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IMPACT OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTION DECISIONS

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ABSTRACT

We analyze the optimal production and inventory assortment decisions of a seed manufacturer facing increased yield variability triggered by extreme weather conditions in addition to long supply lead times as well as supply and demand uncertainty. We also investigate the limits of operational flexibility in the form of postponement using simulation models that are calibrated through field data. Our analysis shows that a minor increase in future yield variability leads to a large increase in the optimal seed production quantities. Such a rise would not only significantly increase the seed manufacturer's working capital requirements, but may also make its current supply capacity inadequate to fulfill its optimal production plans. We also show that the value of postponement decreases with higher yield variability, which also renders low-margin seeds more susceptible to this volatility.

1 INTRODUCTION

A key stakeholder in ensuring the availability of an adequate food supply for the nine billion people projected to inhabit planet Earth by 2050, the commercial seed industry faces long production lead times, demand and yield uncertainty, rapid product portfolio renewal, and changing environmental conditions. Moreover, the industry is facing growing operational challenges related to climate change (Singh et al. 2013), which triggers extreme weather conditions, posing a significant risk to crop yields and thus to the overall security of food supply (Wheeler and Von Braun 2013; Iizumi and Ramankutty 2016).

Climate change is a term used to capture the collective impact of increasing temperatures over land and sea, increased heat content in the oceans, increased water vapor in the atmosphere, receding glaciers and snow caps, thinning sea ice, and rising sea levels. Climate change induces many types of stress on agricultural production. The most visible stress is the non-negligible increase in temperature. However, higher temperatures are also accompanied by other stressors such as increased CO_2 levels, changes in the precipitation patterns, high nighttime temperatures, as well as infestations by weeds, diseases, and pests.

While temperatures are projected to increase by 2 to 4 degrees over the next few decades, plant response to climate change, which is dictated by complex interactions among CO_2, temperature, solar radiation, and precipitation, is highly unpredictable, resulting in an *immediate* increase in the volatility of crop yields. For instance, while higher concentrations of CO_2 may benefit plant growth rates, CO_2 also boosts weed growth, adding to the potential for increased competition for nutrients in the soil between crops and weeds. In the United States, weeds are the largest cause of crop loss (34%), followed by insects (18%), and diseases (16%). Higher nighttime temperatures not only boost the growth of insect populations and incidence of pathogens, they also increase the rate of grain filling and decrease the length of the grain-filling period, resulting in reduced grain yields.

Higher temperatures also lead to more frequent extreme weather events. An analysis of rainfall patterns across Iowa has shown that there has not been an increase in total annual precipitation; however, there has been an increase in the number of days with heavy rainfall. Heavy rain not only results in serious erosion of the soil (and the loss of nutrients) through runoff, but it also can delay planting and create problems in obtaining a good stand of plants, both of which may reduce crop productivity. Heavy runoffs coupled with higher temperatures also reduce the moisture content of the soil, further hampering plant growth.

In summary, a growing body of literature indicates that increased variability in local weather conditions and increased incidence of unpredictable extreme weather events are grave threats to crop yields and, in particular, to the commercial seed industry (Tigchelaar et al. 2018; Nelson et al. 2009; Jaggard et al. 2010). More specifically, Tigchelaar et al. (2018) project that a warming of 2 (4) degrees Celsius would increase the coefficient of variation of corn yield by 110% (315%) in countries that collectively account for 73% of global production and 93% of total exports. In light of this growing yield variability driven by climate change, the seed manufacturer is investing significant resources to examine and mitigate the negative impacts of volatile weather conditions in its seed production operations.

Climate change adds another layer of complexity for seed manufacturers that already operate in a complex setting with long production lead times, demand uncertainties, and continuous product portfolio renewal. To cope with these challenges, one of the key capabilities that seed manufacturers are trying to develop is to increase the accuracy of demand forecasts, which would enable them to obtain better visibility into demand before making allocation decisions of the available yield (supply) into various stock-keeping units (SKUs). Considering the operational impact, this practice can be thought of as a strategic substitute of delaying (or postponing) product differentiation until a better understanding of demand has been acquired. Therefore, we refer to this as the *postponement strategy*. While this capability is well developed in other industries (e.g., Hewlett-Packard in consumer electronics and Benetton in apparel), postponement has not received much attention in agri-business due to myopic cost accounting practices or incentive misalignments between sales and operations teams. On the other hand, we observe that the seed industry allocates a considerable amount of resources to data analytics teams to improve demand forecasts that would facilitate the deployment of the postponement strategy.

Operational flexibility, especially postponement, can help mitigate some of the risk associated with yield and demand variability. The main focus of our work is, therefore, on quantifying the value of operational flexibility – in particular, in the face of increasing yield volatility triggered by climate change in the operating environment.

The remainder of the paper is organized as follows. Section 2 describes the key challenges in seed production. A very brief literature review is provided in Section 3. A two-stage stochastic program is formulated to determine the optimal production and allocation quantities. These quantities are used in driving the simulation study in Section 5. Section 6 offers concluding comments.

2 KEY CHALLENGES IN SEED MULTIPLICATION

To illustrate the key challenges in the corn seed supply chain, a complete sales cycle is depicted in Figure 1. Typically, between December and March, the seed manufacturer forecasts the demand for corn seeds in the next selling season, which corresponds in the Northern Hemisphere to the December–May period of the following year. Most seed manufacturers are not land owners. As a result, after they grow parent seeds (seeds that are cross-pollinated to produce a hybrid), independent farmers are contracted to "multiply" these seeds on behalf of the manufacturer. The contracts with farmers (seed growers) need to be finalized by early April, the start of the planting season for corn. Although the manufacturer outsources seed multiplication to farmers, seed planting is carefully monitored to ensure the purity of a given variety. Corn is harvested by early October and shipped to the processing plants of the manufacturer. The harvest arrives at processing plants as yellow corn to be processed and allocated to end products (SKUs) as commercial seed for different markets based on forecast information.

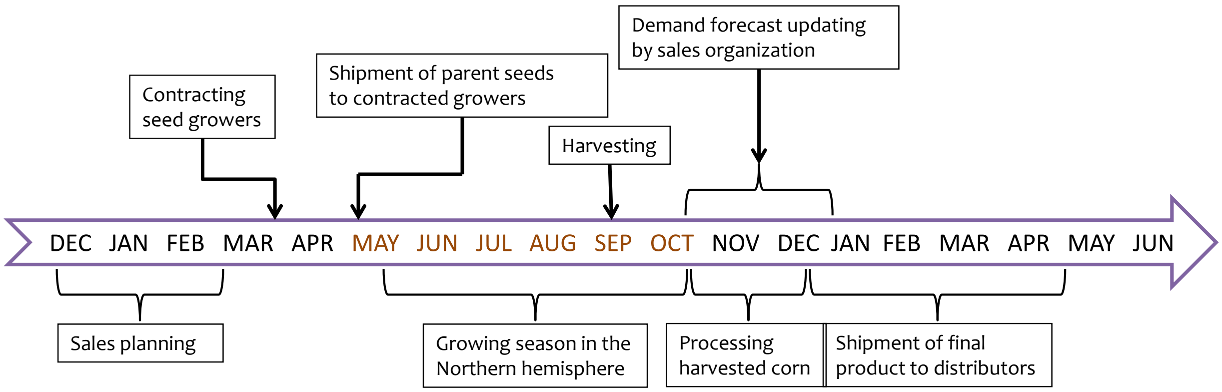

Figure 1: Sequence of events in a typical sales cycle in the Northern Hemisphere.

Prior to the selling season, the demand forecast for each SKU is updated monthly by the sales organization from September to February with increasing accuracy. Therefore, Production planning needs to be carried out in this uncertain setting; in particular, as shipments to distributors start in December, the seed manufacturer immediately starts utilizing its limited capacity to process the incoming crop in spite of significant demand uncertainty. There are multiple operational constraints that make matching supply with demand in seed production challenging. We discuss these constraints below.

- Demand and yield are variable; moreover, demand forecasts are usually unreliable, while the physical availability of the product at the beginning of the planting season is mandatory as most of the sales to farmers are realized within the first few weeks of the season.
- The number of SKUs is large. In a typical season, the manufacturer offers multiple seed varieties, different chemical treatments for each variety, and various packaging formats for each variety-treatment combination. Throughout the paper, we will refer to seeds prior to chemical treatment and packaging operations as *hybrid seeds*, whereas we will refer to seeds after treatment and packaging operations as *commercial seeds*. As a consequence, a single hybrid seed may lead to thirty different commercial seeds (SKUs), resulting in a portfolio of more than a thousand different end products to be sold in different markets.
- SKU life cycle is short. Due to continuous development of superior seeds, less than 30 percent of the seeds remain in the market for more than two consecutive years.
- The cost of inventory replenishment during the selling season is prohibitively high. Unlike for many other products, replenishment of corn seeds once the selling season gets under way is not cost effective.

3 A BRIEF REVIEW OF LITERATURE

Our research is mainly anchored in the literature on operations with random yield and on capacity allocation decisions. There is a vast body of literature on operations with random yield. Yano and Lee (1995) present a comprehensive review of tactical solutions for managing random yield. To the best of our knowledge, Karlin (1958) is the first author to develop a model of inventory and production policies under random yield for agricultural production.

Our paper is also related to the literature on optimal capacity allocation decisions. When demand for various products is random while there is limited production capacity. Cachon and Lariviere (1999) focus on strategic behavior in a supply chain setting where a single supplier serves multiple retailers. In corn seed production, Papier (2016) studies the problem of allocating a limited supply of corn seeds to different markets under advanced demand information.

We extend these streams of research by including random supply (the hybrid seed production quantity) as a decision variable in a two-period setting; one of the key contributions of our work is the demonstration of how the postponement strategies impact the allocation decisions rather than creating a new allocation methodology. Moreover, to the best of our knowledge, we are the first to model climate change in an operational setting.

4 THE MODEL FORMULATION

Consider a seed manufacturer producing a single hybrid seed who, as a profit maximizer, decides on the quantity of hybrid seeds to produce and on the proportion of the resulting yield to allocate into commercial seeds. We focus on a specific variety of hybrid seed; hence, x_t will denote the "production" or "planting" quantity of a hybrid seed in period t, while $q_{t,i}$ will denote the "allocation" quantity to commercial seed i in period t. The notation, whereby capital letters denote random variables and small letters denote their realizations, is recapped as follows:.

x_t: Production quantity of hybrid seed in period t
$q_{t,i}$: Allocation quantity in period t for commercial seed i
$q_{t,0}$: Carry-over quantity of hybrid seed in period t
$y_{t,i}$: Inventory level at the beginning of period t for commercial seed i
$D_{t,i}$: Demand in period t of commercial seed i
V_t: Yield rate of hybrid seed in period t
r: Revenue from selling one unit of commercial seed
c: Cost of producing one unit of hybrid seed
h: Per-unit inventory holding cost of commercial seed
p: Penalty cost per unit of unmet demand for commercial seed

Due to frequent introduction of higher-performance hybrid seeds, we observe that 70% of the SKUs manufactured by our industrial partner are sold over at most two selling seasons. In addition, since seeds are living organisms, their germination rates deteriorate significantly after two years. Therefore, we consider a manufacturer selling N commercial seeds over two periods. Each period represents a selling season and consists of two stages. In the first stage of period t, the manufacturer decides on x_t, the production quantity of the hybrid seed, whereas in the second stage, once the yield is realized ($v_t x_t$ is observed), the manufacturer decides on $\mathbf{q}_t = (q_{t,0}, q_{t,1}, q_{t,2}, \ldots, q_{t,N})$, where $q_{t,0}$ denotes the carry-over inventory of the undifferentiated hybrid seed and $q_{t,i}$ represents the quantity allocated to commercial seed i, for $i \in \{1,2,\ldots,N\}$ and $t \in \{1,2\}$, respectively. As such, the planner solves a two-stage stochastic program in each period. We denote the inventory available at the beginning of period t by $\mathbf{y}_t = (y_{t,0}, y_{t,1}, y_{t,2}, \ldots, y_{t,N})$ where the starting inventory in the first period is equal to zero. At the end of the planning horizon, all leftover inventory is discarded, free of charge. In practice, this represents the replacement of an old variety of hybrid seed with a new one in the manufacturer's product portfolio.

We, therefore, derive the optimal production and allocation policy for a two-period problem. To this end, the manufacturer's production and allocation problem is modeled as a two-period dynamic problem where each period consists of a two-stage stochastic optimization problem. The timeline of events is depicted in Figure 2. The first period's optimization problem can be formulated as:

$$J_1(y_1 = 0) = rE\left[\sum_{i=1}^{N} D_{1,i}\right] - \underset{x_1 \geq 0}{\text{minimize}}\ E_{V_1}\left[\pi_1(x_1, V_1) + cV_1x_1\right], \quad \text{where}$$

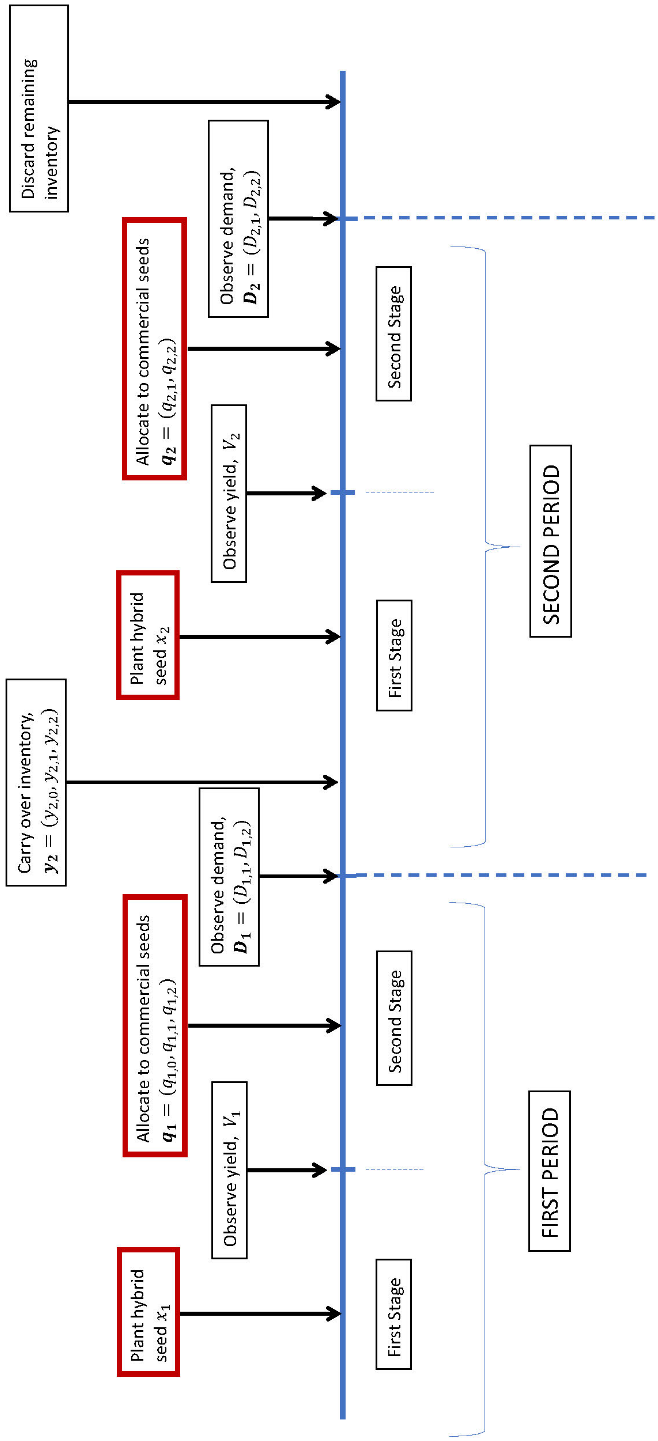

Figure 2: The two-period problem of hybrid seed production and commercial seed allocation.

$$\begin{aligned}\pi_1(x_1,V_1) = \underset{q_1\geq 0}{\text{minimize}} \quad & E_{D_1}\left[\sum_{i=1}^{N}(r+p)(D_{1,i}-q_{1,i})^+ + h(q_{1,i}-D_{1,i})^+ + hq_{1,0} - J_2(y_2)\right] \\ \text{subject to} \quad & \sum_{i=0}^{N} q_{1,i} = v_1 x_1,\end{aligned} \tag{1}$$

and the second-period problem is written as:

$$J_2(y_2) = E\left[\sum_{i=1}^{N} D_{2,i}r + h(y_{2,i}-D_{2,i})^+\right] - \underset{x_2\geq 0}{\text{minimize}}\ E_{V_2}\Big[\pi_2(x_2,V_2)+cV_2x_2\Big], \quad \text{where}$$

$$\begin{aligned}\pi_2(x_2,V_2) = \underset{q_2\geq 0}{\text{minimize}} \quad & E_{D_2}\big[\sum_{i=1}^{N}(r+p)(D_{2,i}-y_{2,i}-q_{2,i})^+ + h(-D_{2,i}+y_{2,i}+q_{2,i})^+\big] \\ \text{subject to} \quad & \sum_{i=1}^{N} q_{2,i} = v_2x_2 + y_{2,0}.\end{aligned} \tag{2}$$

Modeling the seed manufacturer's decision as a two-period problem also helps us to derive tractable solutions while preserving a rich enough setting that enables us to analyze the impact of climate change and operational improvements. However, instead of pursuing analytical results further, we will present some key observations from our simulation study in the next section. Note that the optimal production and allocation quantities determined through the two-stage stochastic program in (1) and (2) are used to drive the simulation experiments. All simulations have been implemented in *R* along with the *JuliaPro* optimization suite.

5 THE SIMULATION STUDY

We leverage industry data to conduct a simulation study for quantifying the impact of increased yield variability on the seed manufacturer's decisions and profits as well as on the value of postponement in mitigating this impact. In addition, we investigate how the manufacturer's decisions and the value of postponement change when commercial seeds have different profit margins.

We use a sample average approximation to numerically solve the two-period stochastic optimization problem with four stages. Kim et al. (2015) provide an overview of sample average approximation. The parameter values used in the experiments are depicted in Table 1. We have estimated the cost parameters from the USDA website and price parameters from the Brazilian commodity market database, Companhia Nacional de Abastecimiento (2018). These values, which are calibrated with our industrial partner, reflect the magnitude of various cost drivers. For example, while the holding cost is largely driven by the opportunity cost of capital, the production cost, which consists of the costs of field production (multiplication) and seed processing (differentiation), is dominated by the cost of multiplication. The revenue, on the other hand, is estimated through leading indicators, including commodity prices, the multiplication fee paid to the growers, and an index that tracks the stock market. Following Tigchelaar et al. (2018) and considering the reported coefficient of variation from Alizamir et al. (2018), we take the yield as normally distributed and the coefficient of variation in the first period as 0.1. We also use demand data from the European market to estimate the demand parameters.

Observation 1: Our numerical study shows that the increase in the optimal first-period production quantity as a function of the second-period yield variability is non-linear. There exists a threshold level for the coefficient of variation of the second-period yield below which the optimal hybrid seed production policy shows a steep non-linear increase.

Table 1: Summary of the parameter values.

Parameters	**Values(in Euros per 50-kg bag)**
Revenue (r)	335.40
Holding Cost (h)	20.70
Production Cost (c)	129.60
Penalty Cost (p)	268.30

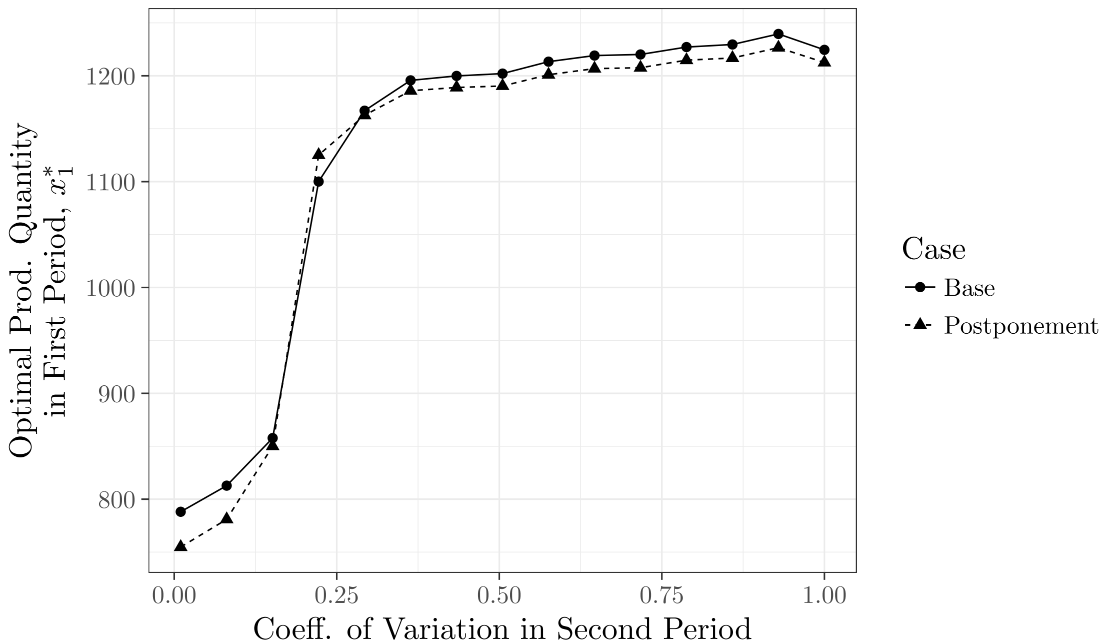

Figure 3: Change in the optimal first-period hybrid seed production quantities with increasing values of the coefficient of variation of the second-period yield.

As reflected in Figures 3 and 4, an increase in future yield variability encourages the manufacturer to produce more in the first period where the increase is convex if the coefficient of variation of the second-period yield is sufficiently low. As the yield variability in the second period increases, the value of the carry-over inventory increases; once the second-period yield volatility reaches a critical threshold, the value of the carry-over inventory (in spite of the holding cost) surpasses the value of risky production in the second period. As a result, the optimal first-period production quantity shows a sharp increase while the optimal second-period production quantity plummets. More specifically, in our numerical study, a slight increase in the coefficient of variation (from 0.1 to 0.2) resulted in a 37% jump in the optimal production quantity.

Based on the data from the US Department of Agriculture, Alizamir et al. (2018) report that the yield of key crops show the following variation (in terms of coefficient of variation) over a ten-year horizon: corn: 0.089; soybean: 0.065; barley: 0.072; oats: 0.065; rice: 0.045. We, therefore, observe that, for most crops, the current yield variability is on the verge of reaching the critical threshold. As a result, the optimal policy switches from a myopic policy where the manufacturer produces each period for that period only to a one-period look-ahead policy where the manufacturer produces in the first period for both periods. One should note that such an increase in the optimal production quantity in the first period is not necessarily good news as it places a higher financial burden on the manufacturer by significantly increasing capital investment for higher production capacity and working capital requirements for larger carry-over inventory.

Unfortunately, the outlook is bleaker for developing countries. According to a recent study, higher variation in temperatures – hence, more severe consequences of climate change – is expected to result in even higher yield variability in poorer countries (Bathiany et al. 2018).

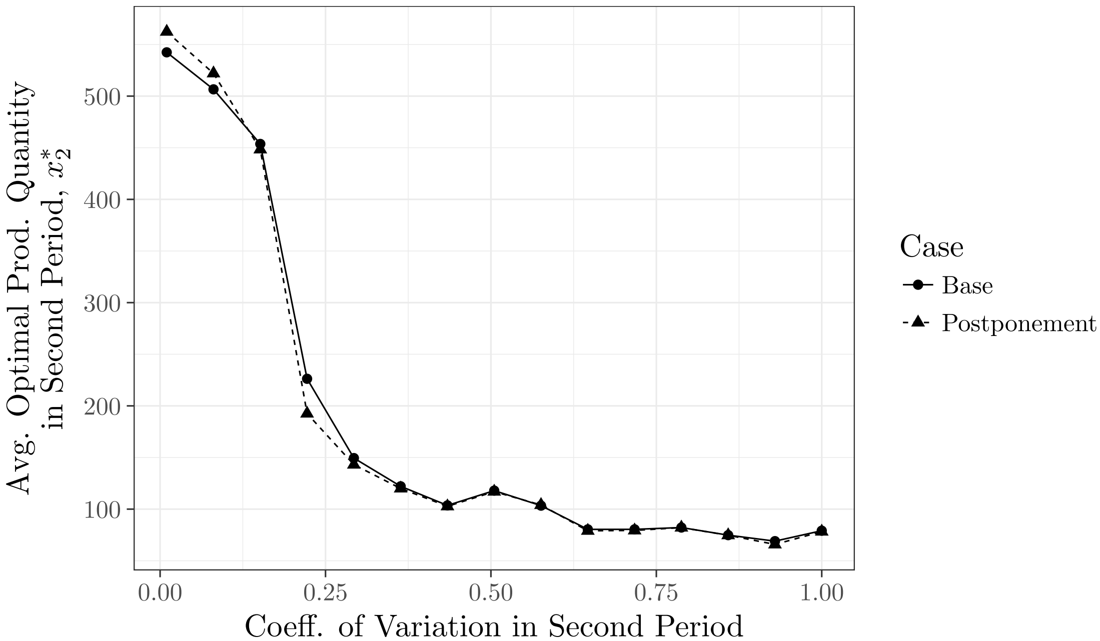

Figure 4: Change in the optimal second-period hybrid seed production quantities with increasing values of the coefficient of variation of the second-period yield.

Observation 2: Although the value of postponement increases with demand uncertainty, it decreases with yield uncertainty in the second period.

Our simulations indicate that, on average, postponement increases profits by 3%. Simulation results show that the optimal hybrid seed production quantity under postponement is lower than that of the no-postponement case. This implies that in the presence of postponement, the demand pooling effect dominates the overage reduction effect. The value of postponement not only decreases as the coefficient of variation of the second-period yield increases (see Figure 5), but also differs from the first period to the second period. Specifically, the expected profit difference between the postponement case and the no-postponement case increases in the first period and decreases in the second period. The difference between the expected total profits also seems to decline as the second-period yield variability increases (see Figure 6). This suggests that increased yield variability hinders the effectiveness of postponement in mitigating demand variability. Thus, classical operational improvement initiatives provide only limited benefit in agri-business that faces increasing climate volatility. As a result, seed manufacturers are encouraged to spend their limited resources in developing more robust seeds that are resistant to wildly varying weather conditions.

We also examine the impact of increased yield variability caused by climate change on commercial seed sales quantities under a broader portfolio consisting of seeds with different contribution margins. To this end, we consider three types of commercial seeds with low, medium, and high profit margins. We observe that, in the no-postponement case, low-margin seeds receive lower allocation quantities: in particular, while the low-margin commercial seed receives an allocation quantity corresponding to the 0.63^{rd} fractile of the demand, the allocation increases up to the 0.94^{th} fractile of the demand for the high-margin commercial seed. As the variability of the yield in the second period increases, we see that the optimal production and allocation quantities of the commercial seeds in the first period increase (to the 0.69^{th} fractile and the

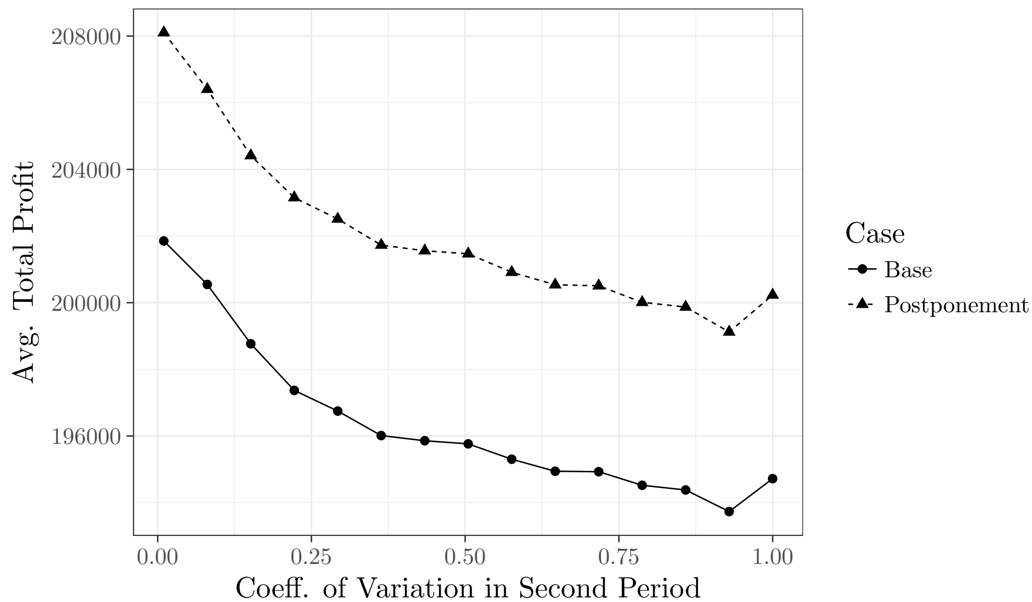

Figure 5: Expected profits under various values for the coefficient of variation of the second-period yield.

0.97^{th} fractile for low-margin and high-margin seeds, respectively). This, in turn can translate into lower availability for lower-margin commercial seeds, turning them into *orphans*.

Observation 3: Postponement not only reduces the fill rate for low-margin seeds, but also makes them more vulnerable in case of insufficient yield (supply) due to extreme weather conditions triggered by climate change.

Consistent with the literature, we use the demand fill rate as a measure to assess the performance of the two cases. In particular, the change in the fill rate as a function of yield variability reveals the robustness of the particular case. When the coefficient of variation of the second-period yield is low, postponement increases the fill rate for high-margin commercial seeds by 2.4% while decreasing the fill rate by 2.3% for low-margin seeds when compared to the no-postponement case. When the coefficient of variation of the second-period yield increases, postponement gives even a higher priority in allocation to high-margin commercial seeds. As a result, postponement increases the fill rate for the high-margin commercial seeds by 3.9% while decreasing it by 5.3% for the low-margin products with respect to the no-postponement case.

Due to the greedy allocation under postponement, the demand for high-margin commercial seeds is filled before the demand for low-margin commercial seeds. In case of insufficient yield, low-margin seeds may face a supply shortage whereby the manufacturer would choose not to fully satisfy their demand. On the other hand, when the allocation decisions are made in a newsvendor setting under the no-postponement case, allocation quantities are proportional to product margins, which guarantees a minimum level of allocation for low-margin commercial seeds. Therefore, while orphan seeds are neglected under postponement, allocations are more "equitable" under the base case. These numbers are summarized in Table 2.

Furthermore, under the no-postponement case, an increase in the coefficient of variation of the yield in the second period reduces the fill rate by 1.5% for high-margin commercial seeds and by 5.8% for low-margin commercial seeds. Under postponement, while the fill rate is maintained for high-margin seeds, it decreases by 8% for low-margin seeds when the coefficient of variation of the yield in the second period increases. In other words, in the face of increasing future yield variability, postponement preserves the same fill rate for high-margin seeds while it reduces the fill rate drastically for low-margin seeds. Therefore,

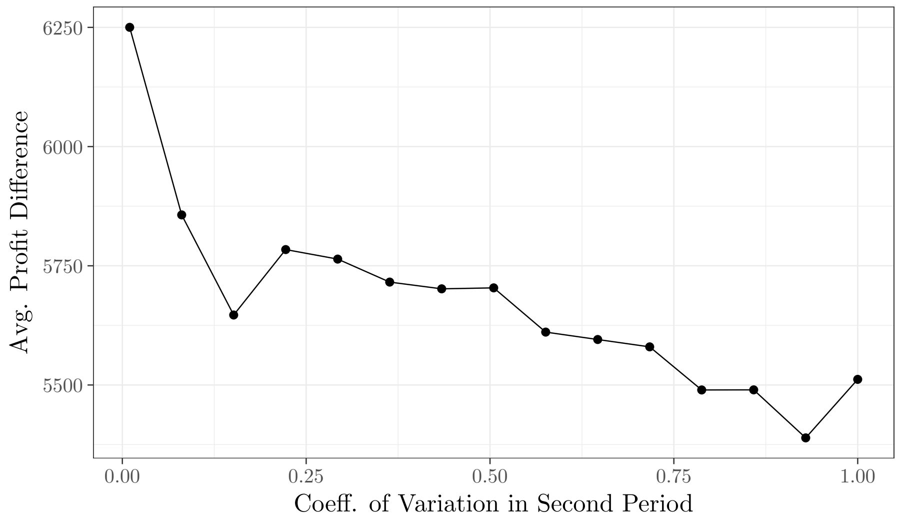

Figure 6: Impact of postponement under various values of the coefficient of variation of second-period yield.

Table 2: Fill Rates

		Base	Postponement
Low CV	Hi Margin	97.6%	100%
	Lo Margin	94.8%	92.5%
High CV	Hi Margin	96.1%	100%
	Lo Margin	89.3%	84.6%

we conclude that postponement not only prioritizes allocation to high-margin seeds, but also guarantees a more robust allocation for them in the presence of climate change. As a consequence, under postponement, orphan seeds not only suffer lower fill rates, but also become even more vulnerable to supply uncertainty triggered by climate change.

6 CONCLUSION

The seed industry is one of the cornerstones of global food security, defined as the ability to provide adequate and affordable food supplies to all people at all times and to ensure economic access to a nutritious diet for all. To ensure a sustainable food supply, seed manufacturers need to address climate change immediately on a grand scale since traditional operational agility initiatives do not seem to provide sizeable improvements to deal with this challenge, especially when the impact of climate change becomes more severe.

The agricultural sector continually adapts to climate change through changes in crop rotations, planting times, genetic selection, fertilizer management, pest management, and water management. These strategies have been effective in increasing agricultural production and efficiency. In the longer term, however, existing adaptive strategies will likely be insufficient in buffering against the impact of climate change. Increased innovation in selective breeding and genetic engineering will, therefore, be needed; however, development of new varieties in specialty crops typically requires 15 – 30 years! Moreover, farm resilience to climate change is also a function of financial capacity to withstand increasing variability in yields, including catastrophic loss.

In closing, we note that our results and insights hold in greater generality and are relevant not only for most field crops, but also for other industries dealing with similar challenges such as the pharmaceutical industry's manufacturing of biologicals.

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