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RESEARCH ARTICLE

Outstanding in the Field: Impacts of Public Small Grains Breeding in Virginia

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Abstract

New production from public and exclusive varieties released by the small grains breeding program at Virginia Tech generated cumulative discounted benefits of $41 million from 2000 to 2018. Fitted yields from field trials were combined with acreage estimates to generate weighted average yields based on adoption of new varieties. Benefits were estimated as the value of additional production from the release and adoption of improved varieties. Public varieties were responsible for most program benefits. The program was found to have a significant impact in Virginia and out-of-state, with much of these benefits due to public-private collaboration.

Keywords: barley; impact assessment; plant breeding; small grains; wheat

JEL classifications: Q16; O31; O32

Introduction

Since the mid-20th century, public breeding of new crop varieties has declined, while changes in technology and intellectual property laws governing germplasm development have induced a shift to private plant breeding. This decline has been particularly evident since 1990 (Shelton and Tracy, 2017). Although most improved germplasm in the United States in the early 20th century was produced by the U.S. Department of Agriculture (USDA) or public universities, public plant breeding programs now must work harder to justify their existence as progressively more breeding is conducted in the private sector. This study examines the impacts from 2000 to 2018 of a university-run small grains breeding program at Virginia Tech (VT) that produces both public and exclusive (university-developed but privately licensed) varieties. It provides information to public officials, university administrators, and stakeholders in the program, illustrating the importance of university research to the modern plant breeding industry and the benefits this research provides to farmers.

This study uses data from field trials conducted in Virginia from 1991 to 2018 to estimate yield changes associated with specific new varieties of wheat and barley. It combines these estimates with acreage data and assesses benefits using yield increases attributable to the breeding program. Most evaluations of university breeding programs focus on public varieties, and this study contributes to the literature by including exclusive in addition to public varieties. It also compares the differences between the two types of varieties in terms of the channels used to market them, benefits generated, and royalties collected via variety licensing.

Varieties released by the Virginia small grains breeding program generate significant benefits within the state and provide even larger benefits to other states and regions. The breeding program provides additional benefits by conducting trials of private varieties and those developed by public entities in other states.

This study considers the importance of royalty payments (especially to program administrators) in addition to public benefits at a time when budgets are tight for public breeding programs. Shelton and Tracy (2017) note the marked decline in the number of public sector breeders and breeder-hours worked in the 1990s, including a loss of 108 breeders nationally from state agricultural experiment stations from 1994 to 2001. They found that 57% of breeders surveyed were skeptical that their university would replace them if they retired or otherwise left their job (Shelton and Tracy, 2017).

Background

Although corn and soybeans are the dominant field crops in Virginia, wheat and barley remain important, with 210,000 acres of wheat and 30,000 acres of barley planted in 2017 compared to 500,000 acres of corn and 600,000 acres of soybeans (National Agricultural Statistics Service, 2020). Because winters are relatively warm in Virginia, most wheat production is soft red winter (SRW) wheat, with the two main uses being as a cover crop or as a source of pastry and biscuit flour. Barley is grown primarily for livestock feed, although farmers increasingly grow malting barley for sale to the rapidly growing craft beer industry.

Varietal improvement in general, and in small grains specifically, falls into two categories: yield and quality improvement. Yield improvement may refer to increasing yields directly by creating or improving traits such as dwarfism or leaf angle, or it may refer to maintaining yields in the face of disease or insect pest pressures by breeding for resistance (Brennan and Murray, 1995). Quality improvement entails selecting for traits preferred by buyers, processors, and consumers. For wheat, end use is determined by which of the six classes of US wheat a variety belongs to, with each class being grown in a different region of the United States (US Wheat Associates, n.d.). Consequently, wheat quality is improved by within-class breeding for desired traits. For example, wheat classes used for bread baking would be bred with other wheats in their class for higher protein or gluten content. For barley, certain varieties are considered sufficiently high quality for malting, but these varieties must be managed and handled to conform to other quality standards such as protein content, moisture, and germination rate (MacLeod, 2018).

Although substantial research has been conducted on the impact of new releases of a single variety, studies focusing on the impact of a state- or national-level breeding program are less common, in part due to increased scope of the data required. Pardey et al. (2004, Pardey et al., 2006) assessed the economic benefits from the Brazilian Agricultural Research Corporation, developing an approach that allows for estimation of national or regional breeding program benefits using breeding trial data. Their approach uses proportional changes in acreage grown of each variety to account for adoption and disadoption of varieties and is flexible in that it allows for the estimation of predicted yields even when data are incomplete across locations or time. It also allows for estimation of benefits for multiple crops under a single program (Pardey et al., 2004, Pardey et al., 2006). The approach has been applied to other breeding programs, such as South Africa's national cultivar trials (Dlamini, Magingxa, and Liebenberg, 2015).

Nogueira et al. (2015) analyze the welfare impacts of wheat breeding in Washington state. They provide a producer and consumer surplus analysis of benefits created by the breeding program and disaggregate impacts for each of five wheat classes. A study of barley breeding in Syria found substantial benefits (Mustafa, Grando, and Ceccarelli, 2006).

Public and Private Grains Breeding

From the nineteenth to the late twentieth century, most new crop varieties in the United States came from public breeding programs run by universities or the USDA. Patenting new asexually propagated crop varieties first became legal in 1930 with the passage of the Plant Patent Act (Shelton and Tracy, 2017). Intellectual property protections for new crop varieties produced from seed (as opposed to asexually propagated crops) were subsequently introduced by the Plant Variety Protection Act of 1970 (PVPA), making it the relevant legislation for protection of new wheat and barley varieties (Klotz-Ingram and Day-Rubenstein, 1999). However, the protection offered by the PVPA was relatively limited in scope, as crop breeders had the right to use protected varieties for breeding and other research purposes. Additionally, the "farmer exemption" in the original PVPA allowed farmers to save, replant, and even sell seeds saved from protected varieties, although a 1994 amendment prevented farmers from selling (but not using) saved seeds protected under the PVPA without permission. Because of these weaknesses, a study of the effects of the PVPA on wheat breeding found that the PVPA alone did not contribute strongly to increased private investment in the wheat breeding sector (Alston and Venner, 2002).[1]

Further developments in the institutional and scientific arenas strengthened incentives for private investment in plant breeding. The Bayh-Dole Act of 1980 played a key role in shaping the germplasm industry by allowing universities to patent technologies resulting from federally funded research and to issue exclusive licenses for patented material (Alston and Venner, 2002). Patenting allowed universities to transfer intellectual property rights to private partners, as is done with exclusive varieties released by VT (Graff et al., 2003). These legal changes increased incentives for private participation in plant breeding, causing the size and number of private breeding programs to swell while those of the public sector dwindled (Shelton and Tracy, 2017). As the regulatory landscape changed to better accommodate private breeding companies, advances in research methods and biotechnology contributed to increased private investment in plant breeding. It is argued that the surge in private patents beginning in the mid-1980s had more to do with changes in research methods, such as the emergence of modern biotechnology, than with the regulatory environment in the United States (Kortum and Lerner, 1999).

Although the private breeding sector grew quickly to eclipse the public breeding sector in terms of total R&D investment, the two sectors focus on different types of breeding projects. In general, private breeders are more likely to focus on hybrid varieties for commercially successful crops, such as corn and soybeans, whereas public breeders are more willing to develop non-hybrid varieties for a wider range of crops, including small grains (Klotz-Ingram and Day-Rubenstein, 1999). However, as investment becomes more heavily concentrated in private breeding programs, especially those utilizing modern genetic engineering techniques, higher-cost public breeding programs using conventional methods often receive less resources as a result, even in the case of less commercialized crops such as wheat (Knight, 2003). As the plant breeding landscape continues to change, public breeding programs face the question of what their role should be.

Public and private plant breeding programs are not direct substitutes. A fundamental difference is that universities generally (though not always) share their germplasm with other universities and public programs (Shelton and Tracy, 2017). Private breeders rarely share proprietary germplasm. All breeders are interested in improving varieties for the market, but private breeders are more likely to safeguard their successes from others in an attempt to maximize their own returns. This safeguarding may entail forgoing potential varietal improvements from collaboration and may limit farmer access to some varieties based on financial or geographic barriers. Public breeding programs may be more likely to balance royalties (which support their programs) with broad access to varieties. Shelton and Tracy (2017) surveyed public plant breeders and found that grants (which often have broad access as a priority) were more important than royalty funding in dictating the focus of their breeding.

[1]Similar papers discussing the effects of the PVPA on barley breeding could not be found, but since both wheat and barley are subject to the PVPA, it is unlikely for new barley varieties to enjoy stronger protections than new wheat varieties or for the PVPA to have caused significantly higher private investment in barley breeding.

Small Grains Breeding and Distribution at VT

The university-run breeding program in Virginia is supported by the Commonwealth of Virginia, USDA grants, the Virginia Crop Improvement Association (VCIA), and royalties. Roughly three quarters of the royalties collected are from exclusive crop varieties (developed by VT and licensed to private companies), with the remainder from public varieties released by the program (Santantonio and Hardiman, 2021). Breeding objectives have changed over time based on producer demands, but generally include disease resistance and quality improvement, especially for specialty varieties such as malting barley and bread wheat (USDA National Institute of Food and Agriculture, n.d.). Varieties with highly specialized end uses or specific geographic adaptations are more likely to be licensed as exclusive varieties in order to meet specific client demands. Since 1990, the program has released 12 public wheat varieties and 11 public barley varieties. It has also licensed and released one exclusive barley variety and 67 exclusive wheat varieties.

The program uses field trials at agricultural experiment stations around the state. The role of these trials is twofold. The first is to compare yields of varieties to provide information to producers on how well the lines are adapted to area-specific production conditions. The second role is to generate germplasm that can be crossed and/or linebred to contribute to development of public and exclusive experimental varieties. Although improved lines (especially public ones) may be used as parents for later lines, much of the experimental germplasm created by the program changes from year to year as new lines are developed and older lines are discarded. Most germplasm used in these experiments is from VT, while a small but significant portion is from other universities or produced in collaboration with other universities.

The role played by exclusive varieties in the program is significant (Santantonio and Hardiman, 2021). Licensing varieties for exclusive release provides two advantages. First, licensing allows the variety to have marketing support that private entities can provide but VT cannot. Consequently, although these varieties are marketed for less time by the private sector, they generally enjoy greater uptake by farmers compared to what they would have if they were marketed as part of a larger public portfolio (Thomason, 2020). Because the resources available to the VT breeding program to market public varieties are finite, the addition of private resources allows more varieties to reach more markets in more places. More varieties available in more markets increase the gross benefits from yield improvement generated by VT germplasm relative to what they would be in the absence of exclusive varieties. The second advantage is that royalties from exclusive varieties provide revenue to support breeding and fund the release of exclusive and public varieties.

Royalties from exclusive varieties might incentivize breeders to emphasize exclusive releases over public ones for their own benefit or to expand the program. However, the royalties are divided among the programs, administrative partners such as VCIA, and university administration, meaning that breeders and their programs do not reap the full benefits of these increased royalties. In fact, Shelton and Tracy (2017) report that breeders and their programs often receive less than half of the royalty funds they generate. Thus, incentives to maximize royalties are more attenuated than they may appear.

Distribution of seeds and administration of royalties from public varieties are undertaken in partnership with VCIA, which acts as the seed certification agency in Virginia. Varieties are marketed within Virginia under the administration of VCIA and in other states with the cooperation of their seed certification agencies. VCIA is also responsible for the production of "Foundation" seed, which is distributed to selected farmers for production of certified seed which is then sold to farmers (Thomason, 2021b). Royalties are collected based on certified seed production and split between VT and VCIA, with smaller royalties collected for out-of-state production (Hardiman, 2021).[2] The process of creation, administration, and distribution of public varieties is shown in Figure 1. Exclusive varieties are produced and distributed by the entity to which it is licensed, and

[2]For Callao, Nomini, Pamunkey Price, Starling, and Thoroughbred barley, VCIA collects only 50% of royalties for out-of-state acreage. The same is true for Jackson, Madison, and Wakefield wheat. For Dan, Eve, Doyce, Atlantic, and Secretariat

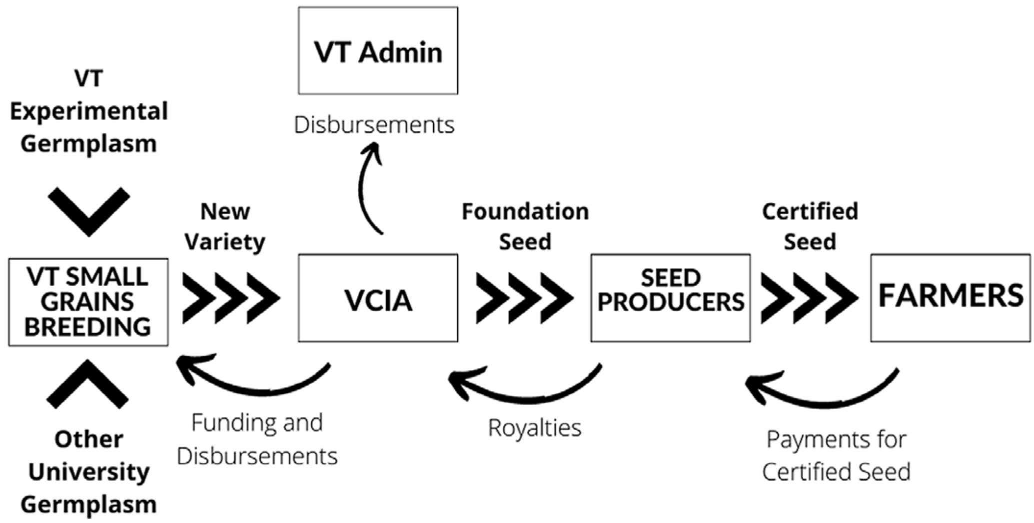

Figure 1. The creation, licensing, and distribution of public varieties created by the Virginia Tech small grains breeding program and the movement of revenues, royalties, and funding from these varieties.

royalties are paid to Virginia Tech Intellectual Properties (VTIP), with payments disbursed to VCIA, other administrative funds within VT, and the breeding program itself. The process for exclusive varieties is shown in Figure 2.

Model, Methods, and Data

Conceptual Model

It is assumed that farmers choose to plant the bundle of crop varieties that maximizes expected utility. In general, expected utility increases as farm profits increase, although farmers may also derive utility from traits such as environmental impacts and yield risk reduction due to drought resistance, among others. Adoption may also be impacted by barriers such as incomplete information on the part of farmers or unequal availability across locations. In expected utility theory, mean profits and their variability are assumed to matter. Farmers may be reluctant to adopt new varieties quickly because of uncertainty, but new varieties can be associated with lower risks of crop loss due to drought, insect pests, and plant diseases. Farmers may plant one or a mix of varieties depending on their preferences (Useche, Barham, and Foltz, 2013). As varieties age, they become more susceptible to insect pests and diseases (Brennan and Murray, 1995), so farmers constantly adopt new varieties for resistance and to take advantage of other new traits.

We assess benefits to farmers from the VT breeding program using methods applied by Pardey et al. (2004, Pardey et al., 2006). The approach allows for trial data that do not include all varieties in all locations in all years, as is the case for the VT program, where new varieties were released over time. It also accounts for adoption and disadoption over time. Although we use the methods used by Pardey et al. (2004, Pardey et al., 2006) to estimate changes in yield and their associated benefits, we do not apportion the source of these benefits between VT and partner institutions as do Pardey et al. We lack information on the genetic lineage of the varieties in the trials or the contribution of work and resources between VT and partners institutions.

barley, VCIA collects 70% of royalties for out-of-state acreage. The same is true for McCormick, Pocahontas, Roane, Sisson, Jamestown, Merl, and Hilliard wheat.

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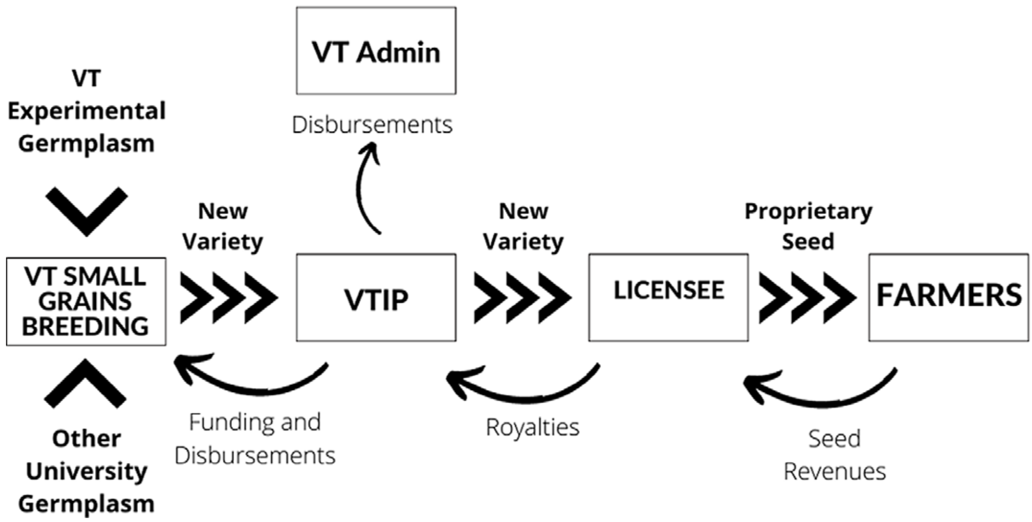

Figure 2. The creation, licensing, and distribution of exclusive varieties created by the Virginia Tech small grains breeding program and the movement of revenues, royalties, and funding from these varieties.

Following Pardey et al. (2004, Pardey et al., 2006), we take proportional yield improvements from research (k) and apply them to the value of total production in Virginia (shown here as the product of commodity price P and total production Q) to assess total benefits (B) from small grains research in a given year t:

$$B_t = k_t P_t Q_t \tag{1}$$

It is assumed that inputs are held constant across varieties in an experimental setting and that differences among varieties in a specific place at a specific time result from varietal differences and differences in environment rather than management. This assumption allows regression of experimental yields on variables reflecting variety, trial location, time, and weather. Experimental yields for observation i of variety j in each year t and test site s are estimated as follows:

$$Y_{ijst} = \alpha_0 + \alpha_j + \beta x_{ijst} + \delta_S + \gamma_t + \phi W_{st} + \varepsilon_{ijst} \tag{2}$$

where Y_{ijst} is the experimental yield in bushels for observation i of variety j at site s in year t; α_j is a variety effect; x is a vector of four possible combinations of tillage and management treatments applied to an observation in a given year;[3] δ_S is a site effect; γ_t is a year effect; W_{st} is an index of weather during the wheat growing season for site s in year t;[4] and ϵ_{ijst} is the model residual. For selected regression results, please see Tables A1 and A2.

Using the parameters estimated in equation (2), we calculate fitted experimental yields (in bushels per acre) for each variety at each site in each year as:

$$\hat{Y}_{jst} = \alpha_0 + \widehat{\alpha_j} + \widehat{\delta_S} + \widehat{\gamma_t} \tag{3}$$

where α_j is the impact of variety selection on yield, δ_S is the impact of site conditions on yield,

[3]Specifically, this variable controls for special management treatments such as pesticide use that were applied to a small proportion of the trials in the data set (0.37% of the barley trials and 5.21% of the wheat trials) as well as use of no-till cultivation methods. Treatments were either recorded as having been applied or not having been applied, and no-till methods were either used or not used, resulting in 4 possible combinations.

[4]Specifically, the effects of weather are included as deviations from trends in average annual temperature and precipitation over time, so holding them at their respective means would give a value of 0.

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and $\widehat{\gamma_t}$ is the impact of growing conditions in each year (after controlling for weather). In equation (3), the effects of management ($\widehat{\beta x}$) and weather variations ($\widehat{\phi_s W_{st}}$) on yield are set equal to zero.[5]

Experimental yield indices are constructed for varieties released by the program (represented here by *J'* to denote a subset of *J,* the set of all varieties enrolled in the field trials) using the fitted yields averaged across all sites for each year combined with the observed area adopted by variety and year as:

$$Y_t^a = \sum_{j=1}^{J'} \sum_s \hat{Y}_{jst} \pi_{jt} \tag{4}$$

where $Y_t{}^a$ represents the experimental yield given current adoption patterns, π_{jt} represents the area of adoption of variety j (including Virginia and other states where the variety is grown) as a proportion of total area A of all wheat/barley varieties released by the program ($\pi_{jt} = \frac{A_{jt}}{A_t}$).[6] In this case, A_t refers the total area planted to varieties released by the VT breeding program, while A_{jt} refers to the area planted to a specific variety j released by the program. Variety-specific yield indices are summed across all varieties to create a weighted average that is proportional to variety acreage in the region and year. Although π_{jt} contains acreage from both inside and outside Virginia, trial data for these varieties are available only from the Virginia trials, so the same fitted yields are used for in- and out-of-state acreage.

The actual-acreage yield index shown in equation (4) is compared to counterfactual yields given adoption patterns of varieties in the base year. This counterfactual represents what yield would be if no new varieties had been released and farmers continued to use only those varieties available in the base year. The counterfactual takes the form

$$Y_t^b = \sum_{j=1}^{J} \sum_s \hat{Y}_{jst} \pi_{jb} \tag{5}$$

The counterfactual is the same as the actual-acreage yield index except that proportional acreage for each variety is determined by acreage planted to the variety in the base year divided by total area in the base period, π_{jb}. Only varieties available in the base year are used to calculate the counterfactual yield index and their proportions of total yields are fixed, while the actual-acreage yield index allows the weights to change as new varieties become available. While yields change over time for the counterfactual yield index, the varieties used and the weights attached to the yield index do not. The counterfactual shows what yields would have been in the absence of improved varieties from the program, while the actual-acreage yield index shows the fitted yields from new varieties released by the program and account for adoption of new varieties over time.

Proportional yield improvements attributable to varietal improvement (k_t) are obtained by comparing actual yield and adoption (in terms of acres planted) to projected yield and adoption rates in the absence of crop improvement research ($k_t = (\frac{Y_t^a - Y_t^b}{Y_t^a})$). We assume that k_t is the same for in-state and out-of-state areas. In reality, different varieties are likely to be better-adapted to some states than they are to Virginia and less well-adapted in others. However, the weighted indices of actual and counterfactual yields include both in-and out-of-state areas, so it is assumed that the yield indices, and thus, k_t are the same for both in-state and out-of-state acreage. This allows for a rough estimate of out-of-state benefits in the absence of trial data for these areas. Because out-of-state acreage is such a large portion of total acreage planted to VT varieties, out-of-state

[5]This holds temperature at their mean values and allows us to estimate the effects of the variety without receiving special management treatments.

[6]Area of adoption is not indexed by site (s) because adoption is determined as a proportion of total area, while the site variable refers specifically to experimental sites rather than parts of Virginia or the study area as a whole.

benefits are an important portion of program benefits, so even a rough estimate of these benefits is important in understanding the scope of the program.

k_t is then combined with estimates of the fitted value of production for acres planted using VT varieties in a given year (Pardey et al., 2004, Pardey et al., 2006) to find total benefits for that year as B_t:

$$B_t = k_t P_t (\sum_{j=1}^{J} (\hat{Y}_{jt} A_{jt})) \tag{6}$$

In equation (6), fitted production of varieties released by the program is substituted for Q in equation (1). Fitted production for a variety is defined as fitted yield for a variety averaged across all sites ($\hat{Y}_{jt}$) multiplied by acreage planted in that variety (A_{jt}).[7] Because the area of each variety grown in the area surrounding each site is not known, fitted yields are averaged evenly across all sites in the field trial data. Fitted production is then summed across all varieties. Because sales by private entities located in Virginia are counted as Virginia acreage and because acreage for exclusive varieties cannot be attributed by state, actual yields and production cannot adequately be disaggregated by location, so fitted yields are used. Although use of fitted yields and fitted production may cause benefits to be biased upwards, it allows for some estimation of benefits, which would not otherwise be possible due to attribution issues.[8]

Finally, total benefits from the program put into are 2018 dollars using the Producer Price Index for grains (U.S. Bureau of Labor Statistics, 2021) and then compounded:

$$\mathrm{PV}(B)_t = \sum_{t=0}^{T} B_t * (1 + r)^t \tag{7}$$

where t runs from 2018 ($t = 0$) to 2000 ($T = 18$). We assume a discount rate (r) of 3% to account for the riskless opportunity cost of research funding. Benefits discussed in the paper are in 2018 dollars.

Because Virginia is a small producer of wheat and barley and VT varieties are small proportions of out-of-state areas, we assume that the program will not impact market prices.

Description of Data

Experimental data are obtained from field trials conducted by VT breeders from 1991 to 2018 (Table 1). These data cover nine test sites across the state and include over a thousand varieties, with more than 20,000 observations for barley trials and 67,000 observations for wheat. Barley yields in the trials averaged 101.56 bushels per acre with a standard deviation of 27.02, while wheat yields averaged 74.95 bushels per acre with a standard deviation of 17.77. Summary statistics of yield and selected other variables are shown in Table 2. Because the trial data available to us did not contain information on crop quality characteristics and because representative data sets containing such information are not publicly available, we assess varietal improvement purely in terms of yield.

Varieties in the trial may be public, private, exclusive, or experimental lines. The data set also identifies public, exclusive, and experimental lines by source. Many lines tested in Virginia are experimental lines from other universities, privately developed germplasm from seed companies, or public varieties from the USDA or other universities (Figure A1). The barley trials include relatively more public germplasm (13.18% of observations) with no exclusive varieties and very few private varieties (0.24%). The wheat trials are more diverse, with observations consisting of 6.32%

[7]Benefits can be calculated using in-state acreage, out-of-state acreage, or the total of both. In the results section, we calculate all three, although we focus primarily on total gross benefits.

[8]For more on acreage data used in this study, please refer to pp. 15-16.

Table 1. Description of variables used in regression and other analysis

Variable	Description
Linecode	Variety or (unreleased) experimental line dummy variable.
No-till	1 if the observation was planted using no-till practices.
Treated	1 if any management treatment such as pesticide or herbicide was applied to the observation
Loccode	Dummy variable denoting trial location.
Year	Year of trial (1991–2018). Included as a factor variable.
VT	Dummy variable where 1 denotes varieties originating at Virginia Tech.
Private	Dummy variable where 1 denotes a variety that was both developed and licensed by the private sector.
Public	Dummy variable where 1 denotes a public variety.
Exclusive	Dummy variable where 1 denotes a variety developed by a university and licensed by the private sector.
Tempdev	Deviations of annual mean temperature from mean of all annual temperatures from 1991 to 2018 for the test location.
Precdev	Deviations of annual mean precipitation from mean of all annual precipitation from 1991 to 2018 for the test location.

Source: Temperature and precipitation data are taken from National Climatic Data Center historical data. All other data are from Virginia Tech wheat and barley field trials.

Table 2. Summary statistics of selected variables[a]

	Mean (barley)	Std Dev (barley)	Mean (wheat)	Std dev (wheat)
Yield	101.506	26.099	74.946	17.767
No-till	0.005	0.070	0.055	0.228
Treated	0.004	0.061	0.052	0.222
VT	0.717	0.451	0.440	0.496
Private	0.002	0.049	0.195	0.396
Public	0.132	0.338	0.063	0.243
Exclusive	0	0	0.053	0.224
N	20,263	–	67,221	–

[a]In this table, yield is presented in bushels. The variables "No-till," "Treated," "VT," "Private," "Public," and "Exclusive" are presented as proportions; for instance, the mean of 0.717 for VT in the barley data set indicates that 71.7% of the trials used VT germplasm.
Source: Virginia Tech wheat and barley field trials.

public, 5.30% exclusive, and 19.53% private germplasm. The remainder consists of experimental germplasm from VT or other universities.

Area planted by year to each variety, shown in Table 3 is estimated for public varieties released by the program since 1990 based on acreage data from 2000 to 2018 and is used to estimate the proportion of total area cultivated in a given variety (π_{jt}). For public varieties, acreage estimates can be separated between Virginia and out-of-state acreage. Acreage data for public varieties are constructed based on royalty receipts by state provided by VCIA, which are used to estimate certified seed sold using the royalty rate per unit of seed. We assume that new certified seed acreage accounts for roughly 60% of total acreage, while saved seed accounts for roughly 40% based on estimates from industry experts (Thomason, 2021c). Public variety royalties paid by seed producers based in Virginia are counted towards Virginia acreage, whereas royalties paid by

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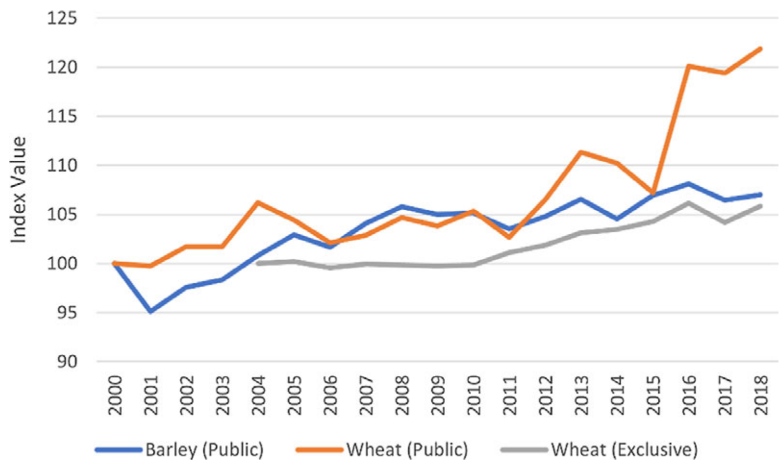

Figure 3. Wheat and barley yield changes from improved varieties (k_t) relative to counterfactual, public and exclusive, 2000–2018. Note: 100 denotes an index value in base year (2000 for public varieties and 2004 for exclusive varieties). Source: Virginia Tech wheat and barley field trial data fitted yields.

universities and crop improvement organizations in other states are counted toward out-of-state acreage. Historical data for wheat and barley production and prices in Virginia (for Virginia acreage) and the United States (for acreage in other states) are used to construct the value of production estimates for each year (National Agricultural Statistics Service, 2020). These value of production estimates are then reported as in-state or out-of-state to allow comparison of the impact of public varieties in Virginia with their impact in other states.

For exclusive varieties, royalty receipts from VTIP are used to estimate acreage using rates per unit as above. However, because licensees for exclusive varieties generally operate in more than one state and royalties are generally paid by one or a small number of multi-state licensees, acreage estimates could not be separated by state for these varieties. Therefore, US prices were used for these varieties.

Exclusive varieties that were omitted from the variety trials were not included in this analysis. Amaze 10, the only exclusive barley variety licensed by VT during the study period, was omitted for this reason, meaning that all exclusive varieties analyzed are wheat varieties. Exclusive varieties were also omitted if royalty rates per unit were unavailable, making it impossible to estimate acres planted in the variety from royalty data. Benefits were estimated for 33 exclusive wheat varieties in total. For Amaze 10 and 13 of the missing wheat varieties, enough royalty data were available to make rough estimates of acreage and yield impacts possible. These estimates are presented in the results section but are not formally considered part of the analysis due to the lack of concrete data. For the remaining 21 exclusive wheat varieties, no royalty data are available. This makes reliable estimation impossible and may also suggest that these 21 varieties were licensed but never actually made it to market.

Weather data were compiled by the National Climatic Data Center (National Climatic Data Center, n.d.). Total precipitation and mean temperature by month during the main wheat and barley seasons in Virginia (October to March) were collected for each trial test site from 1991 to 2018. Data were taken from historical records for the National Weather Service station in the ZIP code nearest to the test site. In cases where the nearest weather station lacked complete records, the closest station with complete records was used. In cases where data from neither of the two closest stations were complete, the more complete station was used as the primary data sources, with the less complete station used to fill in where applicable. Precipitation data were summed, and temperature data were averaged over the growing season. Deviations from a time trend were entered in the regression.

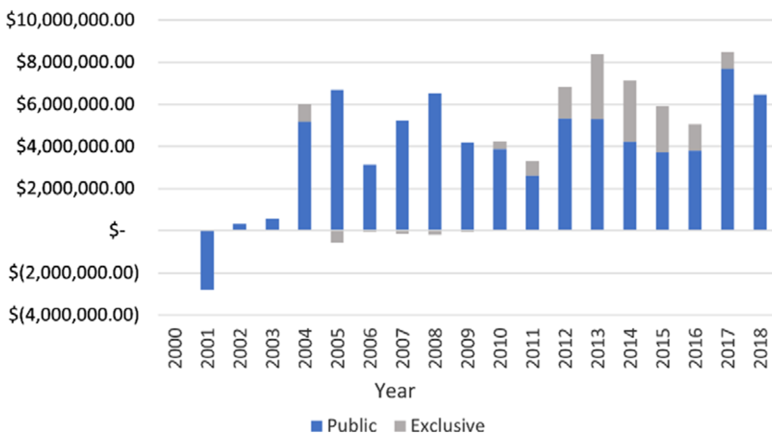

Figure 4. Discounted total program benefits from public and exclusive varieties by year, in 2018 dollars, 2001–2018. Three percent discount rate. Source: Virginia Tech wheat and barley field trial data, Virginia Crop Improvement Association royalty reports, and Virginia Tech Intellectual Properties royalty reports.

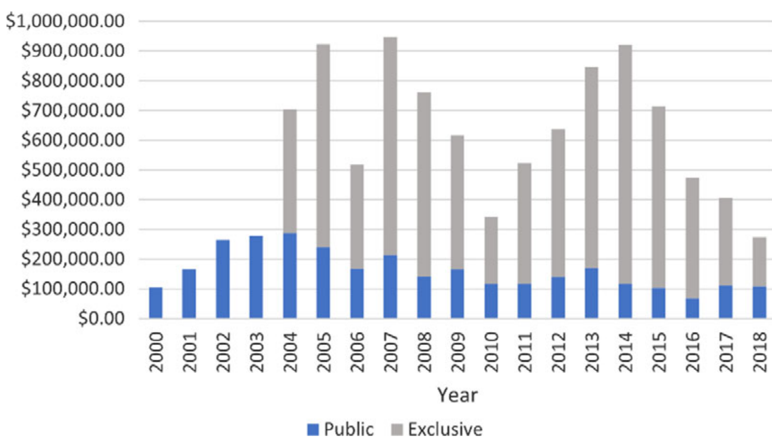

Figure 5. Public and exclusive variety royalty payments by year, 2000–2018. Source: Virginia Crop Improvement Association and Virginia Tech Intellectual Properties royalty reports.

Empirical Procedures

Yield is regressed on variety, year, location, management practices, and weather to provide fitted yields for each variety. Although the regression model was used to calculate fitted yields for both public and exclusive varieties, the actual and counterfactual yield indices (Y_{st}^{a} and Y_{st}^{b}) were calculated separately. This separate calculation preserves the ability to report in- and out-of-state benefits separately for public varieties, where it is possible to separate the two, while disaggregation is impossible for exclusive varieties.

Results

Acreage planted in public wheat and barley varieties released by the program from 2000 to 2018 is shown in Figure A2. Out-of-state acreage is a significant portion of the total for both crops, with out-of-state acreage being particularly dominant in wheat. Acreage planted in exclusive wheat varieties from 2004 to 2018 is shown in Figure A3. Exclusive varieties analyzed here are planted

Table 3. In-state and out-of-state acres planted to public and exclusive varieties developed by VT, 2000–2018

Year	Barley (public)			Wheat (public)			Exclusive
	Acres (VA)	Acres (out of state)	Total acres	Acres (VA)	Acres (out of state)	Total acres	Total acres
2000	102,979	109,301	212,280	159,770	24,573	184,343	–
2001	89,365	87,363	176,728	87,432	162,026	249,458	–
2002	100,408	100,648	201,056	92,129	186,885	279,014	–
2003	107,734	92,986	200,720	43,533	238,964	282,497	–
2004	129,828	91,306	221,134	40,628	220,529	261,157	337,997
2005	129,567	133,266	262,833	41,046	199,536	240,582	555,826
2006	85,128	132,329	217,457	41,242	165,703	206,946	218,337
2007	82,822	133,311	216,133	47,297	189,673	236,970	575,687
2008	126,679	174,900	301,579	14,942	124,664	139,606	472,730
2009	216,742	92,012	308,754	21,843	96,149	117,993	340,563
2010	193,994	101,223	295,217	25,361	53,801	79,162	137,602
2011	170,576	103,618	274,194	34,415	55,865	90,280	213,822
2012	161,878	202,199	364,077	20,698	65,007	85,705	264,323
2013	113,879	131,771	245,650	13,539	65,830	79,369	318,254
2014	130,784	176,399	307,183	11,154	21,343	32,497	389,920
2015	36,948	79,447	116,395	7,125	97,175	104,300	270,166
2016	50,212	82,887	133,099	20,914	28,138	49,052	162,901
2017	63,515	90,692	154,207	64,973	67,245	132,218	117,687
2018	44,849	68,630	113,479	67,520	49,384	116,904	67,588
Total	2,137,887	2,184,288	4,322,175	855,561	2,112,490	2,968,051	4,443,404
Average	112,520	114,963	227,483	45,030	111,184	156,213	296,227

on slightly less acreage (296,000 acres per year on average) than the public varieties (a combined 384,000 acres per year). However, this lower acreage is likely due in part to the lack of acreage or yield information leading to the omission of 34 exclusive wheat varieties and the sole exclusive barley variety produced by the program, as described on p. 14. Rough estimates of acreage were possible for the single exclusive barley variety and 13 exclusive wheat varieties, with a combined average acreage per year of 69,000 acres.

The regression equations described in equation (2) were fitted for both wheat and barley. A post-estimation Breusch-Pagan test on the regressions failed to reject the null hypothesis of homoscedasticity in both cases. Standard errors were clustered by line to correct for potential serial correlation.

The means of the fitted yields generated using this regression were combined with the acreage data to generate actual yields ($Y_{st}{}^{a}$) and counterfactual yields ($Y_{st}{}^{b}$), shown in Table 4. The acreage data are used to weight fitted yields by the variety's proportion of total acreage in each year (π_{jt}). The actual and counterfactual fitted yields for public wheat and barley varieties from 2000 to 2018 are shown in Figure A4.

Public wheat varieties showed a greater relative difference between actual and counterfactual fitted yields than public barley varieties. Thus, public wheat varieties have the highest fitted yield improvements relative to the counterfactual, with improvements of 6.37% per year on average

Table 4. Actual and counterfactual yields for public and exclusive varieties developed by VT, 2000–2018

	Barley (public)		Wheat (public)		Exclusive	
Year	Actual	Counterfactual	Actual	Counterfactual	Actual	Counterfactual
2000	111.41	111.41	78.65	78.65	–	
2001	101.28	106.19	78.66	78.84	–	
2002	104.71	107.24	80.53	79.16	–	
2003	83.94	85.30	61.18	60.11	–	
2004	112.17	111.23	66.38	62.27	69.25	69.25
2005	117.55	114.09	72.52	69.31	76.47	76.30
2006	119.16	117.18	89.62	87.70	94.28	94.69
2007	100.74	96.63	79.08	76.78	83.75	83.77
2008	95.45	89.91	84.33	80.34	87.21	87.33
2009	87.50	83.11	68.52	65.89	72.70	72.87
2010	85.91	81.50	75.90	71.85	78.74	78.83
2011	107.26	103.49	88.34	85.99	94.03	92.97
2012	113.56	108.14	75.65	70.71	79.18	77.70
2013	100.49	93.90	72.35	64.13	73.43	71.11
2014	96.69	92.31	72.21	64.80	74.39	71.79
2015	94.83	88.20	64.56	59.89	69.87	66.88
2016	73.19	67.23	57.02	45.55	56.56	53.07
2017	79.58	74.43	74.98	60.42	71.11	68.13
2018	83.99	78.12	67.49	52.73	64.81	61.00

compared to 3.50% per year for public barley varieties. These improvements are shown in Figure 3.

Exclusive varieties exhibit smaller relative differences between actual and counterfactual fitted yields. As a result, exclusive varieties show smaller average improvements of 1.87% per year (Figure A2). There is little difference in exclusive actual and counterfactual fitted yields until 2012, and the difference between the two remains relatively small at the end of the study period. The difference between actual and counterfactual fitted yields may be smaller for exclusive varieties because the latter are marketed for shorter periods, reducing disease and pest adaptation. This is good news for the exclusive variety portfolio as a whole because the reduced pest and disease pressures keep yields more stable, but it also reduces the importance of individual new releases among exclusive varieties, whereas individual new public variety releases are very important due to the increased time they stay on the market.

Yield improvements over the counterfactual for public and exclusive varieties over the study period are shown in Figure A3. These yield differences can be thought of as representations of the relative differences between the actual and counterfactual yield lines from Figures A1 and A2. These yield improvements do not mean that yields are rising in absolute terms; in fact, all of the varieties studied ended the study with lower yields than they started with. However, many factors impact crop yields from year to year, including weather, pests, and diseases. Improvements relative to the counterfactual represent an improved ability of plants to resist these negative pressures, thereby avoiding even lower yields occurring without varietal improvement.

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Gross benefits from public varieties produced by the VT program, in terms of new production attributable to research conducted by the program, are shown in Figure A6. Discounted gross benefits from public varieties totaled nearly $78 million from 2000 to 2018, with discounted average annual gross benefits of more than $4.3 million. Benefits to other states were an important part of the benefits from public varieties, with total out-of-state gross benefits being over twice the size of in-state gross benefits. This difference in benefits is primarily due to the higher out-of-state than in-state acreage for these varieties, but lower wheat and barley prices in Virginia also play a role, as average US wheat and barley prices were used to estimate benefits for production outside Virginia.

The benefits described here are described as gross benefits because they do not involve explicit estimations of adoption costs for farmers. Because the counterfactual used to calculate improvements in yield assumes that farmers are using older public and exclusive varieties and that they do not switch from public to exclusive varieties or vice versa, costs would likely be similar, although this is not certain. It is also assumed that farmers would save seed at similar rates in the counterfactual and actual scenarios. Additionally, direct costs to farmers of seed purchases were not available and could not be estimated based on royalty payments, as flat royalty payments were paid to VT on a negotiated per-unit basis, so they did not account for changes in the purchase price of seeds for varieties developed at VT. Because royalty data were unavailable for some jointly released varieties, out-of-state gross benefits estimated here reflect a lower bound.

Total gross benefits to farmers from new production attributable to exclusive wheat varieties released by VT from 2004 to 2018 were also calculated. Gross benefits to farmers from exclusive wheat varieties, shown in Figure A7, were nearly $12 million from 2004 to 2018, in 2018 dollars. These benefits are dramatically lower than those for public varieties, due to several factors. First, the yield improvements relative to the counterfactual are much smaller for exclusive varieties compared to public varieties. Second, the exclusive varieties studied here occupy less acreage than the public varieties (taken together). Finally, due to a lack of yield and acreage information, 35 of the 68 exclusive wheat and barley varieties released during the study period were omitted from the analysis. Consequently, gross benefits to farmers from the program's exclusive releases are likely to be higher than what is captured here. Using acreage data estimated from program royalty records and assuming similar yields and rates of yield gain to the exclusive varieties for which field trial data are available, the dollar value of this omission is estimated at roughly $5.1 million. Thus, while the omitted varieties account for a significant portion of the total gross benefits from exclusive varieties, they account for a relatively small portion of total program gross benefits.

Total discounted gross benefits from public and exclusive varieties studied here are shown in Figure 4. Gross benefits to farmers over the study period total nearly $90 million. Most of these benefits are from public varieties, with gross benefits averaging $4.3 million per year, while gross benefits from exclusive varieties total nearly $800,000 per year. More detailed breakdowns of discounted gross benefits for public and exclusive varieties can be found in Figures A6 and A7.

When it comes to royalties, however, exclusive varieties have a clear advantage. Total royalties from the program, shown in Figure 5, are $10.4 million. Despite covering less time, exclusive varieties account for the lion's share of royalties collected ($7.3 million).[9] Although private varieties account for a larger share of gross benefits to farmers, exclusive varieties provide the financial support that is necessary to keep the program thriving.

Estimates of Costs and Net Benefits

When discussing the benefits of agricultural research and other similar programs, it is common to calculate the costs associated with the program and the resulting net benefits. In this case, exact cost figures were not available, as many of the program's activities are not separable from other

[9]Because fitted yields and per-unit royalty rates are not needed to calculate aggregate royalties, this estimate reflects all exclusive varieties for which royalty data are available, not just those for which benefits to farmers were calculated.

activities, including the Virginia Agricultural Experiment Station system, seed certification, producer organizations, and extension activities. This makes it impossible to calculate the costs and net benefits of the program. However, it is possible to give a rough estimate of program costs.

Although it is difficult to estimate the total program costs, the number of breeders and other staff directly engaged in the program can be estimated fairly easily. The number of breeder full-time equivalents (FTEs) over time is estimated to be roughly three at any given time between full faculty, postdoctoral research staff, and other program staff (Thomason, 2021a). Thus, we can estimate a discounted annual benefit of roughly \$1.67 million per breeder FTE. It is also possible to roughly estimate operating costs and net benefits based on assumptions presented in Shelton and Tracy (2017). Of the breeders surveyed by Shelton and Tracy, only 13.4% ran programs with an operating budget of over \$500,000 per year, and 61.6% of programs had operating budgets of \$199,000 or less per year. Because the VT small grains breeding program is fairly large, but not enormous, an annual operating budget of \$500,000 should be a reasonably conservative upper bound of costs. Combined with an assumed salary of \$100,000 per year per breeder FTE, the upper bound of total annual costs for the program would be \$800,000 per year. This results in an estimated annual net benefit of \$4.2 million for the program, and annual net benefits of \$1.4 million per breeder FTE.

Conclusions

The VT small grains breeding program is an example of what can be achieved by university plant breeding programs. New production from public and exclusive varieties released by the program yields substantial benefits. The role of privately marketed exclusive varieties, the presence of non-VT germplasm in the trials, the release of jointly developed varieties with other states, and the role of benefits from VT varieties to other states all suggest that collaboration is an important feature of university breeding programs. As seen here, collaboration can provide additional funding (via royalty revenues), marketing support, and the genetic material needed for program success. On a societal level, this collaboration helps universities fill a role that the private sector has a limited incentive to fill. Because private companies are unlikely to share germplasm, they are unlikely to realize the genetic gains that can result from such cooperation, nor are they likely to host broad trials with varieties from all sources to compare performance head-to-head for the benefit of farmers.

The small grains breeding program at VT has generated significant economic benefits from improved crop varieties. Universities are well positioned to share the benefits of their work among institutions and states, and the VT program illustrates that universities can generate substantial gains for farmers by working with the public and private sectors.

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Conflict of interest. The authors declare none.

Data availability statement. All data and code used in this study are available from the corresponding author by request.

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Appendix

Table A1. Regression results from Virginia Tech wheat field trials, 1991–2018, selected variables[a]

Yield	Coefficient	Standard Error
No-till	−2.4576***	0.362
Treated	−7.7376***	0.403
Loccode		
Blacksburg	–	–
Blackstone	−16.7062***	0.423
Holland	−21.4076***	0.439
Loudon	−15.5277***	0.604
Orange	−3.2753***	0.334
Painter	−9.6221***	0.452
Shenandoah	−12.9404***	0.567
Warsaw	−3.4065***	0.352
Tempdev	−1.8789***	0.180
Precdev	-.3776***	0.197
Intercept	91.2641	
R^2	0.4790	
N	64,312	

***Linecode and year variables were oadmitted due to space constraints. While these variables were a key part of the regression, there were 28 year variables and hundreds of linecode variables in each regression, so it was not possible to represent each of these variables here.
Source: Virginia Tech wheat and barley field trials

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Table A2. Regression results from Virginia Tech barley field trials, 1991–2018, selected variables[a]

Yield	Coefficient	Standard Error
No-till	−8.8370***	2.419
Treated	24.6459***	2.540
Loccode		
Blacksburg	–	–
Blackstone	−23.8962***	1.386
Holland	−27.3613***	1.409
Orange	−13.2736***	1.080
Painter	−17.8897***	1.423
Warsaw	4.4210***	0.965
Tempdev	−3.3976***	0.499
Precdev	−1.9514***	0.373
Intercept	123.1445	
R^2	0.4748	
N	18,848	

***Linecode and year variables were omitted due to space constraints. While these variables were a key part of the regression, there were 28 year variables and hundreds of linecode variables in each regression, so it was not possible to represent each of these variables here.
Source: Virginia Tech wheat and barley field trials.

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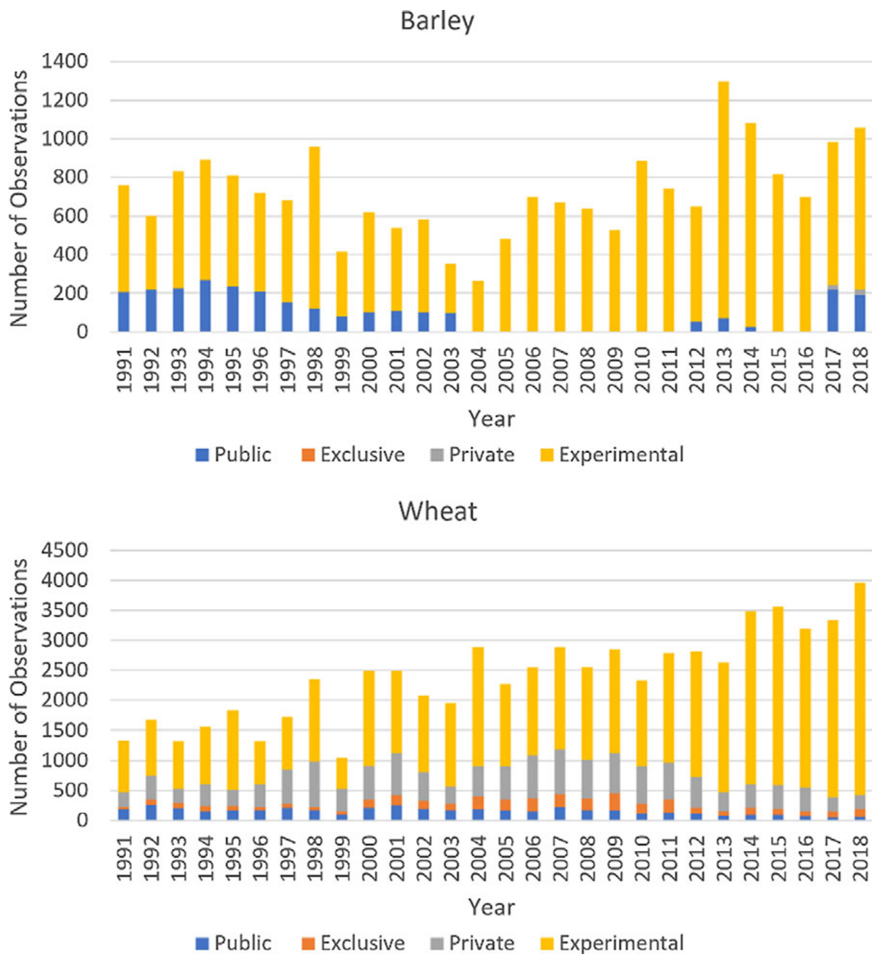

Figure A1. Distribution of germplasm used in wheat and barley field trials conducted by the Virginia Tech breeding program in Virginia, by origin and year. Source: Virginia Tech wheat and barley field trial data.

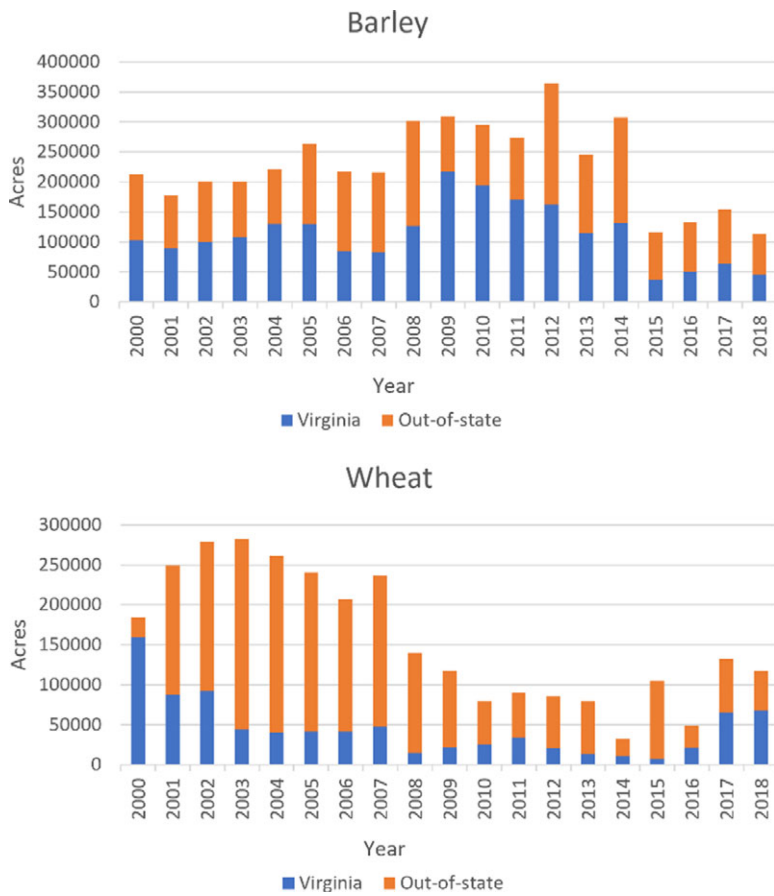

Figure A2. Acres of public wheat and barley varieties planted in Virginia and out-of-state, 2000–2018. Source: Virginia Crop Improvement Association and Virginia Tech Intellectual Properties royalty reports.

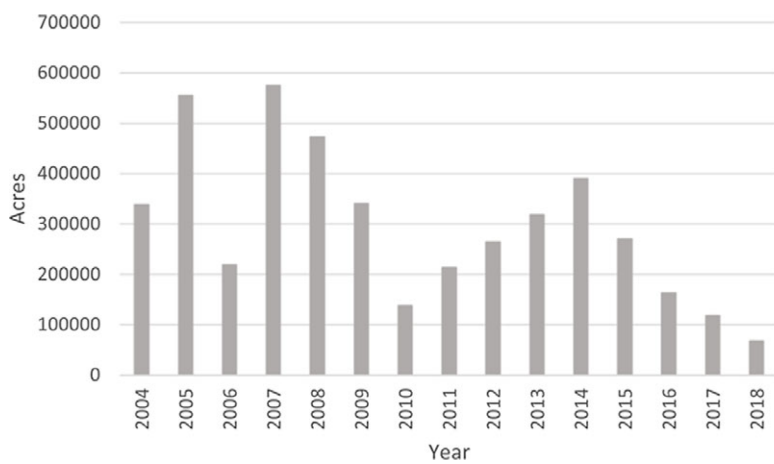

Figure A3. Acres planted in Virginia and elsewhere of exclusive wheat varieties, 2004–2018. Source: Virginia Crop Improvement Association and Virginia Tech Intellectual Properties royalty reports.

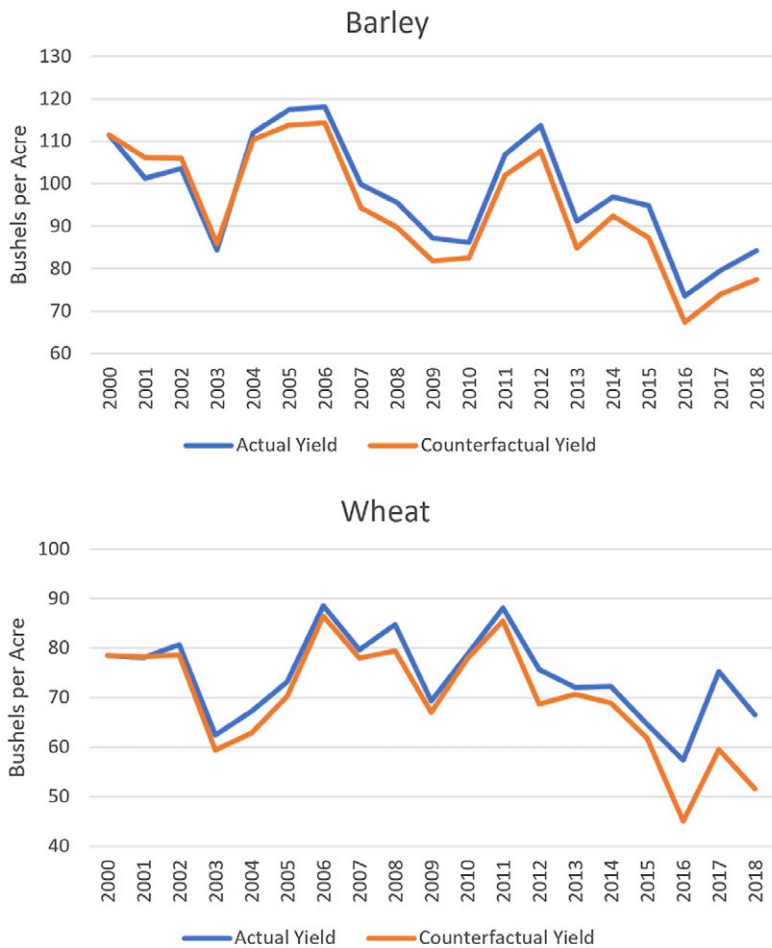

Figure A4. Actual and counterfactual yields by year for public wheat and barley varieties, 2000–2018. Source: Virginia Tech wheat and barley field trial data fitted yields.

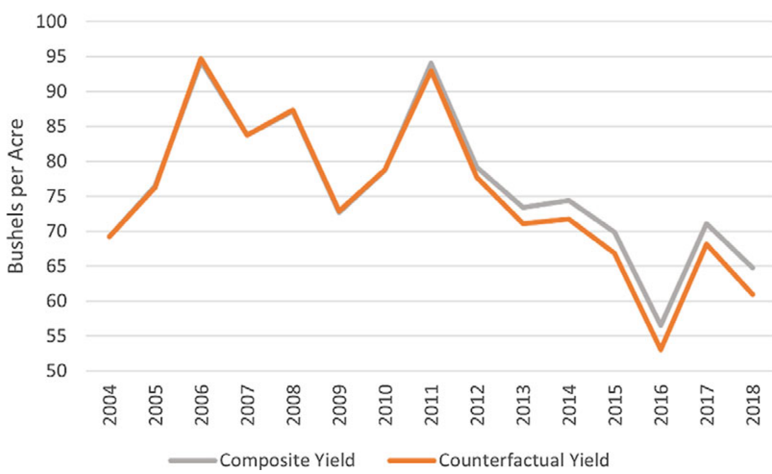

Figure A5. Actual and counterfactual yields by year for exclusive wheat varieties, 2004–2018. Source: Virginia Tech wheat and barley field trial data fitted yields.

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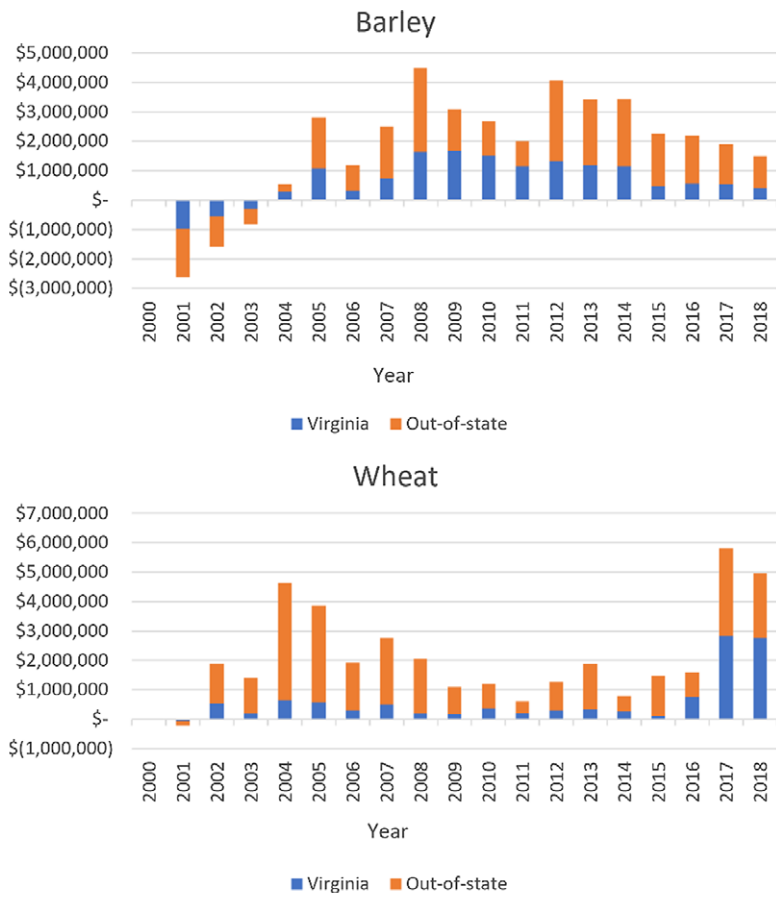

Figure A6. Discounted value of public wheat and barley variety production attributable to VT research by location and year, in 2018 dollars, 2000–2018. Three percent discount rate. Source: Virginia Tech wheat and barley field trial data, Virginia Crop Improvement Association royalty reports, and Virginia Tech Intellectual Properties royalty reports.

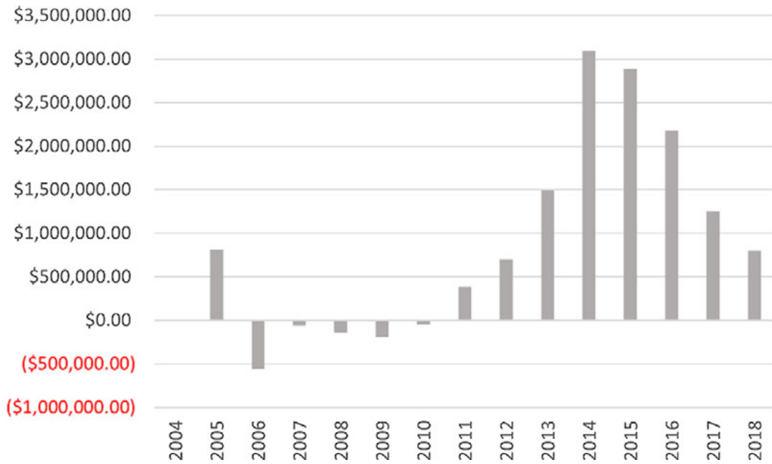

Figure A7. Discounted value of exclusive wheat variety production attributable to VT research by location and year, in 2018 dollars, 2004–2018. Three percent discount rate. Source: Virginia Tech wheat and barley field trial data, Virginia Crop Improvement Association royalty reports, and Virginia Tech Intellectual Properties royalty reports.

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