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Ex ante Economic Evaluation of Technologies for Managing Postharvest Physiological Disorders: The Case of 'Empire' Apples in New York State

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***Abstract*. Recently there has been much progress in the development of technologies that use biomarkers to detect and manage postharvest physiological disorders for apples in long-term storage. Such technologies have the capacity to alleviate fruit loss by allowing storage operators to more effectively manage the disorder by adjusting stock distribution. The technology may also reduce costs for storage materials and associated management activities. However, as is common for many new technologies that have not yet been adopted commercially in agriculture, the net economic value of the technology is not well understood and is difficult to assess *ex ante*. In horticultural markets that include quality (and price) differentiated products, technologies that affect grading are expected to impact revenues in nontrivial ways. Here we develop a framework to assess the likely range of economic implications associated with the adoption of the biomarker technology that allows a greater share of fruit to be marketed in a higher grade and may influence the costs of storing fruit. Results indicate that 10% increases in the share of higher quality fruit lead to increased profits of between 0.99% and 3%. A scenario that leads to a 10% increase in the share of fruit in higher grades and a 10% decrease in material costs for storage would increase profits by ≈4.4%. Our analysis and results are specific to the case of biomarker use to manage postharvest disorders for 'Empire' [*Malus sylvestris* (L.) Mill var. *domestica* Borkh.] apples, yet the framework can be used with cultivar-specific price and yield information to assess the *ex ante* economic implications of adopting the technology more generally.**

The economic implications of new technologies that may be commercialized are of paramount concern for industry stakeholders. Agricultural economists are keenly aware that producers face such choices and offer a range of practices to measure the potential benefits and costs of new technologies. Work has been done that focuses on specific technologies in specific industries; for example, Lemieux and Wohlgenant (1989) and Lesser et al. (1999) present frameworks to examine the *ex ante* economic impacts of specific biotechnologies in animal agriculture that had not yet been deregulated and commercialized. Much of this earlier work examined industries with relatively little product differentiation, and in the modeling effort the technology was assumed to affect all products in the same way. Horticultural crops, however, often are highly differentiated across, and even within, cultivars. For many fruit crops there are different grades, and then within each grade there are various size classifications. If new technologies introduced into horticultural markets affect products differentially, then the economic framework for evaluation needs to accommodate these idiosyncrasies.

An accurate *ex ante* evaluation of novel innovations is difficult when the benefits of the new technology to individual producers are not very well understood. This is further complicated in food and agricultural markets as new technologies are often controversial and the benefits are not shared equally to all constituents (including all products and all producers) in the supply chain. New technologies are typically described as either revenue enhancing or cost reducing. Revenue-enhancing technologies have the capacity to increase yields, increase quality, and influence prices if the final products are transformed or are able to enter new markets. Cost-reducing technologies often introduce innovations that reduce overall input use or allow producers to switch to less expensive inputs. In some cases, we observe innovations that are both revenue-enhancing and cost-reducing.

The empirical example that motivates our work is the use of biomarkers to manage postharvest physiological disorders in long-term controlled atmosphere (CA) apple storage. Such disorders are nontrivial for some of the major apple cultivars produced in the United States, and they can lead to significant economic losses for apple producers (Rudell and Watkins, 2011). Some of the most critical physiological disorders that occur in apple storage include superficial scald for 'Granny Smith', soft scald for 'Honeycrisp', external CO_2 injury for 'Empire', and firm-flesh browning for 'Empire' (see illustrations in Supplemental Fig. 1). Biomarker technologies have the capacity to be a revenue-enhancing technology if they provide reliable information that would allow the storage operator to reduce the share of downgraded fruit and/or to market a greater share of the stored fruit in higher quality grades. The biomarker technology could also lead to reduced costs if fewer materials are needed in storage.

Here, we focus specifically on firm flesh browning of the 'Empire' apple (*Malus sylvestris* var. *domestica* Borkh.), which is a major cause of revenue loss for growers and storage operators in New York State. 'Empire', is a cross between 'McIntosh' and 'Delicious' and was released in 1966 (Derkacz et al., 1993). It is a major cultivar in the northeastern United States, particularly in New York State as well as in Canada. 'Empire', at almost 1860 ha, was the second most planted cultivar after 'McIntosh' in the northeast in 2006 (USDA-NASS, 2012), and is the fifth most important cultivar in the United States with a total production of 170,000 tons in 2011 (Lehnert, 2012). Symptoms of flesh browning in 'Empire' typically become visible after several months in storage (in the May or June following harvest in the northern hemisphere), but can occur earlier in some years. Flesh browning is not externally visible and mostly starts at the stem end of the fruit in the shoulder region (Lee et al., 2012).

'Empire' apples are air stored to meet market demand until about December with fruit for marketing beyond this time usually being CA stored. Both air-stored and CA-stored fruit are often treated with the inhibitor

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of ethylene perception, 1-methylcycopropene (Watkins, 2008). A storage period of at least 10 months is desired by the whole fruit and fresh cut industries, but the cultivar is susceptible to several physiological disorders that limit its storage potential (Watkins et al., 1997; Watkins and Liu, 2010). Flesh browning has been especially problematic for the fresh cut industry as only apples with no internal browning—even slight browning in the stem end region (shoulder)—are acceptable.

Materials and Methods

The objective of this research is to quantify the potential economic benefits of adopting biomarkers that would help to manage a specific postharvest physiological disorder for the Empire cultivar, namely flesh browning. Here, we outline a framework that uses information on prices and yields for specific grades and sizes of fruit, as well as data on the costs of production and storage. Essentially, we develop a tool to help the industry better understand the potential benefits of the biomarker technology and to provide a measure of the value of the new technology. We present results across a range of market simulations to provide a wider spectrum of the potential benefits of the biomarker technology.

Our analysis is done in three stages. In the first stage, we outline the annual costs of orchard production and the costs of storing 'Empire' fruit in a CA room. In the second stage, we employ a range of prices and yields to calculate revenues across the various grades and sizes of 'Empire' fruit. A range of net profits to the producer/storage operator can be evaluated using the information outlined in stages 1 and 2. In the third stage, we simulate how the adoption of biomarkers might affect the shares of fruit marketed in the various grades, and ultimately how that would affect net profits.

The data used in our analysis were calculated based on those available in DeMarree (2010) and Gallardo and Galinato (2012) and then adjusted to reflect the market for 'Empire' fruit produced in New York State. The cost data in the earlier studies were adjusted to better reflect specific costs for disease and pest management practices for the cultivar, as well to add details about the costs of materials used in its storage. The revenue data were adjusted to consider the average yields and prices for the various grades and sizes of 'Empire' fruit produced in New York State. The cost and price data, and a more disaggregated version of the yield data were also used in Doerflinger et al. (2015), however, the data are being used here to answer a related but different research question. Doerflinger et al. (2015) focused on how harvest dates impact yields across the different fruit sizes, and compared the economic implications of marketing fruit that is harvested at different dates in the fall. This research is not concerned with the role of harvest dates on fruit size, assumes all fruit is harvested at the conventional time, and uses data to reflect average yields for each grade and fruit size. Here, the focus is not on fruit size but on fruit grades. We are interested in simulating the economic implications of storage technologies that have the capacity to change the share of fruit that is marketed in higher grade categories.

Table 1. Estimated costs for production, harvest, storage, and marketing for 12.15 ha of 'Empire'.

Name	Costs per unit ($)	Units per 2,000 bins or 12.15 ha	Costs per 2,000 bins or 12.15 ha ($)
Variable orchard costs			
Harvest labor (ton)	32.58	840	27,370.50
Seasonal quality control (h)	11.47	146	1,670.95
FT truck/tractor driver (h)	17.54	146	2,555.22
FT tractor driver (h)	14.37	146	2,093.42
PT truck/tractor Driver (h)	12.71	146	1,851.59
Interest on operating capital (ha)	1,790	12.14	21,730.60
Disease control (Fungi, Insect/mite, Herbicides) (ha)	1,329	12.14	16,134.06
Chemical thinners (ha)	279	12.14	3,387.06
Fruit thinning/return bloom (ha)	1,483	12.14	18,003.62
Fertilizer (ha)	543	12.14	6,592.02
Fixed costs			
Total overhead expense (ha)	919	12.14	11,156.66
Average equipment investment replacement year (ha)	692	12.14	8,400.88
Operators' management only (ha)	704	12.14	8,546.56
Annual equipment expense (ha)	514	12.14	6,239.96
Storage costs			
Marketing and packaging (ton)	24.76	340	8,422.12
Sorting and storing Bins (ton)	13.18	340	4,484.76
1-MCP (SmartFresh) (1.4 m^3)	4,000	1	7,150.46
Diphenylamine and application			4,000.00
Total costs for stored fruit			159,790.50

FT = Full time; PT = Part time; 1-MCP = 1-methylcycopropene.

Table 2. Unit prices per box (18.1 kg), yields, and revenue for 12.15 ha of 'Empire'.

Grade/size	Avg fruit wt (g)	Price per box (10 yr avg)	Net price per box (less fees^z)	Yield (shares, %)	Yield (boxes per 12.15 ha)	Revenue ($ per 12.15 ha)
Extra Fancy						
163	116	13.02	8.38	6.01	2,561	21,470
150	128	9.15	5.90	9.12	3,888	22,924
138	136	12.00	7.73	11.18	4,764	36,803
125	153	12.72	8.19	13.34	5,687	46,573
113	167	19.56	12.60	12.47	5,316	66,971
100	190	18.53	11.93	8.18	3,485	41,586
88	215	18.82	12.12	3.30	1,407	17,052
80	238	19.57	12.61	1.05	446	5,625
72	264	19.55	12.59	0.26	112	1,409
64	298	18.17	11.70	0.05	21	249
1.1 kg bags	126	14.12	9.09	2.96	1,261	11,467
1.25 kg bags	114	12.48	8.04	2.99	1,275	10,245
Fancy						
138	136	8.55	5.51	2.38	1,016	5,593
125	153	8.30	5.35	2.74	1,166	6,235
113	167	6.43	4.14	2.14	913	3,778
100	190	8.00	5.15	1.32	564	2,904
88	215	6.57	4.23	0.45	192	811
80	238	7.09	4.57	0.12	49	224
1.1 kg bags	126	10.60	6.83	3.52	1,502	10,255
Commercial/juice						
1,000		4.00	2.58	16.43	7,003	18,039
Total				100	42,627	330,213

^{z}Fees include a packing charge of 30% and a commission expense of 8%. Costs for storage charges and materials used in storage are considered expenses and included in the costs shown in Table 1.

The unit of observation for this exercise is ≈2000 bins that each contains 382 kg of fruit, or ≈42,100 18.1 kg boxes of fruit; this is the amount of fruit that is used to fill a typical storage room with 'Empire' fruit in New York State. If we assume that a high-density orchard produces 567 18.1-kg boxes per hectare, then ≈42,000 boxes of fruit from 12.15 ha is required to fill one storage room. Therefore, the costs and revenues discussed below are specific to 12.15 ha of fruit production and to one storage room of fruit. The values described below and used in our analysis are meant to be generally representative and to serve as references points; however, the framework is designed to easily accommodate other values that may more accurately reflect market conditions for a different storage operator or for a different cultivar.

In Table 1 we outline the categories of costs involved in the production and storage

Table 3. Summary of the financial results for selected scenarios with the use of biomarkers.

Scenario	Description	Mean	Minimum	Maximum	Standard deviation	Median	Frequency of profits between \$165k and \$198k[z]	% change in mean profits compared with baseline
		Dollars					Percent	
0	Baseline	174,315	121,778	232,065	16,003	174,106	63.78	n/a
1	Shift 10% fruit from Fy to ExFy grade	176,037	127,073	234,357	16,335	175,720	65.00	0.987
2	Shift 10% fruit from C to ExFy grade	179,555	129,814	233,830	16,278	179,006	66.40	3.006
3	Reduce storage costs by 10%	176,815	131,038	232,371	16,025	176,472	65.80	1.434
4	Shift 10% fruit from C to ExFy grade and reduce storage costs by 10%	182,054	134,496	236,945	16,755	181,649	66.90	4.440

[z]This range reflects the mean profits in scenario 4 ± 1 SD.
Fy = Fancy; ExFy = Extra Fancy; C = Commercial.

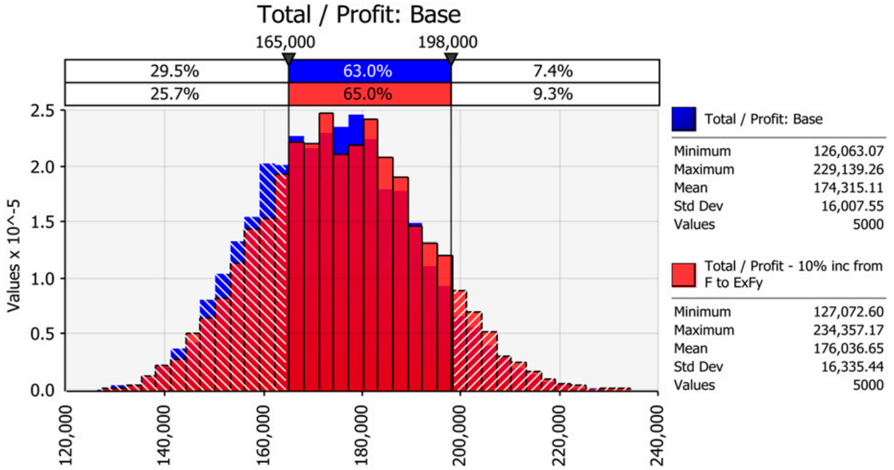

Fig. 1. Scenario 1: Profit distribution for shift of 10% fruit from Fancy to Extra Fancy.

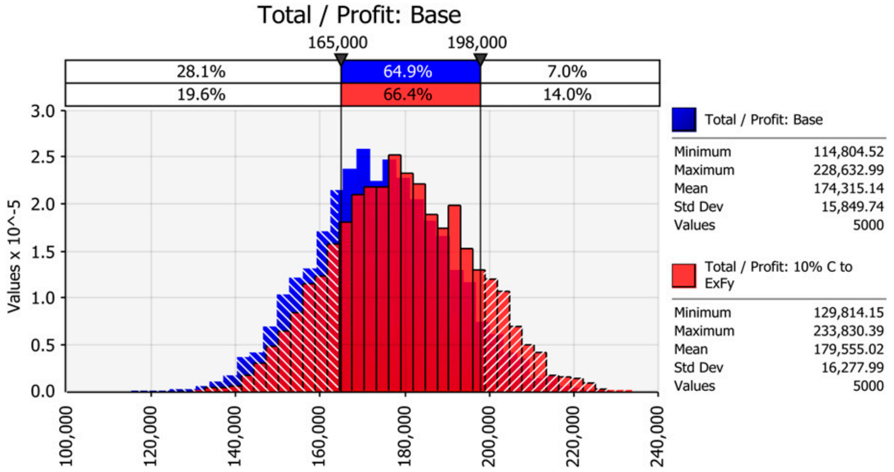

Fig. 2. Scenario 2: Profit distribution for shift of 10% fruit from Commercial to Extra Fancy.

of 42,000 boxes of fruit. Here, our objective is to characterize all of the costs involved in producing and storing the fruit; in some regions the fruit production and storage may be vertically integrated and controlled by a single firm, whereas in other regions these two activities may be operated by separate firms. Variable costs include labor requirements for harvesting and other orchard activities, interest on capital, and the materials applied to the orchard throughout the growing season. Fixed costs include expenses related to overhead, machinery and equipment, and operator salary. The storage costs reflect the costs for managing the fruit in long-term storage including sorting, packaging, and monitoring, and the materials used in storage. The storage costs do not include the fees collected by fruit marketing agency; these fees are deducted from the per box prices used to calculate revenue flows. Overall, variable costs represent ≈63% of total costs, fixed costs represent ≈22% of total costs, and storage costs represent ≈15% of the total costs.

Revenue is derived from prices and yields earned across the various sizes in the different grades of fruit. Four general quality grades are used in the United States: "U.S. Extra Fancy" (ExFy), "U.S. Fancy" (Fy), "U.S. no. 1" (no. 1), and "Commercial" (C) by the U.S. standards for grading of apples (USDA, 2002). In our analysis, we focus on the ExFy, Fy, and C grades given the very small share of 'Empire' fruit that is marketed in the no. 1 grade. ExFy is the highest grade and, therefore, brings the highest price; standards for fruit size and percent red cover for this grade are high, and in some years can be difficult to achieve for the bicolored cultivars. Whole fruit prices are determined by grade as well as size, which ranges between 72 and 163 fruit per box. This refers to an average fruit weight of ≈265 to 116 g. Fresh cut requires from 100 to 115 count boxes with individual fruit weight between 190 to 170 g.

In Table 2 we show the 10 year average prices and yields by grade and then by size within each grade for 'Empire' apples produced and marketed in New York State. The average prices are calculated using data between 2002 and 2011 using industry data (Stannard, personal communication), and this is a period that included a relatively wide range of prices for apples. The prices are highest for the largest fruit in the ExFy grade, and lowest for the fruit in the C grade. The net price represents the price the storage operator (or the grower/storage operator if the fruit production and storage activities are vertically integrated) receives after deducting the appropriate marketing fees and commissions. The yield shares show the approximate percent of the total crop that falls into each grade/size category, and these shares are used to calculate the quantity of fruit marketed under the different grade/size categories.

Results

We simulate four scenarios that may unfold as a result of the adoption of the biomarker technology to manage physiological disorders in stored 'Empire' apples. The simulation work examines the economic effects of a biomarker technology that affects 1) revenue through changes in the share

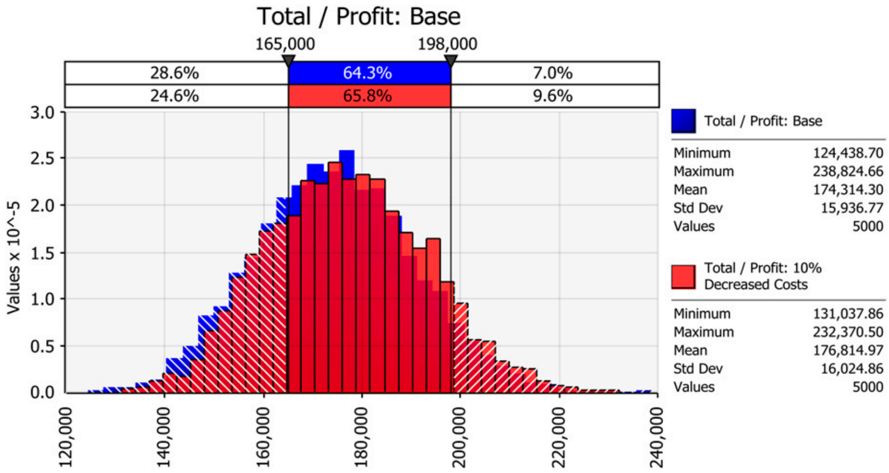

Fig. 3. Scenario 3: Profit distribution for reduction in storage costs by 10%.

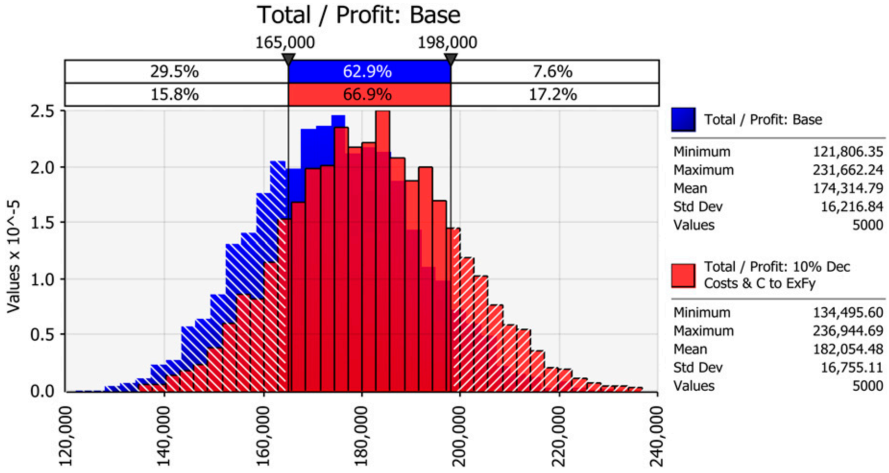

Fig. 4. Scenario 4: Profit distribution for shift of 10% fruit from Commercial to Extra Fancy plus a 10% reduction in storage costs.

of fruit that is marketed in the higher valued grades/sizes, 2) the cost of storing the fruit, and 3) some combination of changes in revenues and changes in costs. For each scenario, we manipulate the baseline cost and revenue data detailed in Tables 1 and 2 to assess the economic implications of a given change in the share of fruit marketed as higher quality or in the cost of storing the fruit. The actual changes in the share of fruit marketed to higher grades of fruit are not known with any certainty given that the biomarker technology has not been adopted commercially. The changes we assume are based on information collected from industry stakeholders that are reasonably familiar with the likely benefits of the technology. Furthermore, the changes that we consider are relatively modest. Results from each scenario are then compared with the baseline case to understand how the conditions in each scenario change net profits for the 12.15 ha/2000 bin unit of production.

The analysis was conducted with a simulation program that uses an iterative process to generate 10,000 probabilistic outcomes. We use the information about the range of prices over the 10-year period to calculate an empirical distribution of prices for each grade/size category. The empirical distribution for prices is combined with the yields for each grade/size category to create an empirical distribution of total revenues for the 12.15 ha/2000 bin operation. This rigorous simulation exercise considers a large number of potential market outcomes and was done as a way of conducting a systematic sensitivity analysis that considers a very wide set of possible revenue (and profit) outcomes. This allows us to report statistical properties of the empirical distribution of potential net profits rather than simply report mean values. However, the results reported here do assume that the range of historical prices and yields can be used to describe market conditions for 'Empire' fruit with the biomarker technology in place.

In the first two scenarios, we consider the effects of the biomarker technology assuming it is able to detect disorders earlier and allow storage operators to market fruit sooner in better quality grades. In the first scenario, we examine the case where the biomarker technology allows 10% of some sizes of fruit to be marketed as Extra Fancy when it was otherwise marketed as Fancy. We decrease Fancy grade fruit in the 100, 113, 125, and 138 sizes by 10% and shift that to the corresponding sizes in the Extra Fancy grade. The full distribution of profits is shown in Fig. 1 and is summarized in Table 3. In this scenario, the mean profits increase by ≈\$1700 or by 0.99%. In the second scenario, we shift 10% of fruit in the Commercial grade to the same four sizes of fruit in the Extra Fancy grade (in equal quantities). Figure 2 illustrates the distributional impacts on net profits for scenario 2, and Table 3 shows that the mean profits increase by ≈\$5200 or 3% compared with the baseline case.

In the third and fourth scenarios, we consider the outcome if the biomarker technology has the capacity to reduce storage costs via less use of diphenylamine (DPA) or less management of other resources used to store apples. In the third scenario, we model the effects of 10% lower storage costs and in the fourth scenario, we couple the lower storage costs with a reallocation of 10% of the Commercial grade fruit to the Extra Fancy grade. Figure 3 shows the distributional effects of a 10% reduction in storage costs, and Fig. 4 shows the distributional effects of the reduction in storage costs coupled with the shift in fruit marketed in the higher quality grade. As shown in Table 3, the reduction in costs alone does not have a significant effect of mean net profits (an increase of 1.4%), but the effects are more significant when coupled with 10% of the fruit shifting from the Commercial grade to the Extra Fancy grade. In scenario 4, the mean net profits increase by ≈\$8000 compared with the baseline case, or by 4.4%.

Policy considerations. The United States and the European Union (EU) have embarked on ambitious negotiations to create a comprehensive free trade agreement known as the Transatlantic Trade and Investment Partnership (TTIP). The agreement aims to promote trade between the two regions through three mechanisms: 1) increasing market access, 2) enhancing regulatory coherence and cooperation, and 3) developing and updating trade rules. Many expect that the TTIP negotiations concerning market access and trade rules will progress without significant debate (Akhtar and Jones, 2013), while the discussions concerning differences in domestic regulations will continue to be highly contested (Fontagné et al., 2013). There also exist a number of nontariff barriers that impact U.S.–EU trade in food and agricultural markets—many that are driven by regulatory differences between the regions—and in several cases quantifying the effects of these policies is not straightforward.

In apple markets, one of the key regulatory differences between the EU and the United States relates to the use of materials to manage pests and other issues in the orchard and in storage. The United States and the EU have regulations that govern the amount of material that can be found on domestically produced and imported food products known as maximum residue levels (MRLs), and there exist many examples

Table 4. Summary of the financial results for selected scenarios in the absence of DPA and biomarkers.

Scenario	Description	Mean	Minimum	Maximum	Standard deviation	Median	Frequency of profits between \$158k and \$190k[z]	% change in mean profits compared with baseline
		Dollars					Percent	
0	Baseline	174,315	121,778	232,065	16,003	174,106	73.0	n/a
5	Shift 10% fruit from Fy to Commercial grade	172,099	117,402	228,131	16,088	171,844	89.5	–1.27
6	Shift 10% fruit from ExFy to Commercial grade	150,355	107,382	202,614	14,179	150,242	29.5	–13.75
7	Shift 10% fruit from ExFy to Commercial grade and reduce storage costs by 10%	152,855	110,474	200,336	14,135	152,574	35.7	–12.31
8	Shift 10% fruit from ExFy to Commercial grade and increase storage costs by 10%	147,855	103,823	195,043	14,347	147,611	24.5	–15.18

[z] This range reflects the mean profits in scenario 0 ± 1 SD.

Fy = Fancy; ExFy = Extra Fancy; C = Commercial.

where there are nontrivial differences in MRLs between EU member states and the United States. These differences are often considered to be nontariff barriers which reduce trade and can complicate trade negotiations such as those concerning the TTIP. In particular, the EU has recently banned the use of DPA as a material in apple storage, and this is a product that has been widely used by storage operators in the United States to control postharvest physiological disorders for selected apple cultivars. Therefore, if the biomarker technology could be effectively used to alleviate the need for DPA (or other storage materials), it may be able to help secure export markets that have banned DPA and may also reduce the net costs of storage. Conversely, a ban on DPA in the absence of other solutions to manage postharvest physiological disorders could have large negative implications for apple producers and storage operators. It is critical to consider how this ban on the use of DPA will affect U.S.–EU trade in apples, and how it will impact profitability of producing and storing apples for EU export markets.

The framework developed here can give us a better understanding for how the adoption of biomarker technologies could mitigate the economic consequences of this ban on DPA to U.S. apple producers and storage operators. We conduct four additional scenarios that examine the economic implications of a ban on DPA in the absence of an effective replacement technology (such as biomarkers). Here, we consider the effects if 10% of the Fancy or Extra Fancy fruit is diverted to Commercial grade, and also consider scenarios with a 10% shift in fruit from Extra Fancy to Commercial grade plus changes in the net costs of storage. The results for these scenarios are shown in Table 4, and each scenario is compared with the baseline case.

We find that shifting fruit from the Fancy grade to the Commercial grade does not have a significant economic impact (net profits to the growers and storage operators fall by 1.3%), however, if the ban on DPA results in a shift of 10% of Extra Fancy fruit to Commercial grade fruit, the economic effects are much larger (a decrease in net profits of 13.8%). The final two scenarios show the economic implications for a shift in the share of fruit marketed as Commercial grade coupled with changes in storage costs. We consider both a net decrease in storage costs (if the reduction in costs for DPA is not outweighed by other additional storage costs) and a net increase in storage costs (if the reduction in costs for DPA is outweighed by other additional storage costs for materials and management labor). The final row shows that a shift of 10% in fruit from the Extra Fancy grade to the Commercial grade plus a net increase in storage costs would reduce net profits by 15.2%. These results suggest that the ban on DPA could be significant, and crucially important for producers and storage operators following guidelines to export fruit to European markets.

Conclusion

The apple market includes a wide range of quality differentiated products (across cultivars, grades, and sizes). The introduction of new technologies in this market can significantly influence how the product is categorized. Therefore, new technologies introduced into markets with highly differentiated products need to be examined carefully. In addition, when prices across the differentiated products vary, and when technologies allow for improvements in quality, the economic effects could be substantial. We study the effects of introducing biomarker technologies that manage postharvest physiological disorders for the ‘Empire’ apple cultivar.

However, our framework is more generalizable and could be used to examine similar issues for other apple cultivars, other crops, and other technologies. For example, if we collected price and yield information across the various grades and sizes for other apple cultivars that were also subject to postharvest physiological disorders (like those shown in Supplemental Fig. 1), we could extend our analysis to assess the *ex ante* economic implications of adopting biomarker technologies more generally. The net benefits of adopting the technology would increase for cultivars that have larger price premiums for higher quality (i.e., higher grades of) fruit. Therefore, our results shown here are expected to serve as a lower bound for other cultivars that have larger price premiums for higher quality fruit.

Our results show that even small changes in the share of fruit that can be marketed in higher grades has the capacity to significantly impact the net profits to the producer and storage operator. For a 12.15 ha/2000 bin storage unit, a 10% increase in the share of Commercial grade fruit marketed as Extra Fancy fruit would increase the net profits by ≈3%. Increasing this share of fruit plus a decrease in storage-related costs by 10% would increase net profits by 4.4%.

Here, we use detailed cost, price, and yield data for ‘Empire’ apples to assess the net benefits to apple producers and storage operators per 2000 bin room (or equivalently to 12.15 ha of orchard). The net benefits that we calculate provide a starting point for assessing the value of the technology to potential adopters. In some ways, this exercise provides us with a framework for evaluating a technology *ex ante*, or before the technology is fully commercialized and adopted. Effectively, the results from the scenarios allow stakeholders to better understand the industry’s maximum willingness to pay for a new technology in cases where the cost and the price of the technology are not well documented, and where it is not yet widely available.

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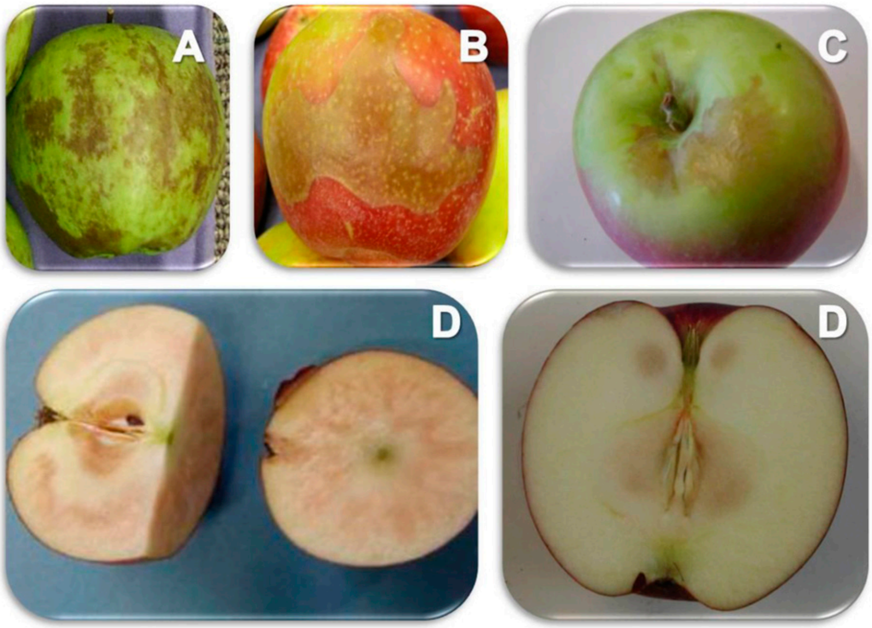

Supplemental Fig. 1. Illustrations of disorders for selected cultivars. Note: (**A**) superficial scald/‘Granny Smith’, (**B**) soft scald (internal-soggy breakdown)/‘Honeycrisp’, (**C**) external CO_2 injury/‘Empire’, (**D**) firm-flesh browning/‘Empire’.