or in this case DT corn seeds. They underestimate the potential risk, which is even more likely as the risk of drought and heat stress increases with climate change.

Commercial Products

As seen throughout the last century, new corn hybrids are a combination of public and private research. From 2018-20, 84% of corn seed was purchased from Bayer, Corteva, AgReliant, or Syngenta.[96] Very little seed is purchased from public sources. These seed companies have commercialized both non-genetically engineered DT corn and added DT traits into the genetically engineered stacked seeds. Gene stacking is when two or more desirable traits are combined into one variety. Drought tolerance genes were added to germplasm that already contained several other desirable traits, including herbicide resistance and insecticidal proteins (BT) corn.

A study on the economic benefits of genetically engineered corn on farmer incomes from 1996-2020, which included genetically engineered DT corn, found that 3.5 million acres of DT corn was planted in 2020.[97] These field trials suggested a net yield gain of 2.6% and a slight cost savings compared with non-genetically engineered DT corn. The average gross farm gain from corn seed stacked with drought tolerance, herbicide tolerance, and pesticide traits between 2014-20 was $42 per acre, compared with only a $10 increase in cost. In 2020, this resulted to an aggregate farm income gain of $35.3 million and over the period 2014–2020, a total gain of $131.8 million.[98] Since the traits are stacked it is difficult to determine each trait's individual impact on yield.

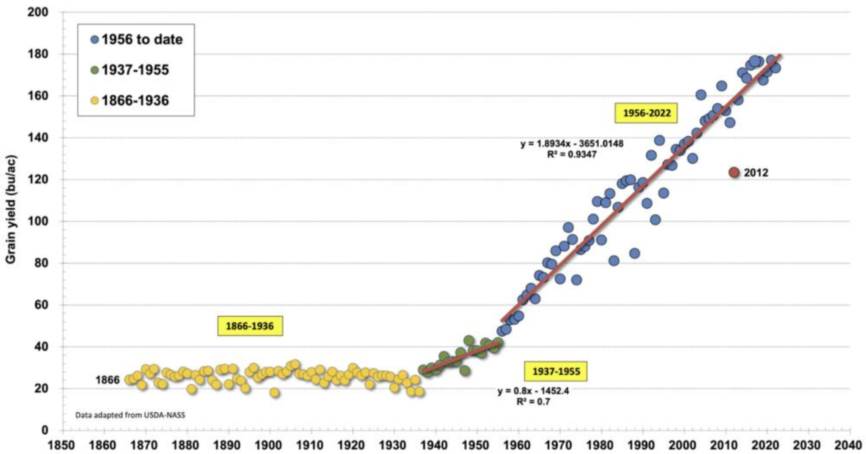
[95] 2013 Corn Prices Suggested by History

[96] Concentration and Competition in U.S. Agribusiness

[97] GE DT corn, not including DT traits stacked varieties. The study compares GE DT to non-GE DT corn.

[98] Farm income and production impacts from the use of genetically modified (GM) crop technology 1996-2020 - PMC

Figure 14: U.S. Corn Grain Yield Trends Since 1866



Source: Purdue University, Corny News Network

U.S. University Researchers

Having established the genetic tools used by private sector firms to develop drought resistant corn varieties, many U.S. universities are also conducting ongoing research into corn drought resistance. This work is being carried out at institutions around the country, including University of Nebraska-Lincoln, a joint effort between Iowa State University and Standford University, Texas A&M University, University of Wisconsin-Madison, Penn State University, University of Illinois Urbana-Champaign and Kansas State University. In addition, there are publicly funded research stations that support breeding trials. The Hatch Act of 1887 authorized the establishment of agricultural experiment stations, to be affiliated with the land grant college of agriculture, with the mission of conducting original research, investigation, and experiments which contributing to the establishment and maintenance of the agricultural industry in the United States[99]. Today the USDA maintains 90 research locations.

USDA NIFA Funding

Between 1998 and 2024, there were 1,007 projects in the USDA's National Institute of Food and Agriculture (NIFA) program funding database containing the keyword drought, worth $1.2 billion. Of these projects 253, worth $364 million, used the keyword drought tolerance. Projects with keywords related to drought tolerance, but not specifically to drought tolerant corn, like irrigation or water delivery, exceeded $1.34 billion.

Foundation for Food and Agriculture Research

The Foundation for Food & Agriculture Research (FFAR) awarded a $1.8 million grant through the Crops of the Future Collaborative to the University of Wisconsin-Madison to identify genetic markers in corn associated with drought tolerance and thereby accelerate the breeding of drought-resistant varieties. FFAR provided $900,000 and Inari, KWS and Syngenta contributed the matching funds for this three-year project through their participation in Crops of the Future.[100]

Historic Seed Innovations

Botanist George H. Shull had a critical role in hybrid corn development at the privately funded Carnegie Institution at the Station for Experimental Evolution in Cold Spring Harbor, New York. He produced corn breeds

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[99] Agricultural Experiment Stations and Branch Stations in the United States - Pearson - 2015 - Natural Sciences Education - Wiley Online Library

[100] FFAR Grant Maps Corn Drought Tolerance Genes - Foundation for Food & Agriculture Research

that bred true (the same as the parents, no genetic recombination) and then crossed these strains, but the crosses were poor quality.[101] Working at Harvard University and the state funded Connecticut Agricultural Experiment Station, Donald F. Jones built on Shull's work. He invented the double-cross method of hybrid seed production in 1917. The resulting progeny were uniform, more vigorous, and some cases more productive than the original open-pollinated varieties.[102]

During Henry Cantwell Wallace's tenure as the Secretary of Agriculture from 1921 to 1924, the USDA funded a hybrid corn research program with experiment stations in several Corn Belt states.[103] The federal program was vital during the 1920s, and Donald Duvick suggested that "the commercial maize breeders probably could not have succeeded in the early years (without the contributions from the public sector), for individually they simply did not have enough inbred lines [genetic material]…".[104]

Had Wallace not used the bully pulpit of the USDA to promote his own commercial and financial interests, had the USDA not supported the research effort in the late 1920s and early 1930s, had the droughts of 1934 and 1936 not occurred, had Hi- Bred not continued a major research effort following 1936, the Wallace crusade might have succumbed as just another fatality of the Great Depression.

-Richard Sutch

The 1936 Corn Belt Drought and Adoption of Hybrid Corn (p.217)

Public research on heterosis, inbred lines, and hybrid crosses was used by Henry A. Wallace[105] and private sector plant breeders to develop hybrid corn seed. At the time there was an exchange of ideas and germplasm between government and private company researchers. In the 1920s the publicly funded Experimental Research Stations in Corn Belt states preformed trials between hybrid and open pollinated corn. This combination of public and private efforts led to the adoption of hybrid corn and a significant increase in corn yields.

Henry A. Wallace commercialized the first hybrid corn (Copper Cross) in 1924, and competitors followed suit in 1928. In 1926, Wallace founded Hi-Bred Corn Company, later Pioneer Hi-Bred, which was the first and largest producer of hybrid corn seed. Initially adoption was slow because hybrid seeds were significantly more expensive than their open-pollinated competition.

Research stations compared open pollinated and hybrid seeds, but the economic advantage was not clear until the mid-1930s. The price of corn fell from $0.80-$0.85 per bushel in the late 1920s to $0.32 per bushel in 1931-1932. The Great Depression lowered corn prices, reducing revenues, and the hybrid seeds were more expensive, increasing cost. The lower profitability of hybrid corn prevented massive adoption. Farmers who adopted the technology prior to 1937 were considered early adopters.[106]

[101] George Harrison Shull (1874 - 1954) - Genealogy
[102] 5. Donald Forsha Jones | Biographical Memoirs: Volume 46 | The National Academies Press
[103] American Dreamer: The Life and Times of Henry A. Wallace - John C. Culver, John Hyde - Google Books
[104] The Contribution of Breeding to Yield Advances in maize (Zea mays L.) - ScienceDirect
[105] Henry A. Wallace, who served as Secretary of Agriculture during the Franklin Roosevelt administration was the son of Henry C. Wallace, who served as Secretary of Agriculture during the Coolidge and Harding administrations.
[106] The Impact of the 1936 Corn Belt Drought on American Farmers' Adoption of Hybrid Corn

In 1936, nearly all farmers who were testing hybrid seed corn planted only a limited acreage next to their open pollinated fields. "Hybrid 307" was introduced in 1936 and proved to be extremely drought tolerant. With the severe drought conditions experienced that year, farmers saw that the yield of hybrid 307 was approximately double the yields of other corn grown on the farm. Richard Sutch posits that these on-farm trials removed the remaining resistance to purchasing hybrid corn, even though the yield differences were low in normal years and the seeds carried a significant price premium.

In 1937-38 there was a tipping point and hybrid corn sales grew rapidly. Pioneer Hi-Bred's sales of hybrid seed increased from 16,525 bushels in 1933 to 40,586 bushels in 1937. The price of seed corn rose from $6.58 per bag in 1933 to $9.96 per bag in 1937.[107] With profits from hybrid seeds sales, the private seed companies invested in new varieties that significantly improved yields in normal years. Better yield in all weather conditions encouraged late adopters to purchase hybrid seed and by 1960, 96% of corn U.S. corn acreage was planted with hybrid varieties.[108]

Wallace believed that his hybrid revolution would have failed without well-financed research effort, from both public and private sources. He reported that his company invested more in research than the federal government and the research stations combined.

Drought-Tolerant Corn Research

Since the 1950s, the public and private sectors have conducted basic corn research and stress tolerance research in corn. Drought is one stress factor; others include plant pests and diseases. They have explored genetic modifications, gene editing, and traditional breeding techniques to improve drought-tolerance in corn. After decades of research, drought-tolerant (DT) corn varieties became commercially available to U.S. farmers in 2011. These corn varieties contain resilient genetics that enable the plants to endure water stress by improving the plant's ability to take water up from soils and convert water into grain under a range of drought conditions.[109] Three seed companies translated this research combination of public and private sector research into DT varieties that they sold for a premium to corn farmers.

There are two parts to drought tolerance research. First, how dry conditions turn into drought stress in the plant and how the drought stress causes vegetation destruction. Corn's physiological response to drought is governed by multiple genes and varies with the drought's timing, duration, and severity. Second, the effects of drought stress and heat stress on the corn plant may differ, adding to the complexity. To compare the various factors impacting drought tolerance, research can focus on:

- water taken up by the plant – research on root systems and weed control (to reduce competition for water), or
- water use efficiency – research on healthy leaves and keeping the plant green, or
- biomass conversion to grain (the harvest index) – number of kernels per year.

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107 Urban, Nelson. 1979. A history of Pioneer's first ten years. Pioneer Hi- Bred International. Manuscript, ISU Library
108 USDA, Agricultural Statistics 1962, Table 46: 41; USDA, Track Records, April 2004: 19
109 Drought-tolerant corn varieties often planted on non-irrigated fields | Economic Research Service

The plant has adaptive mechanisms that make it more tolerant of the adverse effects of drought stress. Plants have avoidance, escape, and tolerance mechanisms.

Types of Research

Drought tolerance research is ongoing, building on the body of knowledge. Recent research has focused on root research and physiological and morphological traits. This section highlights recent work by public institutions.

Roots

Water use efficiency is an important area of research, specifically the development of more efficient root systems. Multiple publicly funded labs are researching different aspects of corn roots and drought tolerance. The parsimonious root phenotype is defined as "unwilling to use resources" and it describes plants with corn roots that are often referred to as "steep, cheap, and deep"[110]. Steep roots are angled downward at a sharper angle, foraging deeper to acquire scarce water and nutrient resources. Cheap refers to the metabolic cost to the corn plant and includes traits such as making fewer roots and making roots with internal air spaces to reduce the number of living cells in the plant. By producing fewer roots, the plant ensures that the roots that are produced have adequate resources to grow deep into the soil, which is important under drought conditions. This research was conducted at Pennsylvania State University and was supported by the Leverhulme Trust, Modelling and Analytics for a Sustainable Society, the University of Nottingham, the Biotechnology and Biological Sciences Research Council — Newton Fund, and the Foundation for Food and Agriculture Research.

Another research team uncovered genetic mechanisms behind root "hydropatterning," or how plant roots branch toward water and avoid dry spaces in soil. The team also learned how ethylene influences how roots grow to seek water. This research received support from the Howard Hughes Medical Institute; U.S. Department of Energy; National Science Foundation; UKRI Frontiers Research, Biotechnology and Biological Sciences Research Council; European Research Council, Horizon Europe; and the Evotree project. [111]

Morphological Traits

Morphological changes included reduced plant height and biomass, which ultimately lowers yield. Though plants are sensitive to moisture stress throughout the life cycle, the early seedling growth and development stage is the foundation for higher yield potential.[112] Early season drought impacts the corn's seedling stage, which causes an early priming and pre-conditioning stage. This in turn reduces growth.[113] A successful seedling emergence ensures optimum crop stand and yield, because seedling vigor is attributed to increased biomass production, which leads to rapid canopy closure, thereby preventing soil moisture evaporation and better root establishment. Together these plant features maintain their water balance.[114]

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[110] Study shows 'steep, cheap and deep' roots help corn plants deal with drought | Penn State University

[111] New study could lead to development of more drought-resistant corn | Stanford School of Humanities and Sciences

[112] Developing Functional Relationships between Soil Moisture Content and Corn Early-Season Physiology, Growth, and Development

[113] Molecular and Physiological Analysis of Drought Stress in Arabidopsis Reveals Early Responses Leading to Acclimation in Plant Growth | Plant Physiology | Oxford Academic

[114] Unveiling Drought-Tolerant Corn Hybrids for Early-Season Drought Resilience Using Morpho-Physiological Traits

Physiological Traits

Soil moisture stress also results in physiological changes like cellular and tissue dehydration. Low tissue water causes leaf wilting and premature senescence. It also causes lower cell expansion rates, increased stomatal closure, reduced photosynthetic rates, and greater biomass partitioning into root systems. The corn plants respond to drought by closing the stomata and folding the leaves to minimize transpiration. Then photosynthetic rates and plant growth metrics (leaf area, height, and dry mass) drop.[115]

The facility used genome modifications to boost a key plant protein that enabled the plant to reduce water use by up to 30% under drought-mimic conditions.[116]

Conclusions

- Corn is a critical staple crop that is used in food, feed, fuel, and is exported. It covers more U.S. acres than any other crop in most years. Drought is unpredictable and can cause severe damage to the crop which has ramifications on producers and commodity markets. Drought tolerant corn offers protection against downside risk during drought years to stabilize yields.
- Drought tolerance is a complex area of research. Multiple genes impact how dry conditions stress a plant, and the impact varies depending on the timing of the drought, its duration, and its severity. Understanding how the drought stress causes vegetation destruction is a different area of study.
- Public researchers studied diverse corn plants and improved varieties based on observed traits. They successfully hybridized corn and created in-bred lines. One benefit of this research was drought resistance. Later seed companies commercialized these hybridized seeds and used part of the proceeds to fund private research. Public and private research worked in tandem.
- In the 1930s and 2010s, hybrids with drought resistance carried a premium. In both cases, adoption was low before an extreme drought devastated corn production. After farmers experience significant losses, adoption of hybrids and DT corn acres increased quickly.
- Farmers view seeds with drought tolerance as a risk management tool. In a way, it is like an insurance policy. A small premium is paid annually and if there is a drought, the farmer does not experience severe yield loss.

[115] Unveiling Drought-Tolerant Corn Hybrids for Early-Season Drought Resilience Using Morpho-Physiological Traits
[116] Husker Research Points to Increased Water Use Efficiency for Crops | CropWatch | Nebraska

Cross Case Study Observations

The goal of this research was to narrow in on what types of public research investment have the highest impact on farmer economics, as measured by net farm income. A case study method was used to explore different aspects of agriculture and reasons for research and development. The case studies covered livestock and crops, commodity and specialty crop production, production across the United States, as well as diseases and environmental stressors. We selected industries that had data available that we could use to analyze and quantify the impact the research had on the industry over time. This allowed us to understand the link between the research and net farm income for the producers.

Research uncovers new knowledge, which is added to the body of knowledge that becomes the basis of future research. Fundamental and basic research created a foundation for future research to be conducted, whether intentionally or unintentionally. The uniform process by which we conduct research, analyze the results, and share the findings is critical to all scientific exploration and to building widespread trust in the results. This trust is necessary for translation and adoption of research in development. The cost and value of this framework is not included. Similarly, research on everything from plant physiology, genetics, and pest vectors was critical to eventually addressing the issues raised in these studies, but this research was not included in the analysis. All this is widely interrelated and drawing divisions on where research on a particular subject starts and stops makes narrowing in on farmer impacts per research dollar subjective.

This underscored another finding, that research impact is often not immediately realized; rather it can take decades to realize the full potential from agricultural R&D investments. In addition, research can be a cumulative endeavor, benefiting from sustained investments.[117] Research and improvements are iterative, adopted research becomes the status quo and new research builds on this new normal. The long lag time creates other complications. First, the markets have time to adjust to the higher output or lower cost of production, causing commodity markets to reach a new equilibrium, which limits the farmer impact. Also, other factors like government regulations, trade relationships, weather conditions, and consumer preferences make it difficult to isolate the impact of research and development on net farm income.

Public research is often praised for adding to the body of knowledge, because the research is done for the sake of greater understanding and not necessarily a return on investment. When research progress is not made in advance of problems, the necessary foundations can be missing. To allow greatest impact, at the time of need, knowledge and tools must be available before a crisis strikes.

Public research, especially at universities, has a secondary impact of training the next generation of scientists in their labs. Without these research opportunities, there is not a pathway to educate future scientists to conduct public and private sector research in the future. Also, without these research opportunities, the system ready to conduct the research in times of need would weaken or cease to exist.

We found that the public and private sector were present in all three case studies but showed up differently.

[117] Investing in Agricultural R&D Should Be a Global Priority | Issues in Science and Technology

- The critical challenges posed by HLB (citrus greening) led to intersecting efforts at the federal, state, and local levels as well as creative partnerships between public, private, and nonprofit sectors in preventing and treating the bacterial causes of HLB. These teams worked side-by-side in a very collaborative way.
- In the cattle case study, public researchers were responsible for much of the genetics research into topics like heredity, but the private sector had access to large number of cattle. They started collecting data on individual cows. By combining the public sector research with detailed information on the cattle herd, the industry created valuable, predictive breeding tools. Eventually, the predictive databases were able to verify individual genetics and to pay a premium, not just for the meat but for the seedstock producers, cow-calf operators, and the feedlots that raised CAB cattle.
- In contrast, in the corn case study, public research made advances on hybrids and understood specific types of drought tolerance. Then, the private sector used this information to develop new varieties. The public sector tested them at research stations across the country. Then the industry commercialized them. With the premium earned on the new varieties, the industry reinvests in additional research, which increases the amount of public and private sector breeding that is happening concurrently.

Another finding is that research can reduce producer risk. For example, in the HLB and drought tolerance case studies, the research provides the farmers risk protection against disease and drought. HLB research has played an important role in keeping the California citrus industry alive as the Florida industry continues to decline. It has largely kept the disease out of commercial citrus groves in California, which provided significant financial benefit to those operations. Similarly, drought tolerant corn provides better yields in drought years, preventing a farmer from experiencing catastrophic loss. In both cases, the producers that have product to sell make more money when disaster strikes, but more importantly it keeps them in business.

Research is most economically beneficial when it is applied and adopted. Sometimes, the economic return of a new technology is enough to spur adoption, but even when technology may have positive expected returns, other intangible factors may influence farmer decisions. Both need to be addressed. Therefore, making the information available to farmers and helping them overcome any resistance to the technology or innovation is essential to maximize the benefits of the research.

The mechanisms encouraging producer adoption varied between each case study:

- Florida implemented a mandatory eradication program for citrus canker from 2000 to 2006. When HLB arrived, there was resistance to additional containment and eradication programs, which eventually caused great harm to the industry. California and Brazil have taken quarantine and eradication efforts seriously and are not facing the same challenges as the Florida citrus industry.
- The Fort Keogh Livestock and Ranch Research Laboratory maintained a Hereford breeding line for 76 years, which is the foundation of today's breeding and genetics knowledge for all cattle. Both the Hereford and Angus breed associations had access to this data however, the American Angus Association leveraged it into a breeding tool for producers and a premium meat brand.
- Both hybrids and drought tolerant corn traits existed with low farmer adoption, until a severe drought hit devastating corn farmers. After the catastrophic losses, adoption rapidly increased. The technology alone was not enough to sell hybrid or drought seeds; instead, farmers needed to experience the right use case to

overcome their resistance. Once adopted, these varieties have helped reduce yield loss from drought conditions or lower irrigation expenses.

Our final finding is that even when research and development benefits farms and has a positive impact on net farm income, they are not the only businesses that benefit from the research. Some research might help producers more than it helps input providers or businesses along the supply chain, but rarely does the benefit solely accrue to farmers.

Appendix 1: NIFA Database Analysis Methodology

CAB Takeaways

- $1.5 billion funded amount and 880 Projects for Angus
- $126 million funded amount and 133 Projects for additional genetic research in beef sector
- $459 million funded amount and 371 Projects for market research in Angus breed or beef sector

Drought Takeaways

- $1.17 billion funded amount and 1007 projects use the keyword drought
- Of these projects, $364 million and 253 projects use the keyword drought tolerance
- 560 additional projects totaling $910 million use similar keywords or objectives related to drought tolerance (e.g., limited irrigation, water delivery)

Methodology Description

The methodology for this analysis began by querying the NIFA database using keywords “angus”, “beef cattle genetics” and “Meat - beef cattle”. We identified applicable data columns and grouped them into distinct project categories. Project Type and Accession Number served as unique project identifiers, and exact duplicates were removed. To analyze keyword patterns, we applied Python-based text analysis techniques. Specifically, we used

- **spaCy** for named entity recognition (NER),
- **Agglomerative Clustering** for clustering the keywords into 50 groups, and
- **Counter** to measure keyword frequency and aid in categorization.

For the Angus Beef Cattle genetic case study, each keyword was assigned to the most appropriate cluster and evaluated. The keywords were mapped back to their respective groupings, ensuring alignment with relevant projects. If a cluster contained keywords that were not applicable, the corresponding projects were excluded from the total funded amount. To refine the results, we manually reviewed and adjusted keyword assignments – focusing on terms like “gene” and “market”—to improve cluster accuracy and minimize omissions. For the drought case study, we followed a similar approach using the keywords “drought”, “drought tolerance”, “drought tolerance breeding”, and “drought corn maize breeding”. The same Python-based clustering and exclusion logic were applied to categorize keywords ad assess project relevance.

Limitations

- **Multi-word Keywords:** Keywords containing multiple words may have been misassigned to clusters
- **Semantic Clustering:** Similar terms may have been placed in various clusters due to the semantic logic applied by SpaCy
- **Manual Bias:** Human judgement in selecting keywords for inclusion overridden automated cluster categorization
- **Exclusion criteria:** The exclusion logic may have inadvertently filtered out relevant projects, leading to underestimation of total funded amounts