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Abstract: New Plant Engineering Techniques (NPETs) have path-breaking potential to improve foods by strengthening their production, increasing resistance to biotic and abiotic stresses, and by bettering their appearance and nutritional quality. Can NPETs-based foods succeed in the marketplace? Providing answers to this question, we first develop a simple economic model for R&D investment in food innovations based on NPETs and traditional hybridization methods, to identify which technology emerges under various parameter characterizations and associated economic welfare outcomes. The framework combines the cost of food innovation with consumers' willingness to pay (WTP) for the new food, highlighting the uncertain and costly nature of R&D processes as well as the role of consumer acceptance of technology, and the cost of ignorance, and regret, if consumers are not fully informed on the technology used to generate the new food. We then apply the framework to a case of NPETs-based new apples using recently elicited WTP of French and US consumers. Our simulation results suggest that NPETs may be socially beneficial under full information, and when the probability of success under NPETs is significantly higher than under traditional hybridization. Otherwise, the innovation based on traditional hybridization is socially optimal. A probable collapse of conventional apples raises the social desirability of new apples generated by NPETs and traditional hybridization.

Keywords: new plant engineering techniques (NPETs); gene editing (GE); consumer information; willingness to pay; food innovation; industrial organization; apple

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1. Introduction

New Plant Engineering Techniques (NPETs), such as gene editing (GE), are a group of recent biotechnologies allowing to accurately target deoxyribonucleic acid (DNA) manipulation of various organisms at a relatively low cost by silencing, suppressing, adding, or altering genetic material without introducing foreign genes.[1] Various applications of those techniques already exist and many others are actively explored for their promising potential in human and animal medicine, as well as in agriculture (Erpen-Dalla Corte et al., 2019; Herrero et al. 2020; NAS, 2016; Ormond et al., 2017; Qaim, 2020; and Zhao et al. 2019). For example, in horticulture, GE and other NPETs have path-breaking potential to alter fruits and vegetables by improving the strength of their production, by increasing their resistance to biotic stresses, and by favoring their appearance and/or their nutritional quality (e.g. improved starch content in potatoes or higher lycopene content in tomatoes, Erpen-Dalla Corte et al., 2019). For arable crops like cereals or legumes, NPETs are essential for strengthening plants' characteristics to endure prolonged droughts or bypassing pesticides resistance, acute problems likely to cripple yields and ultimately supply security. Animal applications are addressed in Zhao et al. (2019).

However, this potential revolution in agricultural and food production innovation may be facing major headwind, especially in countries where a significant proportion of consumers are reluctant to purchase "anything produced with biotechnologies."[2] Under this considerable uncertainty in the marketplace, several questions are paramount and require answers. Will consumers and policymakers treat NPETs-based novel foods the way they had treated GMOs? What are the consequences for R&D investments relying on GE or other NPETs and producer strategies in terms of innovations' adoption, as well as the potential social benefits resulting from these innovations? Will such innovations be speeded up by increasing problems with many diseases and pests, such as the Fusarium fungus affecting Cavendish bananas (Crop Biotech Update, 2021), and the ringspot virus, which has whipped

[1] NPETs also include other techniques such as RNA interference (RNAi) used to silence or suppress specific gene function in plants in a targeted way. These techniques do not rely on the traditional gene splicing of older Genetically Modified Organisms (GMOs). The framework applies to most NPETs although we focus on gene editing in the application.

[2] Policymakers and regulatory delays could also be a major impediment in many countries, especially those in which GMOs faced very stringent and slow regulatory approvals and countries treating NPETs as traditional GMOs (Purnhagen and Wesseler, 2020).

out traditional papayas in Hawaii (Gonsalves et al., 2007)? The papaya case represents a tangible case of the collapse of a conventional crop leading to greater consumer acceptance of GMO-based food innovation (the resistant papaya). Environmental issues such as climate change or water scarcity could also facilitate these innovations.

Our paper provides answers to the above questions and contributes to the current debate on new biotechnologies by studying the link between consumers' preferences and firms' incentives for R&D of new foods through GE and other NPETs, or through conventional hybridization methods. We analyze the social value of food innovations utilizing a simple Industrial Organization (IO) model that combines the cost of food innovations (with different technologies, NPETs or traditional hybridization) with consumers' willingness to pay (WTP) for those innovations. Our analysis relies on three main components. First, the WTP is conditioned on the level of acceptance or rejection of the technology used to innovate. The framework highlights the role of consumer acceptance of technology and their information levels regarding the technology underlying the novel food. Consumer acceptance or reluctance implies a potential cost of ignorance and regret if consumers are not informed on the technology embodied in the new food before they buy it. Second, the model accounts for the uncertain and costly nature of R&D processes for traditional hybridization and NPETs. The model allows identifying each preferred technology (NPETs or traditional hybridization) that emerges under varying assumptions and their respective economic welfare outcomes. Third, the framework is also suitable for analyzing a collapse scenario in which the existing conventional food item (the default option for consumers) disappears and must be replaced by the new food. Consumers can no longer revert to the conventional food, making the new food the unique choice available to consumers. Welfare implications of such a collapse scenario are evaluated.

We follow with an application of the model to a case study of a hypothetical development and introduction of new apple varieties into the market. The application builds upon the results of two experimental surveys of consumers' preferences in France and the US for novel apples, relative to conventional apples (Marette et al., 2021). The experiments use hypothetical and fictitious choices in

a lab and different technology messages (on traditional hybridization and GE as representative case of NPETs), to estimate the WTP[3] of 162 French and 166 US consumers for new apples, which do not brown upon being sliced or cut.[4] Messages center on the social and private benefits of having the new apples relative to conventional ones.

In these surveys, consumers in France and the US exhibit similar preferences with respect to biotechnology. Many, but not all consumers, in both countries discount the apple improvement obtained through GE techniques, relative to traditional hybridization-based innovation. However, there is a significant group of consumers knowingly accepting the new GE apple. This group of accepting consumers is relatively larger in the US than in France, strongly suggesting that the acceptance of GE foods is possible in a significant segment of the population (at least in some countries).

Based on these consumers' WTPs, we derive the demand for the new apples and associated consumer surplus, as well as *ex ante* (e.g., before the actual introduction of the new variety of the good) estimates for the welfare impacts of GE apples onto the market, by taking into account both R&D cost of innovation and probability of innovation success. Our simulations suggest that GE may be socially beneficial if full information on the technology is provided to consumers and if the probability of success under GE is significantly higher than under the traditional hybridization. In the case of partial or no information, consumers discounting the GE apples would buy them unknowingly, experiencing regret losses relative to their true valuation of the GE apples. Thus, in this context, traditional hybridization remains the socially optimal innovation technique.

Our paper provides several contributions to the literature evaluating WTP for novel foods based on NPETs techniques and their emergence. First, recent studies identify significant discounting of GE and other NPETs foods by consumers compared to conventional foods, which is reminiscent of past reluctance to GMO food (Bunge and Dockser Markus, 2018; Caputo et al., 2020; De Marchi et al.,

[3] Even if hypothetical WTP are likely to be upward biased, some contributions downplay risks of biases for marginal WTP related to a quality characteristic or the impact of additional information. By comparing hypothetical and non-hypothetical responses, Lusk and Schroeder (2004) showed that marginal WTP for a change in quality/characteristic is, in general, not statistically different across hypothetical and real (consequential) payment settings.

[4] The fictitious situation is inspired by the Artic© apple, which uses RNAi rather than GE to suppress the gene responsible for browning and bruising in apples. Arctic apples have been approved in the US and Canada. They are sold through food service as well as very limited number of retail establishments in some US states.

2019 and 2020; Edenbrandt et al., 2018; Hudson et al., 2015; Lin et al., 2019; Marette et al., 2021; Muringai et al., 2019; Shew et al., 2018; and Yunes et al., 2019). See Bredahl, 1999; and Lusk, 2011 for earlier studies on attitudes towards GMOs. We go one-step further by providing a conceptual framework to analyse the social desirability, thus value, of NPETs-based food innovations and their potential emergence and success in the marketplace.

Second, the application to apples leverages the recently elicited WTPs into the proposed framework. A welfare analysis uses the WTPs to calibrate the model of food innovations under competing technologies (traditional hybridization, GE as representative of NPETs). The approach accounts for the fixed cost of R&D and the probability of innovation success under both technologies. The proposed framework is applicable to other food novelties that could emerge with similar technologies or other disruptive technologies contributing to a sustainable food supply (see Herrero et al., 2020, for a list of these technologies).

Third, we analyse the situation of a potential agronomic collapse of conventional foods to evaluate if the emergence of NPETs-based foods can be facilitated under this extreme case scenario. We draw some *ex ante* policy implications, before any actual realized outcomes. This inclusion of probabilities of innovation and a collapse case scenario is new and differs from previous contributions to the literature on experimental methods (Lusk et al., 2005a; Lusk and Marette, 2010; Rousu et al., 2007; and Rousu et al., 2014). In those papers, the introduction of new goods is certain and the innovation "predictable" and effectively existing, while our paper introduces R&D uncertainty and sunk costs into the analysis.

The remainder of the paper is organized as follows. Section 2 discusses new genetic technologies for food innovations in agriculture, as a potential solution for addressing risks related to complete collapses (or disappearance) of conventional food crops. Section 3 develops the simple IO model of R&D investment combined with the consumer demand for the new food varieties and consumer surpluses leading to the welfare analysis. Section 4 presents the application of the model to apples and summarizes the hypothetical experiments' results used to derive the consumer demands

and welfare valuations. The main results of the application follow and the extension to the collapse of conventional apples is also studied. In the conclusions, we discuss potential extensions of our research approach and some implications for regulatory policies.

2. NPETs technologies for food

In this paper, we focus on the case of quality enhancement of food brought about by NPETs and rely on a hypothetical case of improved apples. The innovation consists in editing the genetic sequence of the apple to neutralize or delete the gene responsible for browning. More specifically, we refer to the CRISPR-Cas9 technique,[5] which has become an engineering tool that makes it easier and more precise to modify DNA sequences. This process clearly differs from traditional GMOs since no external gene is introduced in the new good.

Beyond the hypothetical cases, the actual commercialization of new fruits and vegetables based on GE or other NPETs is limited. Non-browning mushrooms obtained with GE and non-browning potatoes obtained with RNAis have been patented but not yet commercialized (Jalaluddin, et al., 2019). Currently only the Arctic© apple and the Simplot Innate® potatoes are sold in Canada and the US on a limited basis and with caution.[6]

Innovations and varietal improvement in agriculture are slow and costly processes. For example, it takes around 20 years of R&D for getting a new apple variety. Besides, consumers may react negatively to innovations (Glenna et al., 2007). Consequently, producers and private innovators often prefer newly augmented traditional methods, such as the Marker Assisted Selection (MAS) that combines genetic knowledge and classical hybridization into so-called selective breeding, even if such techniques remain quite expensive (Wannemuehler et al., 2019). GE and other NPETs innovations in food are mainly driven by public research institutes or by marketing orders with checkoff program

[5] CRISPR stands for Clustered Regularly Interspaced Short Palindromic Repeats. The Nobel Prize in Chemistry 2020 was awarded jointly to E. Charpentier and J.A. Doudna for the development of this new and promising method for genome editing.

[6] In 2019, production of Arctic apples reached 4000 short tons for the U.S. market (mostly for expanded sales in food-service). In 2020, production increased to 6500 tons. In retail, there were three sizes of bags with pre-cut apples (10oz, 5oz, and 2oz) available for sale and two varieties (Arctic Golden and Arctic Granny).

funding agricultural research, or with public involvement like the one led by Washington State University for designing new apples. These public organizations of R&D potentially mitigate the reluctance of innovators and producers by maintaining conditions under which new goods could emerge. This is important because of crops' agronomic fragility, pesticide resistance and outbreaks, and even collapse of the conventional variety of the good. Biotechnology appears as potential solution for preventing these risks (Crop Biotech Update, 2021; Le Page, 2019; and NAS, 2016). Examples of major outbreaks include cocoa with the swollen-shoot virus, tomatoes with the brown rugose virus, and bananas with the Fusarium fungal disease (Tropical Race 4). Regarding papayas, a GMO variety was introduced over twenty years ago and saved the entire Hawaiian industry from the ringspot virus (Gonsalves et al., 2007). Now the GMO papaya is ubiquitous and fully accepted by consumers in Hawaii. The papaya case motivates the analysis of a collapse scenario.

NPETs can appear as an important revolution in the field of fruit and vegetables for improving the strength of their production and/or the quality of goods including the context of possible collapse. However, this public R&D should also consider the potential reluctance of many consumers for new goods created with GE and other NPETs – as in the past for GMOs. Consumers' acceptance influencing private and social profits could be estimated *ex ante* via experiments, namely before the actual introduction of a food on a market.

3. An IO model integrating experimental results

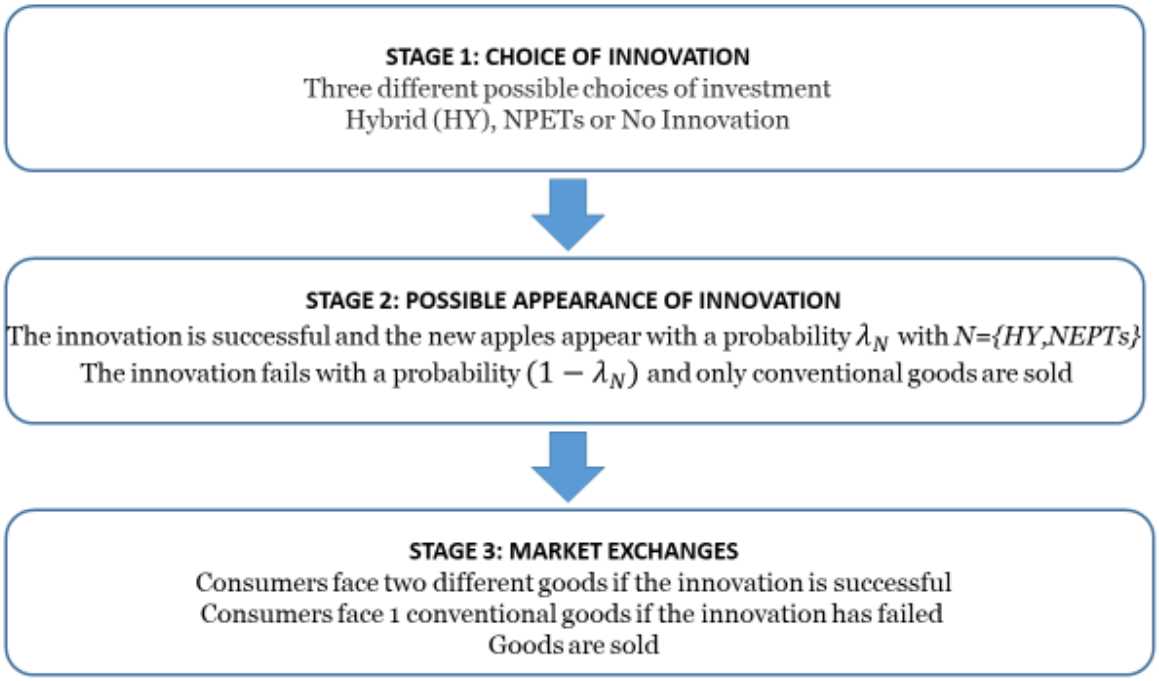
We develop a simplified model incorporating IO considerations and consumers' valuation of novel foods. Our model accounts for the probability of having new goods resulting from R&D investments. This is consistent with a benevolent regulator deciding how to invest in R&D. The proposed model allows for a simplified estimation of potential market effects with one or two goods, which is a proxy for market-adjustments with many imperfect substitutes. For simplicity, we consider decisions based on welfare measures focusing on surpluses of consumers and public investment decisions in R&D to maximize consumer welfare. Extensions to the basic model are proposed in the subsections 4.5 and

4.6 and in Appendix C.

3.1 A three-stage game

The market equilibrium is determined as a 3-stage game summarized in Figure 1. The equilibrium is solved by backward induction (i.e., subgame Nash equilibrium). Assumptions of the game are detailed in Figure 1.

Figure 1. Stages of the IO model



In Stage 1, the benevolent regulator in charge of innovation decides whether to choose one type of innovation, namely hybrid or NPETs, denoted by $N=\{HY, NPETs\}$. If the innovation is selected, the economy incurs a sunk expenditure F_N, associated with the R&D investment, leading to a probability λ_N of getting the new good as revealed in Stage 2. The innovation does not emerge with a probability $(1-\lambda_N)$. Traditional hybridization is characterized by F_{HY} and λ_{HY}, and NPETs is characterized by F_{NPETs} and λ_{NPETs}. It is assumed that $F_{NPETs} > F_{HY}$ and $\lambda_{NPETs} > \lambda_{HY}$, which means that sunk costs and probabilities of innovation are positively correlated.[7] Sunk costs are incurred when investments are

[7] Few empirical cases suggest an opposite relationship for the cost, with $F_{NPETs} < F_{HY}$ and $\lambda_{NPETs} > \lambda_{HY}$. This configuration is not studied in this paper, but it is likely to lead to the welfare dominance of the NPETs if consumers are not too averse to this new technology.

made in the first stage and cannot be recovered (Sutton, 1991). To select the innovation, the regulator considers expected welfare defined by the sum of consumers' surpluses minus the sunk costs of R&D.[8]

In Stage 2, the outcome of the innovation investment previously decided in Stage 1 becomes known. If the innovation is successful, with a probability of success λ_N, new goods (hybrid or NPETS) are offered on the market. Conversely, if the innovation fails, with a probability $(1 - \lambda_N)$, only the conventional goods are sold on the market.

In Stage 3, the exchanges occur. Consumers know the characteristics of the sold good(s), except for the information about the type of innovation. Two cases are considered. First, consumers are fully informed about the underlying technology. Second, they are not or only partially informed on the technology and face costs of ignorance and regret. Market prices of goods are exogenously given for simplicity.

We now turn to equilibria at different stages, by starting, according to the backward induction principle, with Stage 3 and the way consumers' demand is determined.

3.2 Stage 3: Demands and surpluses under different configurations

Consumers' demands depend on the estimations of their surpluses that relate to their WTP. To convert consumers' WTP into demand curves, we assume that each consumer purchases one unit, providing the largest surplus approximated by the difference between WTP and the market price (Roosen and Marette, 2011; Rousu et al., 2014). Choices can be real or inferred, and hypothetical, depending on the type of survey and goods being considered.[9]

For the estimation of purchases in Stage 3, the available goods sold on the market are given and depend on the innovation investment made in Stage 1 and its realization in Stage 2. Consumers individually choose either, to purchase or not to purchase one unit of the goods, without mixing the two types of goods if both conventional and new goods are offered. The unit of the conventional good is sold at a price *P* (observed or relevant at the time of the experiment/survey) and the new good is

[8] Profits in the supply chain are addressed in the extension section.
[9] The consumers' surplus with the integration of the possible cost of ignorance regarding the innovation process is fully compatible with the value of information defined under welfare theory (Foster and Just, 1989; Teisl et al., 2001).

assumed to be sold at the same price $P_N = P$, for simplicity. The WTP for the new good is denoted by $WTP_{N_k}^m$ and the WTP for the conventional good is denoted $WTP_{C_k}^m$ for an informational message *m* on the technology and a consumer *k*. Informational messages *m* cover the technologies {*HY*, *NPETs*} and the case of no information provided on the technology.

Without innovation investment in Stage 1, or if the innovation fails to provide the new goods in Stage 2, the consumer *k* (with *k=1,…,K)* can choose between two outcomes in Stage 3: conventional good and none, with a utility normalized to zero. This case corresponds to the reference baseline of any experiment. Consumer *k* chooses a single unit of the conventional good, when this good brings a positive surplus, given by the difference between the WTP and the market price (and no good otherwise). Thus, the consumer surplus (*SC*) leading to the purchasing decision of a good is given by

$$SC_{C_k}^0 = Max\{WTP_{C_k}^0 - P, 0\}. \quad (1)$$

There is no information to be revealed since no new technology appeared.

With innovation investment in Stage 1, and if this innovation is successful in Stage 2, the consumer can choose between three outcomes in Stage 3: new good, conventional good and none. For a message *m* on the novelty component, consumer *k* chooses the purchasing alternative that generates the highest utility; her surplus becomes

$$Max\{WTP_{C_k}^m - P, WTP_{N_k}^m - P, 0\}. \quad (2)$$

The new good is selected if $WTP_{N_k}^m - P \geq Max\{WTP_{C_k}^m - P, 0\}$, and not selected otherwise, for turning to the other options depending on the comparison between 0 and $WTP_{C_k}^m - P$.

Two subcases can be considered here: i) with full information about the innovation technology and ii) without (or just partial) information about the technology. Under the first configuration, the consumer is fully informed on the innovation process and there is no ignorance cost or regret effect. Thus, the surplus for consumer *k* is described by equation (2) with a valuation for each technology (*HY* and *NPETs*) and with their respective "full-information" messages. Directly from equation (2), we

derive consumer surplus under the full information message (denoted by the superscript *fi*)

$$SC_{HY_k}^{fi} = Max\{WTP_{C_k}^{fi} - P, WTP_{HY_k}^{fi} - P, 0\} \quad (3a)$$

and $$SC_{NPETs_k}^{fi} = Max\{WTP_{C_k}^{fi} - P, WTP_{NPETs_k}^{fi} - P, 0\}. \quad (3b)$$

The second configuration with no (or only partial) information about the type of innovation technology leads to a decision based on equation (2) that subsequently the consumer could regret once that full information is revealed on the technology. Some consumers would make different decisions with the full information provided *ex ante*.[10] Therefore, the costly ignorance effect linked to the lack of full technology information needs to be accounted for by a benevolent regulator in the computation of the "complete" surplus. For a consumer purchasing a specific good, the effect of ignorance is given by the WTP for the good with full information minus the WTP related to the purchase. This allows to measure the difference between the "ideal" choice under full information and the "actual" choice without (or partial) information.

If goods sold are generated by hybrid methods, the complete consumer surplus accounting the absence of information about the technology (denoted by the superscript *ni*) along with the potential cost of ignorance after information revelation is

$$SC_{HY_k}^{ni} = Max\{WTP_{C_k}^{ni} - P, WTP_{HY_k}^{ni} - P, 0\}$$

$$+ J_{C_k}[WTP_{C_k}^{fi} - WTP_{C_k}^{ni}] + J_{HY_k}[WTP_{HY_k}^{fi} - WTP_{HY_k}^{ni}], \quad (4)$$

where J_{C_k} (respectively J_{HY_k}) is an indicator variable related to the effect of ignorance, taking the value of 1 if consumer *k* is predicted to have chosen the conventional (respectively new hybrid) good in the absence of information.

If goods sold are NPETs-generated goods and following the previous notation, the complete consumer surplus under no technology information and accounting for the potential cost of ignorance

[10] With the revelation of information about traditional hybridization or NPETs, consumers who were not initially purchasing a good could start buying it or start buying the alternative good or stop buying any good, and vice versa.

after information revelation is

$$SC_{NPETs_k}^{ni} = Max\{WTP_{C_k}^{ni} - P, WTP_{NPETs_k}^{ni} - P, 0\}$$

$$+ J_{C_k}[WTP_{C_k}^{fi} - WTP_{C_k}^{ni}] + J_{NPETs_k}[WTP_{NPETs_k}^{fi} - WTP_{NPETs_k}^{ni}], \quad (5)$$

where J_{C_k} (respectively J_{NPETs_k}) is an indicator variable related to the effect of ignorance, taking the value of 1 if consumer *k* is predicted to have chosen the conventional (respectively new NPETs) good in the absence of information.

Under the different configurations, the regulator will take into account the expected average surplus for one unit of the good over the *K* consumers in the economy (with *E(.)* the expectation operator), namely $E(SC_C^0)$ for the baseline without the new good, $E(SC_{HY}^{fi})$ and $E(SC_{NPETs}^{fi})$ for hybrid- and NPETs–generated goods under full information about the technology, $E(SC_{HY}^{ni})$ and $E(SC_{NPETs}^{ni})$ for hybrid- and NPETs-generated goods under no (or partial) technology information.

3.3. Stage 1: Choice of investment in R&D and expected welfare

The innovation investment in Stage 1 is decided based on expectations of events and market equilibria related to Stages 2 and 3. Stage 2 determines the realization of the investment resulting in a new good. For innovation investments *N*={*HY*,*NPETs*}, the innovation agency has a probability λ_N to get the innovative good leading to a welfare with new goods, and the innovation does not emerge with a probability $(1 - \lambda_N)$ leading to the welfare without innovation. Sunk expenditures F_N are associated with R&D investments and the authorization of new goods. They are incurred by the innovation agency and withdrawn from the welfare of consumers.

Under full information about technology and if the regulator chooses to invest with the technology *N*={*HY*,*NPETs*}, the expected welfare takes into account the probabilities λ_N and $(1 - \lambda_N)$. For the hybrid investment, the overall expected welfare (*W*) summed over all the consumers with their average consumption is given by

$$W_{HY}^{fi} = [\lambda_{HY} E(SC_{HY}^{fi}) + (1 - \lambda_{HY}) \times E(SC_C^0)] \times EXT - F_{HY}, \quad (6)$$

with *EXT* being an extrapolation parameter equal to the number of consumers multiplied by expected average consumption over a year. For the NPETs investment, the overall expected welfare is

$$W_{NPETs}^{fi} = \left[\lambda_{NPETs} E(SC_{NPETs}^{fi}) + (1 - \lambda_{NPETs}) \times E(SC_C^0)\right] \times EXT - F_{NPETs}. \quad (7)$$

In the absence of information about technology, the corresponding welfare measures are

$$W_{HY}^{ni} = \left[\lambda_{HY} E(SC_{HY}^{ni}) + (1 - \lambda_{HY}) \times E(SC_C^0)\right] \times EXT - F_{HY}\ , \quad (8)$$

$$\text{and } W_{NPETs}^{ni} = \left[\lambda_{NPETs} E(SC_{NPETs}^{ni}) + (1 - \lambda_{NPETs}) \times E(SC_C^0)\right] \times EXT - F_{NPETs}. \quad (9)$$

Finally, without any innovative investment and any new good, the expected welfare with conventional goods only is $W_C^0 = [E(SC_C^0)] \times EXT$.

For a given context of information (*fi*, *ni*,*0*), the comparison of *ex ante* welfares determines the regulator choice. For instance, for the case under full information, the regulator chooses the strategy resulting from $Max\{W_{HY}^{fi}, W_{NPETs}^{fi}, W_C^0\}$, which depends on surpluses and parameter values. Interestingly, the welfares comparison may lead to inequalities helping to define optimal strategies. The inequality $W_{HY}^{fi} > W_C^0$ is equivalent to $\varphi_{HY} < \lambda_{HY}\left[E\left(SC_{HY}^{fi}\right) - E(SC_C^0)\right]$, with $\varphi_{HY} = F_{HY}/EXT$, being the sunk cost per unit of sold good. In other words, this is a sunk cost by sold unit without being passed onto consumers into the market price. The same parameter will be used for $\varphi_{NPETs} = F_{NPETs}/EXT$. The relevant inequalities will conduct to the determination of the optimal policy, now applied to the apple case.

4. Application to apples

4.1 Summary of the apple experiments

We now apply the framework to a case study of novel apples. We first summarize the results from two recent experiments on WTP for apples under different technology messages (Marette et al., 2021).[11] We then expand and build upon these results by deriving consumer demands and performing a welfare analysis of the potential emergence of the new apple innovation.

[11] The experiments and the estimated WTPs are reported in details in Marette et al. (2021).

These hypothetical experiments were undertaken in France (Dijon) in December 2019 and the US Midwest (Ames, IA) in early March 2020. The number of surveyed consumers was equal to 162 in France, and 166 in the US. Successive rounds of WTP elicitation were conducted (see Figure A1 in Appendix A). An initial round (the baseline) focused on the conventional apples without informative message (message #0). Then, both conventional and new apples were presented in following rounds and consumers were asked to value conventional and new apples with improved attributes (non-browning and reduced bruising) under three different messages. These messages were as follows:

– The first message mentioned the innovation slowing the browning process without specifying the technology generating the innovation (corresponding to message *ni*);
– The second message delivered full information and specified traditional hybridization as the underlying technology (message *fi* for hybrid technology);
– The third message also provided full information and indicated gene editing (GE) as the source of the innovation (a specific case of NPETs) (message *fi* for GE).[12]

Pictures of goods were presented, and no specific apple variety reference was indicated. A multiple-price list (payment card) was used for eliciting WTP of consumers for 1kg of apples in France and 1 pound in the US, for both conventional and new apples. During each round, consumers were asked to choose whether (or not) they will buy the good for prices varying from €1.60 to €3.30 for 1 kg of apples in France and from \$0.70 to \$2.40 for 1 pound in the US (the quantity gap is justified by differences in consumption habits between these two countries). For each round and each good, the WTP was determined by taking the highest price consumers were willing to pay (namely, the highest "Yes" checked off in the list). If a consumer never replied "yes" to each line of the multiple-price list, the selected WTP was supposed to equal 0.

These rounds of information lead to WTPs for new apples denoted by $WTP_{N_k}^m$ (*N=HY, GE*), and for conventional apples denoted $WTP_{C_k}^m$ for an informational message *m*={0, *ni, fi for HY, fi for GE*}

[12] A fourth message noted GMO as the biotechnology used to generate the innovation. Given the overwhelming discounting of the new apple under that technology, it was clear that GMO apples would not emerge as an acceptable innovation. We therefore exclude this last round of WTP elicitation in the present paper.

and consumer *k*.

Experiment results show strong heterogeneity in consumers' WTP for both the conventional and new apples in both countries. To highlight this heterogeneity and compare the two countries, we normalize the WTP expressed by a consumer for the new good by the WTP he expressed for the conventional one for a given message. For an informational message *m* and a consumer *k*, the ratio is thus $(WTP^{m}_{N_k}/WTP^{m}_{C_k})$x100. Figure 2 presents the unitless ratios for informational message *ni* (only mentioning the benefits from the new good but not the underlying technology) and message *fi* for GE (detailing the GE innovation as a specific case of NPETs). We abstract from the ratios for the traditional hybridization (with message *fi* for HY) because they were nearly similar to those under message *ni*. The graph on the left presents results for France, while the graph on the right reports results for the US. In each graph, observations related to consumers are on the X-axis, and ratios on the Y-axis. Ratios are sorted by increasing order.

For both countries and curves, three groups of consumers can be distinguished: those who do discount the innovation (left part of curves with ratios lower than 100), those who are indifferent between both goods (central part of curves with ratios equal to 100), and those who value the new non-browning GE good with a positive premium (right part of curves with ratios higher than 100).

The impact of full information on GE technology on consumer WTP can be seen by the comparison between the blue curve (after message *ni*) and the red curve (after message *fi* for GE). The provision of GE information leads to a significant decrease in WTP expressed for the new good. A larger number of surveyed consumers discount the innovation with a negative premium. The decrease in premia is noticeable in the US and substantial in France. This result questions the acceptance of the GE innovation by some consumers, particularly in France.

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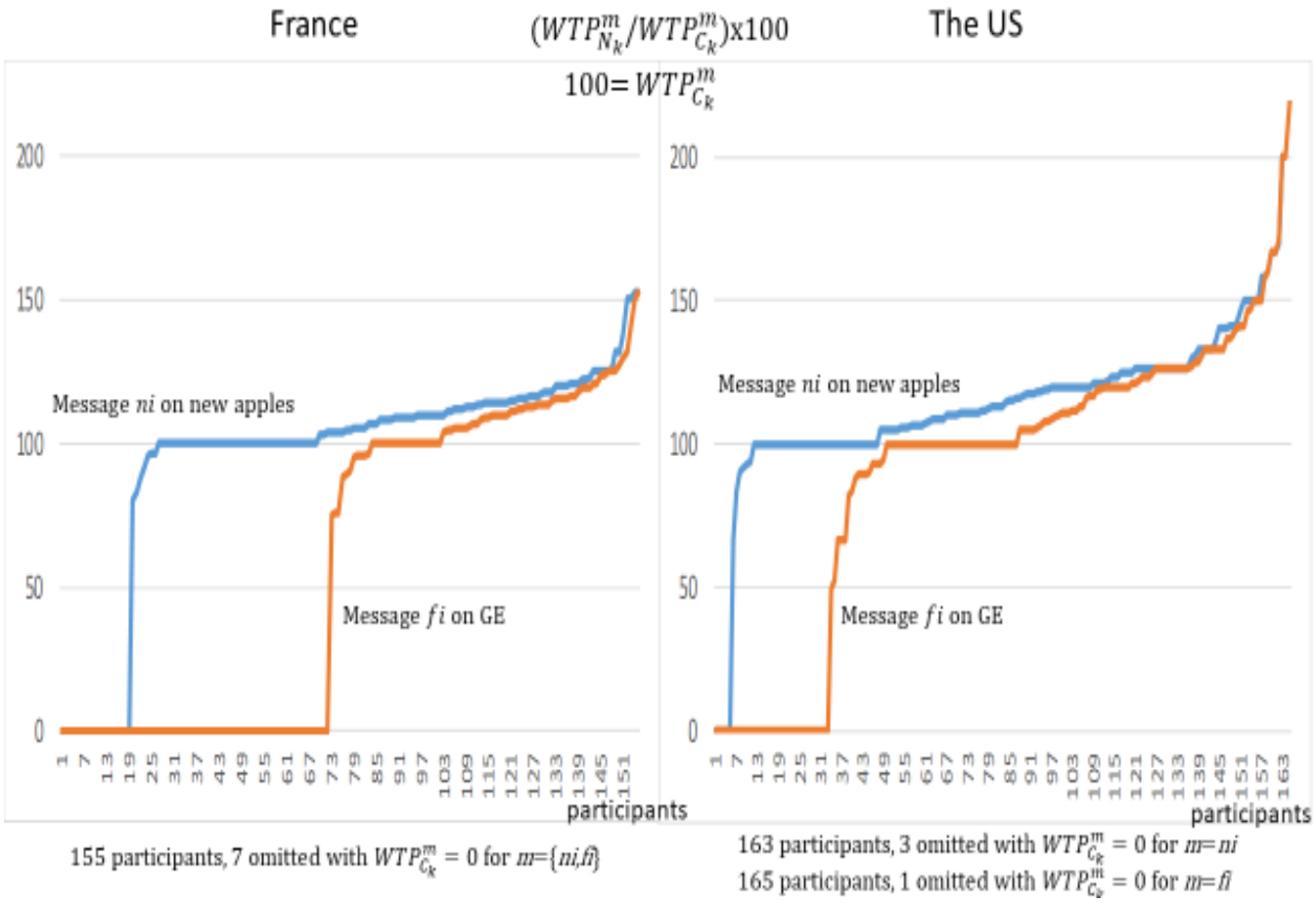
Figure 2. WTP expressed for the new GE apples relative to the WTP expressed for the conventional apples.



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However, in both countries there is also a significant group of consumers with a positive premium (ratios higher than 100) when fully informed about the GE innovation process (the right part of the orange curves), and *a priori* accepting the controversial technology. This group of accepting consumers is relatively larger in the US than in France. Moreover, in the US, a few consumers give

very high value to the GE innovation (extreme right of the orange curve). This group of accepting consumers is likely to make the adoption of GE possible and potentially socially desirable when full information about the GE technology is provided.

The values shown in Figure 2 become the basis for the surpluses computed in the next sub-section. The heterogeneity in consumer preferences (with pro- and anti-GE) particularly matters for understanding market adjustments and consumers' surpluses.

4.2 Simulations

Some additional assumptions are necessary before conducting simulations to select the socially optimal innovations. Consumers' surpluses derived from equations (1) to (5) are obtained by comparing their WTP and market prices. To set prices, we rely on observed prices in supermarkets at the time of the experiments and use the average observed price P_C for the conventional apples equal to €2.10 per kg in France and \$1.20 per pound in the US.[13] For simplicity, we keep assuming $P_N = P_C = P$ for the new good.[14] For allowing comparisons between both countries, the average surpluses for 1 kg with the French experiment are converted in a value of 1 pound (kg 1= LBs 2.2) in \$, by multiplying the French average surplus by (1.10/2.20), with €1 equal to \$1.10 on March 1, 2020 at the time of the second experiment. We now turn to simulations' results.

4.3 Estimated surpluses

Table 1 presents the average surpluses estimated for each country and for the different configurations as described in Stage 3 of Figure 1 and presented in equations (1)-(5), with GE being the specific NPETs technology.

Table 1 shows that for each configuration, the average surpluses are higher in the US than in France. For each country, surpluses with the new apples coming from the innovations are generally higher than the surpluses under the absence of new apples, except the case with GE under no

[13] These average prices are not in the middle of the price interval of the multiple-price lists for allowing higher valuations related to the innovation process.
[14] Prices could be different and endogenously determined, by considering a retailer choosing a price for the new good (with the price of the conventional apple being given) based on the WTP and assuming some ability to mark prices up.

technology information (message *ni* in the experiment, GE apple variety). Still the situation without information about the process of innovation leads to a surplus lower than the surplus under full information for the equivalent good (messages *fi* for HY and *fi* for GE). This result comes from the cost of regret in the absence of information on technology, which is included in the total consumer surplus.

Table 1. Average surplus for one pound of apples in US$ under the different configurations

	France	
Configuration: only conventional apples		
	Conventional variety	
Baseline (message *0*)	$E(SC_c^0) = 0.11$	
Configuration: both conventional and new apples (after the innovation success)		
	Hybrid variety	GE variety
No information (message *ni*)	$E(SC_{HY}^{ni}) = 0.16$	$E(SC_{GE}^{ni}) = -0.11$
Full information (message *fi*)	$E(SC_{HY}^{fi}) = 0.18$	$E(SC_{GE}^{fi}) = 0.17$
	The US	
Configuration: only conventional apples		
	Conventional variety	
Baseline (message *0*)	$E(SC^0) = 0.53$	
Configuration: both conventional and new apples (after the innovation success)		
	Hybrid variety	GE variety
No information (message *ni*)	$E(SC_{HY}^{ni}) = 0.70$	$E(SC_{GE}^{ni}) = 0.34$
Full information (message *fi*)	$E(SC_{HY}^{fi}) = 0.72$	$E(SC_{GE}^{fi}) = 0.65$

The surpluses with hybrid apples are higher than the respective surpluses with GE apples, since consumers are more enthusiastic about the hybrid technology than its GE counterpart. The discounting of the GE technology implies significant regret costs under the *ni* message, when consumers would only learn *ex post* about the technology. This explains why GE without technology information (message *ni*) leads to a much lower surplus ($\$-0.11$ for France and \$0.34 for the US) than the configuration where only the conventional good is available in the market (\$0.11 for France and \$0.53 for the US). The negative surplus for France ($\$-0.11$) is explained by the very high effect of ignorance leading to costly regrets.

In both countries, the surpluses with GE and full technology information (message *fi*, GE variety) are higher than those without the new good (message 0, conventional variety), but lower than the surpluses with hybrid apples (message *fi*, HY variety). However, the innovation with GE under information provision can be favored because of higher probability of innovation success for GE than for traditional hybridization. These probabilities are now considered in *ex ante* welfare analysis to understand the R&D investment decision.

4.4 Socially optimal innovation investments

We now derive *ex ante* welfare values in Stage 1 of the game, based on the consumers' WTP and related surpluses reported in Table 1. The comparison of *ex ante* per-unit welfare measures permits the selection of the socially optimal innovation strategy. We look at the potential investment choices maximizing per-unit welfares and leading to possible emergence of innovation with a probability λ_N for $N=\{HY,GE\}$, with $\lambda_{GE} > \lambda_{HY}$, meaning that GE accelerates the innovation and the likelihood of success.

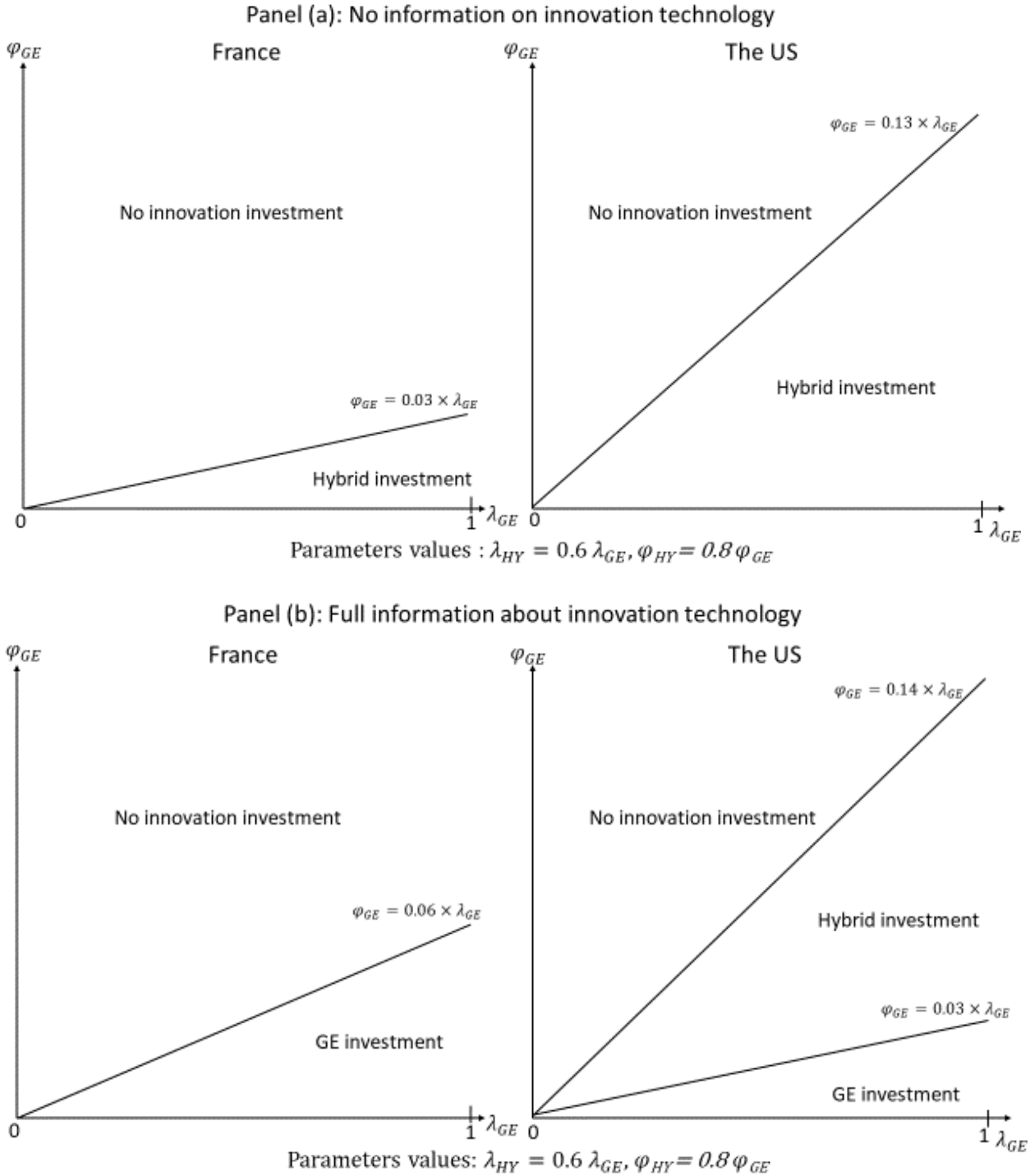
We start with the configuration under no technology information, in which the social objective is given by $Max\{W_{HY}^{ni}, W_{GE}^{ni}, W_C^0\}$. The comparison of per-unit welfares leads to simulations presented in Figure 3 panel (a), with the French configuration presented on the left chart and the US configuration presented on the right chart. On both charts, the probability λ_{GE} of getting the GE innovation is represented on the X-axis. The sunk cost per unit of sold good for the GE investment, $\varphi_{GE} = F_{GE}/EXT$, expressed in \$, is represented on the Y-axis. Specific parameter values ($\lambda_{HY} = 0.6\ \lambda_{GE}$, $\varphi_{HY} = 0.8\ \varphi_{GE}$) are used both for France and the US. The parameters related to the hybrid technology are implicitly represented, since in the simulations, $\varphi_{HY} = b\varphi_{GE}$ and $\lambda_{HY} = r\ \lambda_{GE}$, with $r,b<1$.[15]

Figure 3 panel (a) shows that the hybrid investment is socially optimal for relatively low levels of per-unit sunk cost. For relatively high-values of per-unit of sunk cost, there is no innovation investment and no emergence of the new good. Interestingly, the optimal hybrid investment linked to one unit of apples leads to a larger area in the US compared to France, because the per-unit surpluses

[15] Comparisons of welfares were performed using Mathematica software.

in Table 1 are higher in the US than in France.

Figure 3. Social choices maximizing the per-unit welfare in France and in the US



Note: The sunk cost per unit of good $\varphi_{GE} = F_{GE}/EXT$ coming from the GE investment is represented on the Y-axis. On each chart, the constraints are derived from welfare comparisons for reaching max $\{W_{HY}^{ni}, W_{GE}^{ni}, W_C^0\}$. For France, the equation $\varphi_{GE} = 0.03\,\lambda_{GE}$ is given by the equality $W_{HY}^{ni} = W_C^0$. For $W_{HY}^{ni} > W_C^0$, the inequality $W_{HY}^{ni} > W_{GE}^{ni}$ is systematically verified, and for $W_{HY}^{ni} < W_C^0$, the inequality $W_C^0 > W_{GE}^{ni}$ is systematically verified, which leads to the choices of the chart on the left. For the US, the same is observed with $\varphi_{GE} = 0.13\,\lambda_{GE}$.

This result suggests that return to innovations would be higher in the US than in France, providing larger R&D incentives in the US. This effect is amplified by the larger number of US

consumers embodied in the US extrapolation parameter *EXT* appearing in welfare equations (8) and (9). For both countries, the GE investment under no technology information does not emerge, because the cost of regret undermines the positive valuation of the novel apples. As shown in Table 1, the average per-unit surplus with GE under no technology information is lower than the one without new apples and with only conventional apples, eliminating any incentive to invest with GE.

Figure 3 panel (b) reports the simulations coming from a configuration under full information about the innovation technology with the regulator's maximization problem being $Max\{W_{HY}^{fi}, W_{GE}^{fi}, W_{C}^{0}\}$. The axes and the parameters values are similar to the ones of Figure 3 panel (a), except for the expected surpluses under different information contexts (see Table 1). Figure 3 panel (b) shows that, under full information, the GE investment is socially optimal for relatively low level of per-unit sunk cost φ_{GE}. As the per-unit surplus with the GE under full information is relatively high and close to the hybrid one (Table 1), the GE is socially beneficial since the probability of success is higher than the one with the hybrid investment (with $\lambda_{HY} = 0.6\,\lambda_{GE}$). In France, the GE investment dominates the hybrid investment for these relative success probabilities.[16] Moreover, because of consumers' preferences (Table 1), the traditional hybridization is preferred in the US for medium values of the sunk cost f_{HY}, since this sunk cost is lower than the one for GE with $\varphi_{HY} = 0.8\,\varphi_{GE}$. When the sunk costs of investments rise high enough, no investment is selected.

Beyond these simulations, the comparison of Figure 3 panels (a) and (b) shows that the emergence of GE is clearly linked to the context of information about the innovation technology. However, information about GE-based innovation might be difficult to grasp for consumers in actual situations, because of imperfect recall, labels/messages proliferations, and the complexity of the scientific knowledge leading to misunderstandings and confusions (Yokessa and Marette, 2019). This issue is larger than novel food as most goods consumed (cars, phones, computers, online services, etc.) embody complex technologies and production processes beyond the grasp of many consumers.

4.5. Extension with a collapse configuration

[16] For $\lambda_{HY} \geq 0.7\,\lambda_{GE}$, the hybrid investment replaces the GE investment in France.

We now investigate the risk of a collapse with the possible disappearance of the conventional product. Section 2 explored the acute issue of crop vulnerability. To account for this effect, we introduce ψ, the collapse probability of the conventional good following a disease, in Stage 2 of the game (see Section 3.1). The collapse does not happen with the probability $(1-\psi)$. The probability ψ is taken into account in Stage 1 by the benevolent regulator.[17] In such case, the conventional good disappears from equations (1) to (5); while $(1-\psi)$ is the probability of having the conventional good on the market as in equations (1) to (5) (see Appendix B for the detailed equations and Table B1 for the per-unit surpluses under this collapse case scenario).

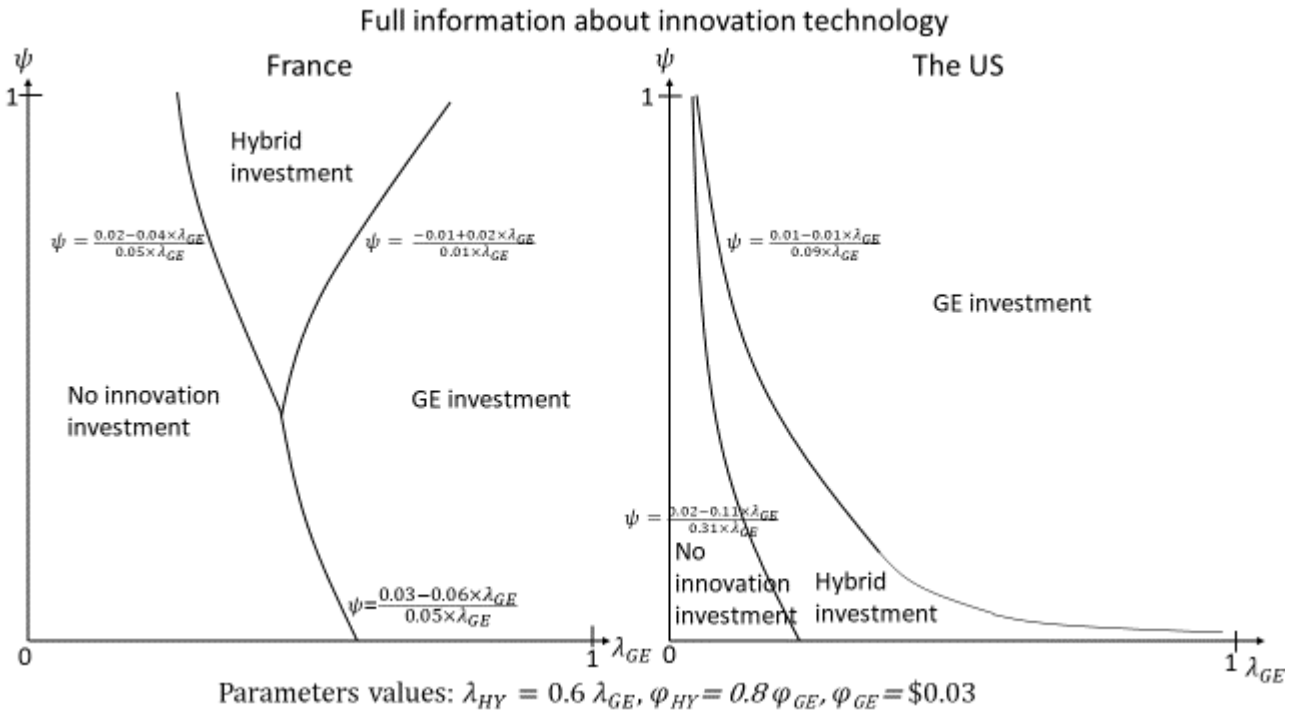
New *ex ante* welfare values in Stage 1 integrating the probability of a collapse are computed based on the consumers' WTP and related per-unit surpluses (Table B1 in Appendix B). The comparison of *ex ante* welfare measures (B3) to (B6) in Appendix B leads to the selection of the socially-optimal strategy. The simulations are shown in Figure 4, for France and the US (under full technology information only, for simplicity). A given level of per-unit sunk-cost is assumed with φ_{GE} = \$0.03. On each chart, the probability λ_{GE} of getting the GE innovation is represented on the X-axis and the probability ψ of collapse of conventional apples is represented on the Y-axis.

Figure 4 shows the respective influence of both probabilities λ_{GE} and ψ. When the probabilities of successful innovation λ_{GE} and $\lambda_{HY} = 0.6\,\lambda_{GE}$ are relatively low, the innovation investment is not selected (left side of each chart), because of low social benefits from new apples relative to the sunk cost φ_{GE} = \$0.03. Conversely, a relatively high value for the probability of collapse ψ (even with a low value of probabilities of innovation λ_{GE}) leads to the selection of innovation investments. The hybrid investment is socially optimum for medium values of λ_{GE} (middle of each chart). On the other hand, for high value of λ_{GE} (right side of each chart and bounded by $\lambda_{GE} = 1$), the GE investment clearly dominates because of the likely emergence of the innovation. Thus, the GE strategy is reinforced with the risk of a collapse. Note that this important significance of the GE investment also

[17] This is a simplifying assumption making the regulator able to predict the probability of accident. In many configurations, the collapse cannot be predicted in Stage 1 and cannot directly influence the R&D investment with the timing for the innovation to emerge that is very long (20-25 years). Despite the absence of a clear probability, a R&D policy can be implemented for having an option value with new foods if a collapse happened.

exists under no technology information for the US with small areas, but not for France because of negative values of surplus from Tables 1 and B1 for GE under no technology information.

Figure 4. Risk of collapse and socially optimal choices in France and in the US



Note: The sunk cost per consumer $\varphi_{GE} = F_{GE}/EXT$ coming from the GE investment is represented on the Y-axis. On each chart, the constraints are derived from welfare comparisons for reaching max $\{\overline{W}_{HY}^{fi}, \overline{W}_{GE}^{fi}, \overline{W}_{C}^{0}\}$ with expressions given in Appendix B.

4.6. Extension with costly regrets limited to a subgroup of consumers

We now explore the effect of ignorance under no technology information (see equations (4) and (5)). In our analysis, the ignorance effect integrates differences in WTP under various contexts of information provision and concerns all consumers. In the real world (e.g., in stores outside the lab) however, regrets due to the ignorance effect are likely to only be costly for very concerned consumers.[18] To address this bias that may affect our analysis and identify consumers really concerned in practice by the innovation process (natural such as traditional hybridization vs. based on biotechnologies such as GE and other NPETs), we rely on the exit questionnaire answered by surveyed

[18] The lab creates a focalization bias towards specific questions related to food innovation which some consumers will forget outside the lab.

consumers during the experiment. This questionnaire provides clues regarding food habits and the level of concerns in real world contexts. In particular, a strong consumption of organic fruits and vegetables is likely to indicate a significant concern regarding information about NPETs such as GE, as many of these consumers try to shun GMOs via organic choices.

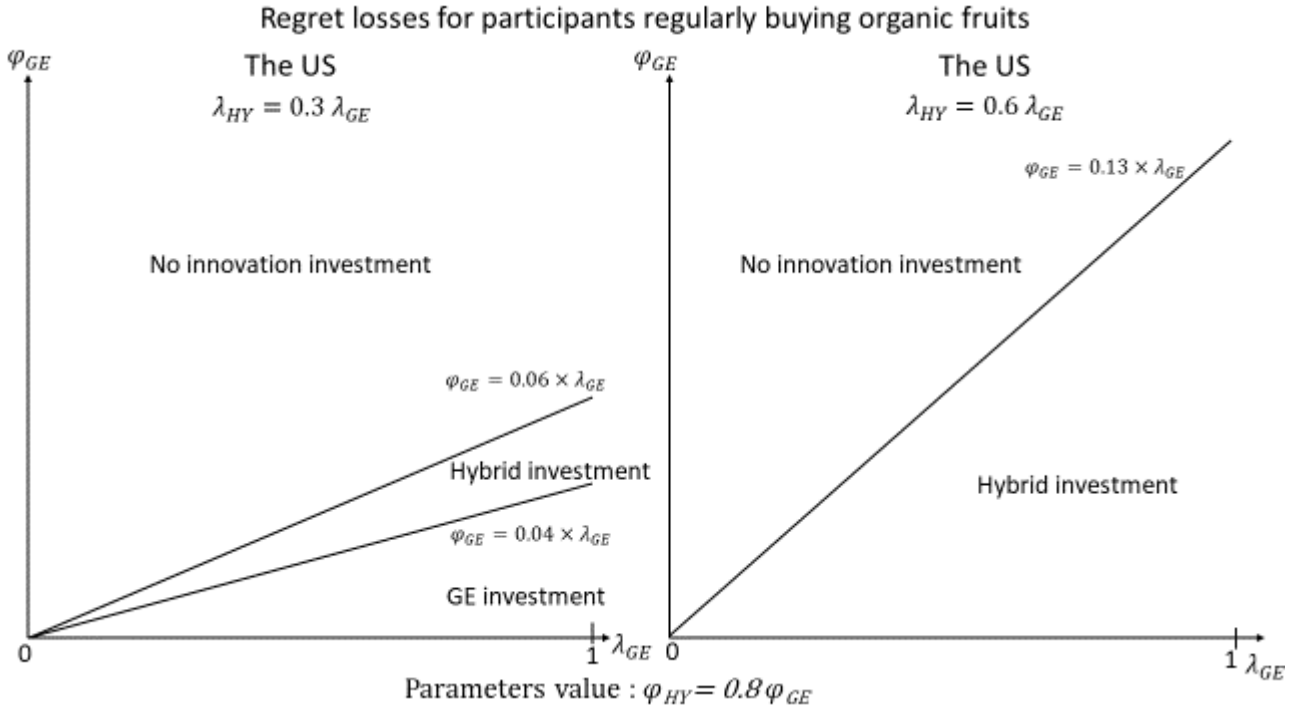
From the exit questionnaire, we isolate consumers with a regular and exclusive consumption of organic fruits and vegetables and create a new dummy variable equal to 1 for those consumers (and 0 otherwise). This dummy variable is multiplied to J_{C_k} and J_{NPETs_k} in $SC^{ni}_{NPETs_k}$ given by equation (5). In other words, the effect of ignorance really matters for those concerned consumers only, while others are indifferent to it outside the lab. Applying the new dummy variable to the US case only (and with GE as a specific case of NPETs) for simplicity, leads to an increase in the expected surplus for the GE innovation under no technology information from Table 1, with a shift from $E(SC^{ni}_{GE}) = 0.34$ to a new value $E(SC^{ni}_{GE})' = 0.59$, reflecting the lower number of consumers really affected by regrets. This new value integrated in equation (5) leads to a higher acceptance of the GE technology under no technology information.

Figure 5 shows the social optimum R&D choice for the US under this new configuration. Results reported in the left chart suggest that GE may be socially beneficial when consumers' losses from regrets are limited to a subgroup of very concerned consumers, and when the probability of success with the GE is significantly higher than the one for traditional hybridization (λ_{HY} =0.3 λ_{GE}), and for low values of the sunk cost. However when the probability of success of hybrids gets closer to that of GE (right chart, with λ_{HY} =0.6λ_{GE}), GE does not emerge as socially optimal as it was already the case in Figure 3 panel (a).

We consider further extensions in Appendix C, extrapolating our results to the whole country. We also discuss how to incorporate a supply chain with seedlings, apple producers, and retailers. In addition, prices for novel apples could be endogenized. Some dynamic elements could also be considered with multiple periods and consumers becoming more accepting of biotechnology as in the papaya case. The model could be extended to international trade with the associated regulatory issues

for biotech goods to cross borders.

Figure 5. Social choices maximizing the per-unit welfare in the US under no technology information



5. Conclusions

In this paper, we emphasized the important role of consumers' preferences, along with R&D spending, and uncertainty in the resulting success of innovative foods in the marketplace. We developed and utilized a simple IO model for R&D investment in food innovations based on NPETs and traditional hybridization methods, to identify which technology emerges under various parameter characterizations and associated economic welfare outcomes. Our simulations show that information delivered to consumers matters for determining social benefit outcomes resulting from innovations based on NPETs and hybridization. Performed simulations also suggest that NPETs, such as GE, may be socially beneficial when consumers are informed about the technology, or when they experience limited regret losses (thus, when not informed, before their purchases take place). Otherwise, the innovation based on traditional hybridization is socially optimal, which is particularly true when the values of the probabilities of success under NPETs and hybridization are relatively similar. Finally, the reluctance for NPETs-based novel foods by some consumers makes the adoption of this technology

uncertain, particularly in France.

We further explore a series of potential and easily implementable extensions, in Appendix C, to flesh out the developed and utilized approach beyond the essence of consumers' WTP, sunk cost of R&D processes, technology information and probabilities of success of those technologies. Noteworthy, we look at a collapse scenario by altering the choice set for consumers in which the conventional food is no longer available,

Despite limitations resulting from stylized WTP elicitations and IO approaches, our methodology can be replicated for R&D related to all sorts of food novelties and other potentially disruptive technologies as pointed out by Herrero et al. (2020). The case of apples demonstrates the feasibility of the approach and suggests it could be applied in varying configurations. The consumers' acceptance influencing private and social profits could be estimated *ex ante* via experiments before the effective introduction of a novel food on a market. Welfare estimates would help to guide public debates about the future of foods generated by new and sometimes controversial technologies.

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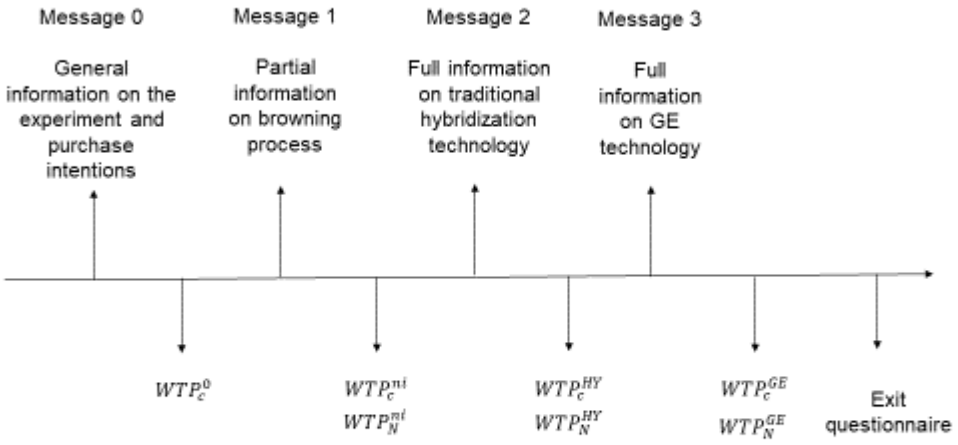
Appendices (not intended for publication)

Appendix A. Additional figure

Figure A1. Experiment design and timeline



Note: C: conventional product; N: new product ; ni: no information; HY: hybrids; GE: gene editing

Appendix B. Welfares under the collapse case

Surpluses if the conventional good collapses

With the collapse of conventional apples, only the innovative apples are sold on the market, and the previous surpluses can be rewritten by withdrawing all the options linked to the conventional good (and by adding a bar above surplus and welfare expressions to differentiate them). The equation (1) now leads to a surplus equal to zero under the absence of innovation and collapse. Equation (2) becomes $Max\{WTP_{N_k}^m - P, 0\}$ with the disappearance of the conventional good. From equations (3a) and (3b), the surpluses under full information on technology are now $\overline{SC}_{HY}^{fi} = Max\{WTP_{HY_k}^{fi} - P, 0\}$ and $\overline{SC}_{NPETs}^{fi} = Max\{WTP_{NPETs_k}^{fi} - P, 0\}$. From equations (4) and (5), the surpluses under no technology information can also be rewritten. If goods sold are generated by hybrid methods, the complete surplus is

$$\overline{SC}^{ni}_{HY_k} = Max\{WTP^{ni}_{HY_k} - P, 0\} + J_{HY_k}[WTP^{fi}_{HY_k} - WTP^{ni}_{HY_k}], \quad \text{(B1)}$$

where J_{HY_k} is an indicator variable related to the effect of ignorance, taking the value of 1 if consumer *k* is predicted to have chosen new hybrid good after the message with no technology information (denoted by the superscript *ni*). If goods sold are NPETs-generated goods and following the previous notation, the complete surplus becomes

$$\overline{SC}^{ni}_{NPETs_k} = Max\{WTP^{ni}_{NPETs_k} - P, 0\} + J_{NPETs_k}[WTP^{fi}_{NPETs_k} - WTP^{ni}_{NPETs_k}], \quad \text{(B2)}$$

where J_{NPETs_k} is an indicator variable related to the effect of ignorance, taking the value of 1 if consumer *k* is predicted to have chosen NPETs-generated good after the message with no technology information (denoted by the superscript *ni*).

The collapse may (or not) occur in Stage 2 of the game (see section 4.5). In Stage 1, the regulator anticipates the risk of collapse by integrating the probability ψ with the surplus detailed in the previous paragraph, and the absence of collapse by integrating the probability $(1-\psi)$ with the related surplus detailed in equations (1) to (5). The regulator also accounts for the probability of innovation success (λ_N) and the probability of innovation failure (1-λ_N), depending on the type of investment (see sections 3.1 and 3.2). Thus, the expected welfare measures computed in Stage 1 integrate the probability of different events.

Under full information and for the hybrid investment, the overall expected welfare of the economy is given by

$$\bar{W}^{fi}_{HY} = (1-\psi)\left[\lambda_{HY}E\left(SC^{fi}_{HY}\right) + (1-\lambda_{HY}) \times E(SC^0)\right] \times EXT$$
$$+ \psi\lambda_{HY}E(\overline{SC}^{fi}_{HY}) \times EXT - F_{HY}, \quad \text{(B3)}$$

with the expectation *E(.)* and *EXT* being an extrapolation parameter equal to the number of consumers multiplied by average consumption over a year.

Under full information and for the NPETs investment, the overall expected welfare of the economy is given by

$$\bar{W}^{fi}_{NPETs} = (1-\psi)\left[\lambda_{NPETs}E\left(SC^{fi}_{NPETs}\right) + (1-\lambda_{NPETs}) \times E(SC^0)\right] \times EXT$$

$$+\psi\lambda_{HY}E(\overline{SC}_{NPETs}^{fi}) \times EXT\ - F_{NPETs}. \quad \text{(B4)}$$

The corresponding welfare measures for the hybrid and NPETS investment under no technology information are as follows

$$\bar{W}_{HY}^{ni} = (1-\psi)\left[\lambda_{HY}E\left(SC_{HY}^{ni}\right) + (1-\lambda_{HY}) \times E(SC^0)\right] \times EXT$$

$$+\psi\lambda_{HY}E(\overline{SC}_{HY}^{pi}) \times EXT - F_{HY}\ , \quad \text{(B5)}$$

and

$$\bar{W}_{NPETs}^{ni} = (1-\psi)\left[\lambda_{NPETs}E\left(SC_{NPETs}^{ni}\right) + (1-\lambda_{NPETs}) \times E(SC^0)\right] \times EXT$$

$$+\psi\lambda_{HY}E(\overline{SC}_{NPETs}^{ni}) \times EXT - F_{NPETs}. \quad \text{(B6)}$$

Without any innovative investment and without any new good, the expected welfare with conventional goods only is $\bar{W}_C^0 = (1-\psi)[E(SC^0)] \times EXT$.

Results from the experiment with apples

The simulations under the collapse case based on the experiment with apples lead to the results reported in Table B1, with GE being the specific NPETs technology (as indicated in the subscripts).

Table B1. Average surplus for one pound of apples in US$ under the collapse case with no conventional apples on the market

	France	
Configuration: no apples	$E(SC) = 0$	
Configuration: only new apples (after the innovation success)		
	Hybrid variety	GE variety
No information (message *ni*)	$\overline{SC}_{HY}^{ni} = 0.15$	$\overline{SC}_{GE}^{ni} = -0.15$
Full information (message *fi*)	$\overline{SC}_{HY}^{fi} = 0.17$	$\overline{SC}_{GE}^{fi} = 0.11$
	The US	
Configuration: no apples	$E(SC) = 0$	
Configuration: only new apples (after the innovation success)		
	Hybrid variety	GE variety
No information (message *ni*)	$\overline{SC}_{HY}^{ni} = 0.69$	$\overline{SC}_{GE}^{ni} = 0.30$
Full information (message *fi*)	$\overline{SC}_{HY}^{fi} = 0.70$	$\overline{SC}_{GE}^{fi} = 0.52$

These per-unit surpluses under the collapse case and the ones detailed in Table 1 under the absence of collapse are integrated in welfare equations (B3) to (B6), leading to Figure 4.

Appendix C. Other extensions of the approach

In the previous sections, we considered *ex ante* welfares based on several simplifications. To focus on the main economic mechanisms at work, we kept the mathematical aspects as sparse as possible by using simple assumptions. Our analysis could accommodate alternative situations using the following extensions.

(1) In the previous section, we focused on per-unit welfare for facilitating comparisons, which is a limitation. Extrapolations of surpluses were made with the parameter *EXT* allowing to get the welfares over one year for the whole country and all apples. For instance, in 2018, the average apple consumption per inhabitant in France was equal to 6.95 kg/year.[19] Multiplying this quantity by the 67,064,000 inhabitants in France leads to an extrapolation parameter *EXT* = 466,532,174 and significant social welfare estimates. Thus, the overall surplus over a year for the whole population is calculated by integrating this parameter *EXT* in equations (6) to (9). Despite the fragility of extrapolations, they provide clues for identifying potential benefits compared to R&D sunk costs.

(2) Our analysis abstract from production and supply chain. We could integrate cost functions for producers of apples, retailers and seedling industries. To do so, equation (6) could be rewritten for example, as follows:

$$W_{HY}^{fi} = \lambda_{HY} \times \left\{\Pi^{fi}(HY) + \Pi^{fi}(C) + E\left(S_{HY}^{fi}\right) \times E\right\} + (1 - \lambda_{HY}) \times \{\Pi^{0}(C) + E(SC^{0}) \times E\} - F_{HI}, \quad (10)$$

for the technology HY, and by denoting $\Pi^{fi}(HY)$ (resp. $\Pi^{fi}(C)$) the profits for the supply chain offering new goods (resp. conventional goods) under the innovation regime. Profit $\Pi^{0}(C)$ denotes the profits for the supply chain offering conventional goods without introduction of novelty in the market. Different types of models could be used for determining profits using demand calibrated with price elasticities, and or experimental results for the characteristics influencing that demand (Marette et al., 2008). Alternatively to this profit characterization, marketing orders bringing together farmers and

[19] See https://rnm.franceagrimer.fr/bilan_campagne?pomme.

Universities could also be studied with a per-unit paid by farmers for financing the R&D and impacting the price of apples.

(3) Prices of conventional and new goods are exogenously given both in our model and in the empirical application. Endogenous adjustments of prices could be also made by considering profits presented in equation (10).

(4) We considered just one period of exchanges. Several periods of exchanges with different probabilities of success in the innovation could be envisaged. For two periods of exchanges (for simplicity), the probability λ_N of having innovation immediately at the first period or $(1-\lambda_N)\lambda_N$ at the second period leads to an "overall" benefit including the discount factor between the two periods equal to δ (and with *N={HY,NPETs}*). Extending equations (8) and (9) with a fourth additional stage in the model integrating a second period of exchanges with similar parameters regarding the market configurations, the net welfare for a society investing in R&D at Stage 1 is defined by $\left[\{\lambda_N(1+\delta)+(1-\lambda_N)\lambda_N\delta\}\times E(SC_N^{pi})+\{(1-\lambda_N)+(1-\lambda_N)^2\delta\}\times E(SC^0)\right]\times E-F_N$. This equation can be expanded through multiple time periods.

(5) In a dynamic context, consumers may update their preferences and WTP when GE apples are introduced (with GE as specific case of NPETs). After a certain period of time, particularly if the safety of new apples could be established, consumers may revise their WTP for GE apples upwards, making the market introduction easier than the one underlined in previous simulations. For the consumers discounting GE, the revision of beliefs may lead to update WTP for new apples and bring those values closer to WTP for conventional apples. Moreover, WTP may be evaluated with other methodologies, including field experiments in supermarkets when the new apples are effectively introduced and sold.

(6) Other methods for fruit and vegetables improvements exist and could be added in the analysis, leading to more goods and regulatory options to evaluate. For instance, there are classical GMOs such as the resistant papaya now sold on the US market (see section 2). Alternatively, Marker Assisted Selections and DNA-assisted selective breeding methods tend to partially use the GE for

helping and refining the classical technique of plant hybridization. These alternative techniques could be also taken into account in the analysis with new and specific probabilities λ_N of getting new goods. A meta-analysis isolating the WTP for different foods generated with various technologies (Lusk et al, 2005b) may also be used for replicating consumers' attitudes toward new foods, when R&D programs are launched. Other technologies of interest are mentioned in Herrero et al. (2020).

(7) The regulator may simultaneously promote both technologies for boosting chances of innovation. One solution would consist of having classical hybridization in one research center and NPETs in another research center. If both programs are simultaneously decided and launched, the probability of innovation would be $\lambda_{HY}\lambda_{NPETs} + (1 - \lambda_{NPETs})\lambda_{HY} + (1 - \lambda_{HY})\lambda_{NPETs}$.

(8) The configuration with or without information about the technology could be endogenous, meaning that the regulator decides whether or not to perfectly inform consumers about the process of innovation, namely traditional hybridization or NPETs, by incurring additional cost, entailing a campaign of information and/or a label.[20] These costs could be taken into account in a cost-benefit analysis accounting for R&D and markets adjustments.

(9) Additionally, the sunk costs F_{NPETs} and F_{HY} and the probabilities λ_{NPETs} and λ_{HY} could be evaluated with interviews, questionnaires and financial analyses. Their evaluations could increase the credibility of any *ex ante* analysis searching to define the social benefit related to new food innovations.

(10) In the model, we only focused on a per-country situation, similar to a quasi-autarky situation. However, countries may import/export with the sensitive question of the new goods authorization. Trade could be a powerful way to boost success probabilities by benefiting from more sales, lower prices coming from competition and foreign R&D investments increasing the diversity of goods. The international regulatory aspects regarding new and innovative goods appear as an important

[20] According to the FDA Labeling Cost Model, administrative costs (in 2017 dollars) per UPC for minor, major and extensive labeling changes range from $341 to $2,971, $776 to $5,993, and $1,039 to $7,632, respectively. The fixed costs (documentation and generation of records) associated with labeling range from $35 to $113 per UPC. In addition, costs of printing and applying new labels may be incurred and range from $288 to $814 per UPC. Finally, administrative and signage costs to grocery stores (retail display sign costs) range from $20 to $200 per sign. Coordinating a regulatory mandated label change with changes that are already occurring for other business reasons (e.g. change in marketing or need to restock label supply) can dramatically lower costs. Firms only incur additional printing costs if the regulatory mandate requires acceleration of printing and/or the disposal of existing label stock. (RTI International, 2015).

question.