New Plant Engineering Techniques, R&D Investment, and International Trade

Stephan Marette, Anne-Célia Disdier, Anastasia Bodnar, John Beghin

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Stéphan Marette (Paris-Saclay)[a*]

Anne-Célia Disdier (PSE)[b]

Anastasia Bodnar (USDA OCE)[c]

John Beghin (UNL)[d]

Abstract: New Plant Engineering Techniques (NPETs) may significantly improve both production and quality of foods. Consumers and regulators around the world might be reluctant to accept such products, which may cripple adoption and global market penetration of these products. We develop a parsimonious economic model for R&D investment in food innovations to identify conditions under which NPET technology emerges in a context of international trade. The framework integrates consumers' willingness to pay (WTP) for the new food, the uncertainty of R&D processes, the associated regulatory cost of approval, and the competition between domestic and foreign products. With generic applicability, the model enables the quantitative analysis of new foods that could be introduced in markets and then traded across borders. We apply the framework to a hypothetical case of apples improved with NPETs. Simulation results suggest that import bans and high values of sunk costs can reduce R&D investment in NPETs to suboptimal levels.

Keywords: new plant engineering techniques (NPETs); genome editing (GenEd); trade; willingness to pay (WTP); food innovation; industrial organization; apple, nontariff measure (NTM)
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[a]Corresponding author: Université Paris-Saclay, INRAE-AgroParisTech, UMR Economie Publique, Avenue Lucien Brétignières, 78850 Thiverval-Grignon. France; Email: marette@agroparistech.fr. [b]Paris School of Economics-INRAE, 48 boulevard Jourdan, 75014 Paris, France. Email: Anne-Celia.Disdier@psemail.eu. [c]US Department of Agriculture Office of the Chief Economist. Washington DC. Email: Anastasia.Bodnar@usda.gov. [d]Yeutter Institute of International Trade and Finance and Department of Agricultural Economics, University of Nebraska Lincoln, Lincoln NE 68583, USA. Email: beghin@unl.edu.
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1. Introduction

New Plant Engineering Techniques (NPETs) refer to recent developments in tools used in biotechnology. NPETs include cisgenesis (genetic modifications using genetic material from the same or related species), targeted deletions or substitutions of gene sequences with genome editing (GenEd), and other methods (Lusser et al., 2011). NPETs can result in improvements such as increased resistance to biotic and abiotic stresses or improved food and feed quality. GenEd in particular is faster and less costly than other genetic engineering techniques (Ricroch et al., 2017), and allows a wider variety of genetic changes. Small insertions, single nucleotide substitutions, and deletions can be made with precision. GenEd requires less scale in adoption to cover the fixed costs associated with research and development (R&D) and regulatory approval, particularly for those products that could have resulted from conventional breeding (Bullock et al., 2021; Purnhagen and Wesseler, 2020). International trade in these products could enhance profit opportunities for producers and benefit consumers with access to improved goods and more choice.

Our paper analyzes the emergence of NPETs-based food innovations using a parsimonious model combining the cost of uncertain food innovations with heterogeneous consumers' WTP for those innovations in a context of international trade. In our setup, two countries can compete in innovations, produce improved foods, and exchange them, if allowed, across borders. We apply this model to a calibrated case study of a hypothetical development and introduction of GenEd improved apple varieties into domestic and/or international markets, and analyze the welfare impact of NPETs regulatory and trade policy heterogeneity across countries.

1.1 Research and development

Public investment in R&D potentially mitigates some reluctance of innovators and producers by maintaining conditions under which improved foods developed with NPETs could emerge. Many countries have made significant R&D investment to improve agricultural production. In high-income countries[1], publicly funded agricultural R&D expanded in real (inflation-adjusted) terms between 1960 and 2009, then began to decrease, even as agricultural productivity continued to increase (Heisey, 2018).

The US invests in agricultural R&D, including for biotechnology, through many federal agencies, including the US Department of Agriculture (USDA), (Jahn, 2020), though the percentage of federal R&D funds spent on agriculture declined from 40% in 1940 to just 2% today (Rowley, 2020). The EU has a long history of public R&D funding for biotechnology, including as part of "Horizon 2020," an EU-wide effort to address societal challenges (Aguilar et al, 2012; European Commission, 2021). More recently, India, Brazil, and other countries are increasing agricultural R&D investment (Clancy, 2016), including for foods improved with NPETs. Notably, China is leading in GenEd-related publications (Ricroch et al., 2017) and patents (Menz et al., 2020) in agricultural applications.

Even with adequate investment, innovations and varietal improvements in agriculture can be a slow and costly processes. Development of new varieties of tree crops, such as apples, can be particularly costly due to the length of time between generations, although dwarf rootstock has accelerated the process (Crassweller and Pollock, 2021). For example, Washington State University's development of the Cosmic Crisp apple variety with traditional breeding methods began in 1997 but trees were not widely available to growers until 2019 (Wilhite, 2014).

Using GenEd, scientists can introduce a new trait directly into an existing variety, greatly decreasing the time needed for breeding and varietal testing from more than 10 years to 4-6 years (Alvarez et al., 2021). To date, GenEd has been used to improve traits such as flowering time and

[1] Australia, Canada, most European Union (EU) members, Iceland, Israel, Japan, New Zealand, Norway, South Korea, Switzerland, and the UK (Heisey, 2018),

disease resistance in apples, though GenEd apples have not yet been commercialized (Ramirez-Torres, 2021). The reduced time and cost needed for GenEd make this breeding method accessible to smaller companies and academic institutions using public research funding or checkoff program funding, such as the program at Washington State University for developing new apple varieties.

1.2 Hurdles to innovation commercialization

Despite great promise, improved foods from plants and animals developed with NPETs (hereafter, improved foods) face two significant hurdles: consumer acceptance and regulatory heterogeneity across borders.

Consumer acceptance is uncertain as some consumers dislike biotechnology, whereas other consumers value new attributes that may be brought about by NPETs (Lusk et al, 2005; Caputo et al., 2020; Marette et al., 2021; Beghin and Gustafson, 2021). Consumer food choices are based on many factors, including price and quality (Lusk et al., 2011). Improved foods may have qualities of interest to consumers that are limited or not present in conventional foods, such as non-browning in apples. Improved foods may be higher priced than conventional foods to account for such qualities, or may be lower priced due to lower production costs or other factors. Further, consumers may have specific preferences for varieties (horizontal differentiation) of foods, and specific preferences for domestic foods (home bias). For NPETs specifically, consumer choice may also be based on knowledge of the innovations used to develop foods.

When asked to identify concerns about food, only a small percentage of consumers mention biotechnology; a higher percentage expresses a negative opinion when specifically asked about biotechnology (e.g., Armstrong et al., 2021). Information to consumers is likely to play a crucial role in NPETs acceptance, but simply providing information about technologies used to produce a food can reinforce negative beliefs (Grunert, 2002). However, specific applications of biotechnology may be more accepted (Tallapragada et al., 2021). Generally, consumer knowledge of NPETs is limited and is partially informed by labels announcing the presence or absence of ingredients developed with biotechnologies (Kolodinsky et al., 2019; Caputo et al., 2020; Beghin and Gustafson, 2021).

Perhaps more importantly, the regulatory landscape for NPETs is deeply heterogeneous across countries (Hamburger, 2019; Menz et al, 2020; Turnbull et al., 2021), potentially compromising the adoption and acceptance of NPETs in some countries. International trade and market penetration of these food innovations across borders could be obstructed (Sheldon, 2002; Qaim, 2020). The double hurdle of regulatory approval and consumer acceptance is reminiscent of the long controversy on genetically modified organisms (GMO) which started three decades ago (Sheldon, 2002; Disdier and Fontagné, 2010; Anderson, 2010; De Faria and Wieck, 2015). Heterogeneous regulations across borders, lack of transparency in approval process, import bans, trade disputes, co-mingling issues, and traceability requirements are tangible problems facing NPETs.

The heterogeneous regulatory environment across borders is characterized by additional uncertainty because many countries have not yet set regulatory policies for some NPETs, including GenEd (Menz et al., 2020). Second, among countries which have defined or are defining regulations, the "process versus product" dichotomy remains problematic. Some countries regulate based on the production process (such as genetic engineering, genome editing, or conventional breeding), while other countries regulate based on the end product, regardless of how it was produced. For example, the USDA since 2020 exempts from additional regulation certain modifications that could have been obtained with conventional breeding (USDA, 2021). Other US agencies with biotechnology regulatory authorities – the Food and Drug Administration (FDA) for foods or the Environmental Protection Agency (EPA) for pesticidal proteins (plant-incorporated protectants) or other pesticide related traits – are currently revising their regulations and policies on this topic. Similarly, the United Kingdom recently announced plans for reduced regulatory scrutiny for certain GenEd products (Stokstad, 2021).

By contrast, the Court of Justice of the European Union ruled in 2018 that products resulting from GenEd and other NPETs are akin to transgenic products, thus subject to a stringent regulatory approval process whether or not they include only genetic material from the same or related species. However, several EU member states and the EU scientific community are pushing for major regulatory changes (Turnbull et al., 2021). A European Commission study regarding the status of NPETs under EU law called for additional policy action, particularly for products that could have been obtained with conventional breeding (European Commission, 2021). Other countries, such as Japan and Argentina, have policies combining product- and process-based standards on food safety, the depth of novelty, and the departure from foods already approved and in the marketplace (Hamburger, 2019; Turnbull et al., 2021). Table A1 in the Appendix A summarizes the approaches implemented in the US, EU and rest of the World (RoW). Strong heterogeneity across countries is observed at each step (research, trade policy, domestic policy, farmer production, and consumer information).

1.3 Modeling development and introduction of innovations in open economies

The model considers the emergence of improved foods in a context of international trade, accounting for R&D and production costs and consumers' WTP for these innovations. Our setup includes two countries competing in R&D, producing improved foods, and exchanging them, if allowed, across borders. The model application is a case study of a hypothetical development and introduction of improved apple varieties into domestic and/or international markets. The application builds upon the results of two experimental surveys of consumers' preferences in France and the US (Marette et al., 2021a). The experiments used fictitious choices and different technology messages (on traditional breeding and GenEd as a representative case of NPETs), to estimate the WTP of 162 French and 166 US consumers for hypothetical improved apples, which do not brown upon being sliced. Many consumers in both countries discount apple improvement obtained through GenEd, relative to traditional breeding. However, a significant group of consumers in both countries knowingly accepts and value the hypothetical GenEd apples.

Based on the consumers' WTP values in the two countries and using a Mussa-Rosen model of vertical differentiation (Mussa-Rosen, 1978) to accommodate the perceived quality differences between improved and conventional apples, we derive the demand for the improved apples. We compute market equilibrium in a trade model considering the EU and the US as innovators, and the RoW as a residual trade partner absorbing some of the excess supplies of the two countries. The preference for improved apples by some consumers allows us to calibrate the high-quality of improved apples in the Mussa-Rosen specification. For the RoW, we assume that the proportion of consumers accepting improved apples and their WTPs are similar to those in Europe. This is a conservative assumption, given the reluctance of a significant share of European citizens for GenEd foods (in line with past experience with transgenic crops (see McCluskey et al., 2003)).

Then, we derive *ex ante* (i.e., prior to the introduction of an improved food) estimates for the welfare impacts of improved apples entering onto the market, accounting for the R&D and regulatory costs, probability of R&D success, and regulatory heterogeneity across countries.[2]

[2] Lassoued et al. (2019) estimate an average of US $10 million and 5 years for regulatory approval of GenEd crops if they were determined by regulators to be exempt from certain regulations, and an average of US $24.5 million and 14 years for GenEd crops not determined by regulators to be exempt from certain regulations. An earlier survey of large companies found an average estimated cost of US $17.2 million for regulation, and $136 million and 13.1 years overall to discover, develop, and obtain approval for a new plant trait developed with biotechnology, but those surveyed indicated that costs were increasing (McDougall, 2011). Bullock et al (2021) provide comparable figures on these relative costs and time requirements.

The simulations lead to characterization of countries' decisions to invest in R&D, depending on market opportunities (domestic and abroad), probability of R&D success, and sunk costs. It would be optimal for countries to make investment decisions based on global welfare, inclusive of all countries' welfares, but the simulation results suggest that R&D investment could be compromised by possible import bans.

To our knowledge, we are the first to provide a quantitative analysis of the trade and welfare implications of foods improved with NPETs in the context of uncertain R&D success, a costly and heterogeneous regulatory environment, and heterogeneous consumer acceptance of such foods across and within countries. We provide an analytical framework for improved foods that have not yet been introduced in markets. Non-tariff measures (NTMs) in the form of restrictions on importation can negatively impact investment and probabilities of success in R&D. Specifically, restrictive regulatory environments can disincentivize R&D investment, slow or stop research, and even push research to other countries (European Commission, 2021). For example, growers of many staple crops have benefitted from varieties with genetically engineered traits, but there is no genetically engineered wheat available to growers. Genetically engineered wheat that could decrease production costs was first developed in 1992 but grower concern about exporting to countries with NTMs has prevented commercialization (Bass, 2004). The methodology described here can measure the impact of this kind of NTMs on R&D investment and welfare. Finally, the approach is modular and scalable; extensions can be easily added to the model.

Related to our paper, Kalaitzandonakes and Kruse (2015) examined delays in regulatory approvals and their impact on innovations and agricultural international trade, using a multi-market global partial-equilibrium model. Vigani et al. (2012) analyzed the impact of heterogeneous GMO regulations across country pairs on bilateral flows of agricultural products constructing a composite index of regulatory dissimilarities and using panel data and gravity type of approach. Disdier and Fontagné (2010) looked at the cost of delays in EU approvals of GM crop on key agricultural exporters who initiated or joined the WTO dispute on EU GMO regulation. Sobolevsky et al. (2005) used a partial equilibrium world trade model to analyze trade and welfare effects of the partial adoption of Roundup Ready® soybean. Their model includes the costly segregation of conventional and biotech products, and the authors analyze the implications of potential import bans. Related to NPETs, Marette et al. (2021b) investigate the emergence of an improved food in a close economy context, using a different demand approach.

Relative to this literature, our contribution is to evaluate the link between uncertain R&D, regulation, and welfare considerations integrating consumers' preferences for a hypothetical improved food in an open-economy context. The remainder of the paper is organized as follows. In section 2, we develop the model with its key attributes. In section 3, we apply the model to a case study of the development and introduction of hypothetical improved apples into the domestic and/or international market. We present our conclusions in section 4.

2. A trade model integrating experimental results

We develop a parsimonious trade model incorporating industrial organization considerations in the sense that agents behave strategically and anticipate the impact of policies. The model also accounts for consumers' valuation of improved foods. We first present the sequential framework of the model, then detail the three-stage game, as well as the equilibria at each stage.

2.1 Framework

Our model accounts for the probability of improved foods resulting from R&D investment in NPETs in an international trade context. Many countries globally are investing in such R&D, but for simplicity, we limit our analysis such that the EU and the US can invest in and develop improved foods, while the aggregate RoW does not invest in R&D leading to improved foods.

The proposed model allows the estimation of potential market effects for two foods which are imperfect substitutes (improved food and conventional food). For each country, the decision criteria are its domestic welfare defined as the sum of farmers' domestic and export profits, surpluses of domestic consumers, and the subtracted public costs from both R&D and regulation. We model publicly funded R&D, with the success of innovations leading to improved foods that may become available only to domestic farmers.

Generally, there are two components to a country's decisions about commercialization of agricultural products of biotechnology: a scientific assessment and a political determination. A regulatory risk assessment considers scientific characteristics of a product or group of products, and may include aspects such as assessment of similarity to conventional products, toxicological evaluation of a product or components of a product, investigation of potential environmental impacts, and exposure to a product or components of a product via food, feed, or in the environment (National Academies, 2016). Such assessments may be standardized across all products within a predetermined grouping, or assessments may be determined on a case-by-case basis. Assessments may be tiered to or informed by regulatory investigations conducted by other countries or groups of other countries. Finally, assessments may be based on properties of a product itself, the process used to develop a product, or both.

In addition to regulatory assessment, a country may also make a political decision for each product or group of products. This political decision may or may not be based on the regulatory assessment and may consider issues such as concerns of consumers, needs of domestic producers, and potential economic impacts both domestically and abroad (Smith et al., 2021). Regulatory and trade policies may or may not be coordinated with R&D policies. Appendix Table A.2 summarizes the decisions by various economic agents in the model and by stage.

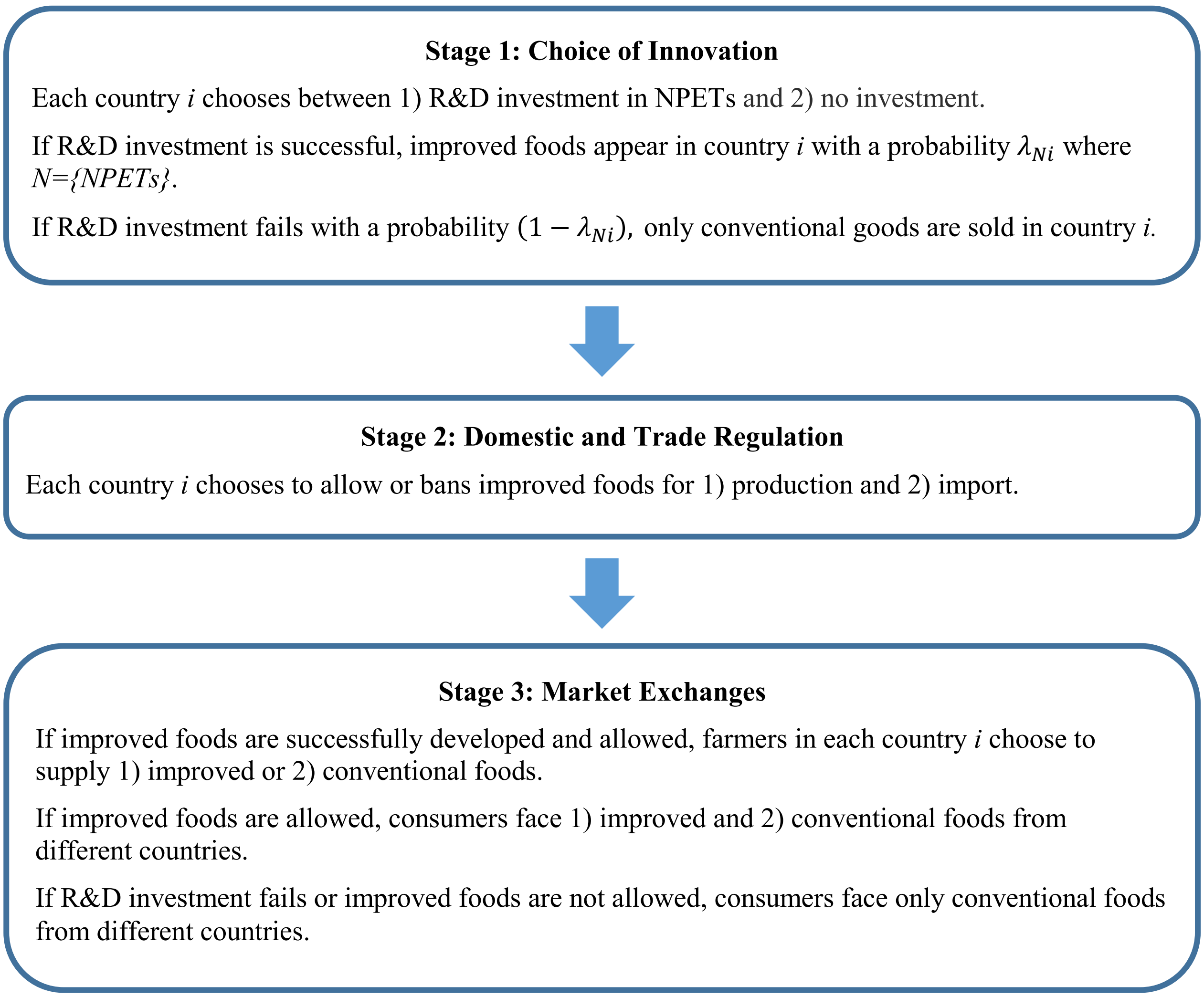
2.2 A three-stage game

The market equilibrium is determined as a three-stage game summarized in Figure 1. The equilibrium is solved by backward induction (i.e., subgame Nash equilibrium). In Stage 1, research agencies in country *i={US, EU}* choose whether to invest in R&D to develop improved foods with NPETs. If country i invests in R&D, it incurs a sunk expenditure F_{Ni}, associated with R&D investment and regulation, leading to a probability λ_{Ni} of the improved food being available to domestic producers at the end of Stage 2. The R&D process fails with a probability $(1-\lambda_{Ni})$. Uncertainty of stage 1 is resolved at stage 2. Sunk costs are incurred when investments are made and cannot be recovered (Sutton, 1991). When deciding whether to fund R&D, research agencies consider the aggregate welfare induced by the innovations, defined here as the farmers' profits and sum of consumers' surpluses from the various consumptions, minus the sunk costs of R&D.

In Stage 2, the public regulatory agencies in country *i={US, EU}* decide whether to allow domestic production and consumption of a food improved with NPETs, denoted by *NPETs*. Furthermore, the public regulator in country *i={US, EU, RoW}* defines trade policy by allowing or banning importation of such foods from other countries.[3] Countries may allow importation for food, feed, processing, transit, or cultivation. For simplicity, we consider regulatory approval as a binary; products may be approved for all uses or banned for all uses. With our specification, banning domestic production while allowing imports assumes that the country does not invest in R&D, leading to the absence of production of the improved food since farmers would not be able to purchase foreign seeds or seedlings for planting.

[3] We rule out issues of low-level presence or unauthorized transboundary movement if new foods are banned.

Figure 1. Stages of the model



In Stage 3, producers and consumers adjust themselves to the presence or the absence of improved foods. The overall output of conventional foods includes domestic production and exports to other countries. For simplicity, we abstract from any supply chain, and assume trade occurs directly between farmers and consumers. When improved foods are both allowed and available in country *i={US, EU}*, a given proportion of farmers switch to producing these foods, and profits may come from both domestic and foreign sales. Farmers producing improved foods are vulnerable to possible bans by foreign countries including the RoW. Because of dedicated channels of commercialization or seasonality, a country may simultaneously export and import conventional and improved foods.

For the purposes of this model, consumers in country $i=\{US, EU, RoW\}$ are informed about the technology used to produce improved foods and do not have preferences for variety or origin of foods. For consistency with issues of lab experiments presented below, consumer preferences follow a vertical product differentiation specification, as defined by Mussa and Rosen (1978). Consumers are risk neutral and want to purchase only one unit of food. The parameter $k > 0$ represents the quality level of a food. A consumer has a WTP equal to θk, which differs across consumers. The heterogeneity of consumers' WTP for the foods is characterized by the uniformly distributed parameter $\theta \in [0, 1]$. A consumer who buys one unit of a quality k at a price p has an indirect utility equal to $\theta k - p$ (see Mussa and Rosen, 1978). In each country i, the conventional quality is denoted k_i and the high-quality of improved foods is denoted k_{Ni} with $k_{Ni} > k_i$. Consumers benefit from the introduction of high-quality foods leading to a higher indirect utility $\theta k_{Ni} - p_N$, with this gain depending on prices of foods. Farmers' choices and imports/exports influence these prices. In a country i, the mass of consumers is equal to M_i.

For simplicity, prices are determined at the end of Stage 3. We assume integrated markets for which a single price for each quality (conventional and improved) is determined across countries, namely at the world level. There are endogenous adjustments of both prices depending on bans or authorizations of foods produced with NPETs. We now turn to details regarding equilibria at different stages, by starting, according to the backward induction principle, with Stage 3 and the way consumers' demand is determined.

2.3 Equilibria at different stages

Stage 3: Supply adjustment

A conventional food in each country i=*{US, EU, RoW}* is produced by a group of farmers with an overall supply Q_{Ci} and an overall cost function $f_i Q_{Ci} + c_i \frac{Q_{Ci}^2}{2}$, that is the quadratic variable cost, where f_i and c_i are parameters of the cost function that are greater than or equal to zero. For a price p_C and with price taker producers, the maximization of overall profits leads to the overall supply $Q_{Ci}(p_C) = (p_C - f_i)/c_i$, calibrated with aggregate data (as explained in the next section). A proportion d_i of the supply is sold on the domestic market and a proportion exp_{ijC} is exported to the trading partner *j*. Thus, the domestic supply is equal to $d_i(p_C - f_i)/c_i$ and the export supply towards country *j* is $exp_{ijC}(p_C - f_i)/c_i$, with $\sum_j exp_{ijC} + d_i = 1$ and $0 \leq d_i \leq 1$.

If domestic production of improved foods is allowed in country i (the US or the EU), a group of producers departs from producing conventional foods for growing improved foods and fully specializes into producing Q_{Ni}. We assume that the cost of producing conventional and improved foods is the same and that a given share x_i of producers is switching to grow improved foods. This proportion is exogenously given and is applied to all sub-segments of the supply curve. Thus, by only detailing the supply for the domestic market, $d_i(p_C - f_i)/c_i$, the supply for improved food is given by $Q_{Ni} = x_i d_i(p_N - f_i)/c_i$ and the supply for the conventional food is $(1 - x_i)d_i(p_C - f_i)/c_i$. The same proportion x_i applies to the export supply under the following constraint, $x_i \sum_j exp_{ijN} + (1 - x_i) \sum_j exp_{ijC} + d_i = 1$. This setup corresponds to short/medium term adjustments, in which profits are not exhausted. Once the model is initially calibrated, changes in prices (p_C, p_N) imply changes in domestic and export quantities and shares.

Stage 3: Domestic demand and surpluses under different configurations

For a country *i*, demand depends on the foods that are available for purchase.

Configuration 1. Only conventional foods are available; improved foods are banned (Stage 2) or without R&D investment/unsuccessful innovation (Stage 1).

Only conventional foods are offered in each country. The consumer knowingly purchases a quality k_i at price p_C related to the conventional food. The marginal consumer indifferent between buying a food and buying nothing is identified by the preference parameter $\bar{\theta} = pc/k_i$ (such that $\theta k_i - pc = 0$). Since parameter θ is uniformly distributed between 0 and 1, and with a mass of M_i consumers, demand for the food is:

$$M_i \int_{\bar{\theta}}^{1} d\theta = Q_C = M_i(1 - pc/k_i). \qquad (1)$$

The inverse demand in this first configuration is $p_C(Q_c) = k_i\left(1 - \frac{Q_C}{M_i}\right)$. For any given price p_{C_0}, the consumers' surplus is then $CS_{Ci}(pc_0) = M_i \int_{pc_0/k_i}^{1} (\theta k_i - pc_0) d\theta$. Producer surplus is realized at home and abroad through exports. Hence, welfare for any country i depends on its farmers' profits in other countries:

$$W_0^i = CS_{Ci}(pc_0) + \pi_{iCi}(pc_0) + \sum_{j \neq i} \pi_{iCj}(p_{C0}), \qquad (2)$$

where $\pi_{iCi}(.)$ represents domestic farmers' profits from domestic sales, and $\pi_{iCj}(.)$ represents domestic farmers' profits from exports to country j.

Configuration 2. Improved foods are available with successful R&D investment (Stage 1) and authorization (Stage 2).

For each country i, consumers can now choose between three outcomes: the improved food, conventional food, or none. Furthermore, a proportion β_i of consumers see foods improved with NPETs as better compared to conventional foods. The higher quality is denoted k_{Ni} with $k_{Ni} > k_i$. In this case, the consumer indifferent between high-quality and low-quality foods is defined by $\tilde{\theta} = (p_N - p_c)/(k_{Ni} - k_i)$, where $\theta k_{Ni} - p_N = \theta k_i - p_c$. The parameter $\bar{\theta} = p_C/k_i$, defines the consumer indifference between consuming low-quality food and not purchasing. Since the parameter θk_i is uniformly distributed, the demand for high-quality food is $\beta_i M_i \int_{\tilde{\theta}}^{1} d\theta = Q_N =$

$\beta_i M_i[1-(p_N-p_c)/(k_{Ni}-k_i)]$ and the demand for low-quality food is $\beta_i M_i \int_{\underline{\theta}}^{\tilde{\theta}} d\theta = Q_C = \beta_i M_i[(p_N-p_c)/(k_{Ni}-k_i)-p_C/k_i]$. The inverse demands are:

$$p_C(Q_c, Q_N) = k_i\left(1-\frac{Q_C}{\beta_i M_i}-\frac{Q_N}{\beta_i M_i}\right),$$

$$p_N(Q_c, Q_N) = k_{Ni}\left(1-\frac{Q_N}{\beta_i M_i}-\frac{Q_C}{\beta_i M_i}\right). \quad (3)$$

For these consumers the surplus is

$$CS_{CNi}(p_c, p_N)=\beta_i M_i \int_{\frac{p_C}{k_i}}^{\frac{p_N-p_C}{k_{Ni}-k_i}}(\theta k_i - p_c)d\theta + \beta_i M_i \int_{(p_N-p_c)/(k_{Ni}-k_i)}^{1}(\theta k_{Ni}-p_N)d\theta.$$

Eventually, the market demand of $(1-\beta_i)M_i$ consumers seeing the innovation as a low-quality food that is not fit for purchase is $(1-\beta_i)M_i(1-p_C/k_i)$. As the price of the improved food is higher than the price of the conventional food, these consumers never buy the improved food. With only conventional foods available, the consumers' surplus is $CS_{Ci}(p_c) = (1-\beta_i)M_i \int_{p_c/k_i}^{1}(\theta k_i - p_c)d\theta$.

Note that the introduction of an innovative food leads to an increase in consumer surplus.

Producer surplus again here depends on domestic and foreign markets of both innovative and conventional foods, leading to total welfare in country i:

$$W_N^i = CS_{CNi}(p_c, p_N) + CS_{Ci}(p_C) + \pi_{iCi}(p_C, p_N) + \pi_{iNi}(p_C, p_N)$$
$$+ \sum_{j\neq i}\pi_{iCj}((p_C, p_N) + \sum_{j\neq i}\pi_{iNj}((p_C, p_N), \quad (4)$$

where $\pi_{iCi}(.)$, and $\pi_{iNi}(.)$ represent domestic farmers' profits from domestic sales of conventional and improved foods, and where $\pi_{iCj}(.)$, $\pi_{iNj}(.)$ represent domestic farmers' profits from exports of conventional and improved foods to country j.

Stage 2: Domestic and trade regulations

In each country i, the public regulator allows or bans improved foods produced with NPETs for production and/or for import. These decisions are considered as given for studying the impact on R&D investment.

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

The decision of whether to invest in R&D in Stage 1 is based on expectations of events and market equilibria related to Stage 3. Welfare related to market equilibria in Stage 3 determines the realization of the investment for each country resulting in an improved food or not with an exclusive availability for farmers of the investing country. If the innovation succeeds in one country, the innovation is not diffused across border at least in the short term. If a research agency invests in R&D, the resulting improved food has a probability λ_{Ni} to emerge, leading to a welfare metric with that improved food.

The R&D investment fails with a probability $(1-\lambda_{Ni})$, leading to a welfare metric without an improved food. Sunk expenditures F_{Ni} are associated with R&D investment and regulatory authorization incurred by research and regulatory agencies, and subtracted from consumer welfare. For different configurations, the welfare in a country depends on R&D investment and success in other countries. With the welfares W_N^i and W_0^i previously defined in equations (2) and (3) and by considering the sunk cost F_{Ni}, the expected welfare for country i inclusive of the cost of R&D investment is:

$$\lambda_{Ni}W_N^i + (1-\lambda_{Ni})W_0^i - F_{Ni}. \qquad (5)$$

This expected welfare is compared to the absence of investment leading to a welfare W_0^i.

3. Application to apples

We apply the model to a case study of the hypothetical development and introduction of apples improved with NPETs into the domestic and/or international markets. The model is initially calibrated in such a way as to replicate prices and quantities for conventional apples over a year.

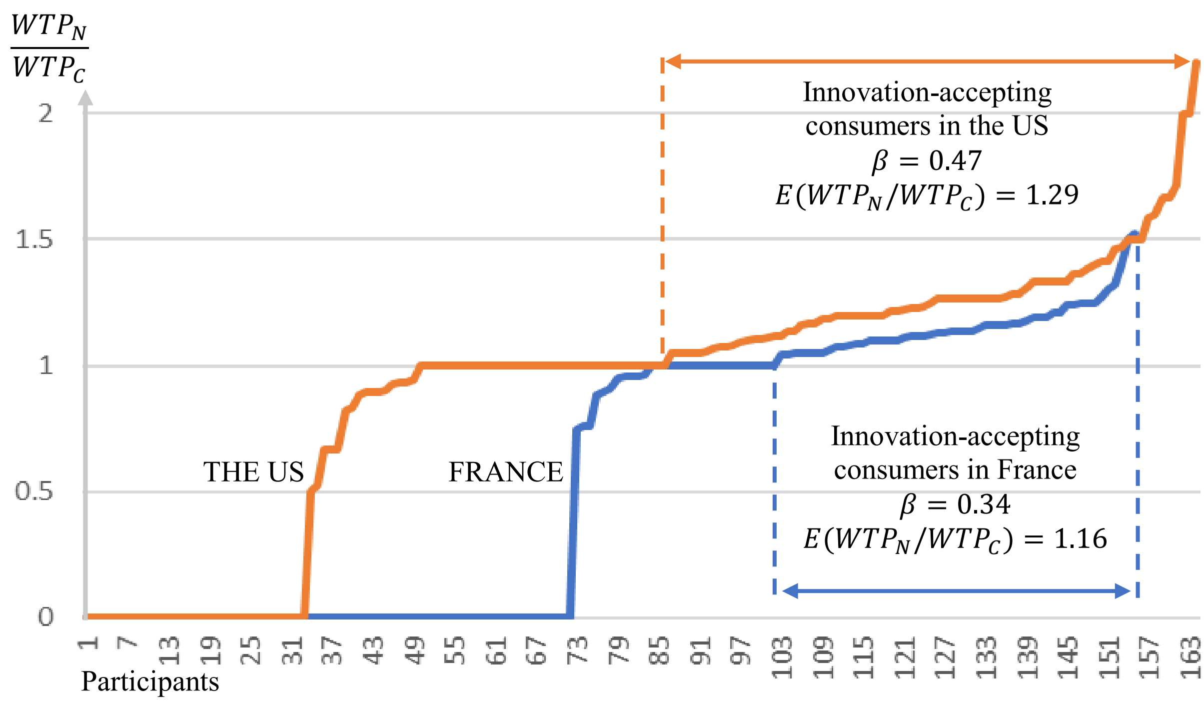
Then, relying on elasticities of demand for conventional apples obtained from time-series econometrics (Devadoss et al., 2009) and average consumer WTP for improved apples revealed in a lab experiment, we derive the demand system for both conventional and improved apples as in Equations (1) and (3).

3.1 Summary of the apple experiments

We apply the framework to a case study of hypothetical GenEd (as a representative NPET) apples. These apples would not brown upon being sliced, implying a lower level of waste and thus corresponding to the demand under vertical differentiation. We use the results from two recent experiments on WTP for improved apples when consumers receive information about GenEd technology, conducted in the US and France (Marette et al., 2021). Experiment results show strong heterogeneity in consumers' WTP for conventional and improved apples in both countries. To highlight this heterogeneity and compare the two countries, we compute the ratio between the WTP expressed for improved and conventional apples by each consumer in each country. For consumer *h,* the ratio is thus (WTP_{N_h}/WTP_{C_h}). Figure 2 presents the unitless ratios, with observations related to consumers on the X-axis and ratios on the Y-axis. Ratios are sorted by increasing order.

For both countries, three groups of consumers can be distinguished: those who discount improved apples (left part of curves with ratios lower than 1), those who are indifferent between improved and conventional apples (central part of curves with ratios equal to 1), and those who value the improved apples with a positive premium (right part of curves with ratios higher than 1). A larger number of surveyed consumers discounted innovation with a negative premium, especially in France. However, in both countries, there is a significant group of consumers with a positive premium (ratios higher than 1), that *a priori* accept the new technology. This group of accepting consumers is larger in the US than in France. Moreover, in the US, a few consumers give very high value to innovation (right of the orange curve). This group of accepting consumers is likely to make the adoption of foods improved with NPETs possible and potentially socially desirable when information about the technology is provided.

Figure 2. WTP expressed for improved apples relative to WTP expressed for conventional apples



The Mussa and Rosen (1978) framework with accepting consumers is tailored to the WTP structure in Figure 2. As accepting consumers (right side of the figure) are ready to pay a higher price for improved foods, the higher price will deter non-accepting consumers who have a lower WTP for improved foods compared to conventional foods (left side of the figure). These non-interested consumers are considered in the model and are impacted by changes of conventional food prices.

In the simulations, we apply the WTP expressed by French consumers as well as the share

(β_i) of consumers seeing NPETs as producing high-quality foods (here, GenEd apples) to both the EU and to the RoW. Given the reluctance of many French consumers for foods improved with NPETs, this approach is rather conservative and should provide a lower bound for acceptance by the RoW.

3.2 Calibrated supplies and demand for apples

The supply function for conventional apples is calibrated with the own supply elasticity and the average quantity (and price) over a year. Elasticities are based on Devadoss et al. (2009). Similarly, the demand function for conventional apples is calibrated with the own price elasticity of demand. For a country i, using existing data on the quantity Q_{Ci} of the conventional apples sold over a period, the average price p_c observed over the period at the world level, and the direct price demand elasticity ε_{Ci}, the calibration leads to estimated values for the demand such that $M_i/k_i = \varepsilon_{Ci}Q_{Ci}/p_C$ and $Q_{Ci} = M_i(1 - p_C/k_i)$. Table 1 presents the parameters used for the calibration.[4]

Table 1. Parameters used for calibration

Country	Description	Values	Sources
US	Consumption, average 2017-19 (tons)	4,216,821	FAO
	Average price per kg 2017-18-19 (US $)	1.67	FAO
	Imports in % of consumption	3%	FAO
	Supply own-price elasticity	0.2	Devadoss et al. (2009)
	Demand own-price elasticity	−0.3	Devadoss et al. (2009)
EU	Consumption, average 2017-18-19 (tons)	11,483,049	FAO
	Average price per kg 2017-18-19 (US $)	0.91	FAO
	Imports in % of consumption	5%	FAO
	Supply own-price elasticity[a]	0.12	Devadoss et al. (2009)
	Demand own-price elasticity[a]	−0.3	Devadoss et al. (2009)
RoW	Consumption, average 2017-18-19 (tons)	109,657,949	FAO (2021)
	Average price per kg 2017-18-19 (US $)	0.95	FAO (2021)
	Imports in % of consumption	6%	FAO (2021)
	Imports in ROW: % from the US[b]	44%	BACI CEPII
	Imports in ROW: % from the EU[b]	66%	BACI CEPII
	Exports of Row: % to the EU[b]	79%	BACI CEPII
	Exports of Row: % to the US[b]	21%	BACI CEPII
	Supply own-price elasticity[c]	0.37	Devadoss et al. (2009)
	Demand own-price elasticity[c]	−0.31	Devadoss et al. (2009)

Notes: [a] Average of elasticities in France, Germany, Italy and the Netherlands. [b] From the imports in ROW and the

[4] The Mathematica codes are available from the authors upon request.

exports of ROW to the EU and the US, one can easily determine the origin of imports and exports for the US and EU. [c] Average of elasticities in Brazil, China, India, Middle East and Southeast Asia.
Sources: BACI CEPII data: http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=37 ; FAO data: http://www.fao.org/faostat/en/#home. Data downloaded in June 2021.

Regarding the hypothetical improved apples, assumptions are made regarding both supply and demand sides. The shifts in supply come from the introduction of the improved apples in production reducing the supply of conventional apples as explained above. We assume that 20% (x_i=0.2) of the initial suppliers of conventional farmers switch to supplying the new apples. This means that the market adjustment is limited in the short to mid-term, which is the context of this calibration and apple production. Once that specialization has occurred, each segment of the apple supply responds to its own price.

The ratio of the WTP expressed by consumers for the improved apple over the WTP expressed for the conventional substitute provides a measure of the value of k_{Ni}. In other words, this ratio of WTPs is extrapolated to measure the variation of demands. The inverse demand curves can be viewed as indicators of WTP when 1 unit of a food is purchased, namely in equation (3) with $p_C(1,0)$ for the conventional food and $p_N(0,1)$ for the improved food. Thus, the average ratio of WTPs can be equalized to the ratio of the inverse demands, and we can write the equality

$$E\left(\frac{WTP_{N_i}}{WTP_{C_i}}\right) = \frac{p_C(1,0)}{p_N(0,1)}, \quad (6)$$

leading to a value $k_{Ni} = k_i \times E(WTP_{N_i}/WTP_{C_i})$ integrated in (1). This simple yet useful application of WTP from experiments has been overlooked in the literature dealing with product differentiation and quality. The values used in Figure 2 are integrated in equation (6) to determine the demand for improved apples given by (3).

3.3 Simulations with the socially optimal R&D investment

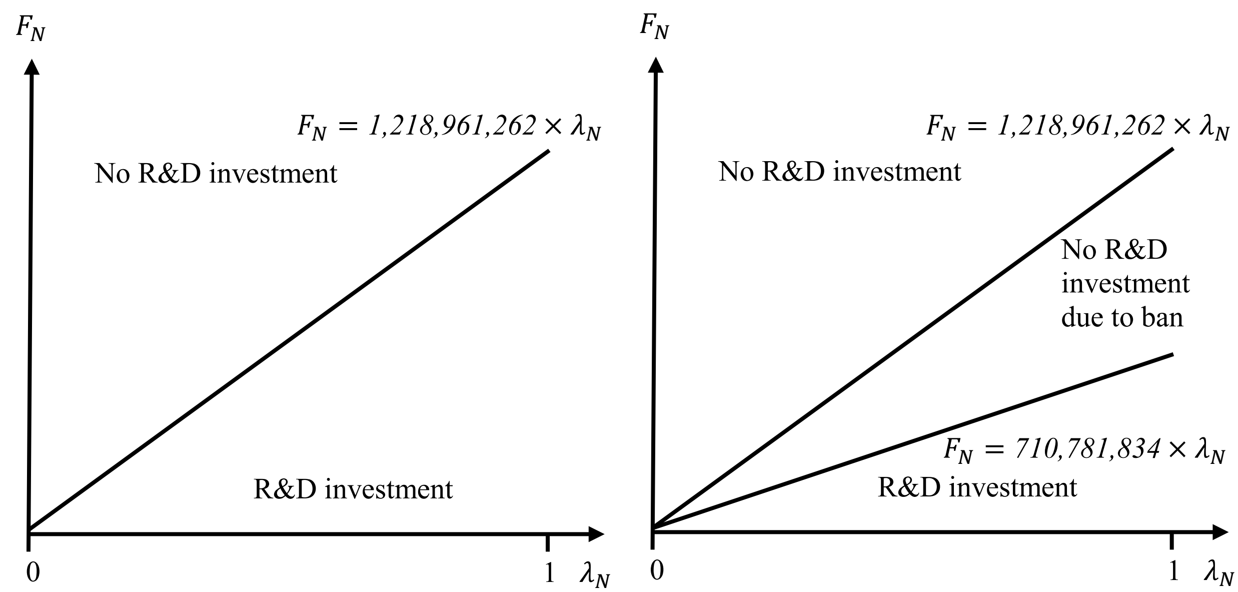
The comparison of welfares at Stage 2 permits the selection of the socially optimal innovation strategy for the different countries. We look at the potential investment choices maximizing welfares and leading to possible emergence of improved foods. Simulations are presented in

Figures 3-5. For simplicity, we assume $\lambda_{NUS} = \lambda_{NEU} = \lambda_N$, with λ_N the probability of access to improved foods represented on the X-axis. For simplicity, we also assume $F_{NUS} = F_{NEU} = F_N$, with F_N the sunk cost for the R&D investment expressed in US $ and reported on the Y-axis.

We start with our first scenario, where the US is the only country to potentially access improved foods, due to adequate R&D investment and favorable regulatory authorizations, but with several potential situations in which resulting improved foods may or may not be sold in foreign supermarkets. In this benchmark scenario, the EU and the RoW do not have access to improved foods. Figure 3 shows the decision by the US to invest or not invest in R&D for improved foods. In the left side of the figure, these foods are allowed to be sold in all countries, while in the right side, imports of these foods are banned in the EU and in the RoW.

Figure 3. Scenario 1: innovation technology accessible only for the US

3a. Improved apples allowed in all countries **3b. Improved apples banned outside US**



When improved apples are allowed in all countries, R&D investment is optimal for the US for relatively low levels of per-unit sunk cost F_N, even if the frontier has a relatively high coefficient (Figure 3a). If improved foods emerge with certainty ($\lambda_N = 1$), the investment is socially desirable for a sunk cost (F_N) lower than US $ 1.218 billion, a significant amount. For relatively high-values of per-unit of sunk cost F_N, there is no R&D investment by the US and no emergence of improved foods. The frontier under which R&D investment is socially optimal at the world level (i.e., by integrating the welfare of all countries around the world) is higher but close to the US frontier,[5] meaning that foreign countries collectively benefit from US R&D investment that leads to high-quality foods improved with NPETs.

Figure 3b shows the impact of import bans in the EU and in the RoW. This chart clearly exhibits a new area for middle values of the sunk cost F_N in which the investment is shackled by import bans on improved foods. As US farmers lose some opportunities for profits from foreign markets, the US is unable to cover the sunk cost F_N when it is relatively high. Figure 3 characterizes country choice in R&D investment, which depend on market opportunities, the probability of R&D success, and the sunk cost of R&D and its spread over markets. R&D investment may be impeded by import bans in some countries. The proposed methodology makes possible a quantification of scenarios in which R&D investment is deterred by import bans on improved foods outside the investing country. The criteria are not only the absence of trade, but much more so the absence of R&D investment leading to the absence of trade in improved foods and the negative impact on global welfare.

Scenario 2 introduces a new "competitor"; the EU is now able to produce foods improved with NPETs. R&D investment decisions by the US and the EU are reported in Figure 4. Sunk costs (F_N) are similar in the US and in the EU in the left side of the figure, and assumed to be higher in the EU in the right side. As shown in the left side of Figure 4, R&D investment is optimal for both countries for relatively low levels of sunk costs, normalized by output. Because the apple market is larger in the EU than in the US, the profits and surpluses linked to the introduction of improved

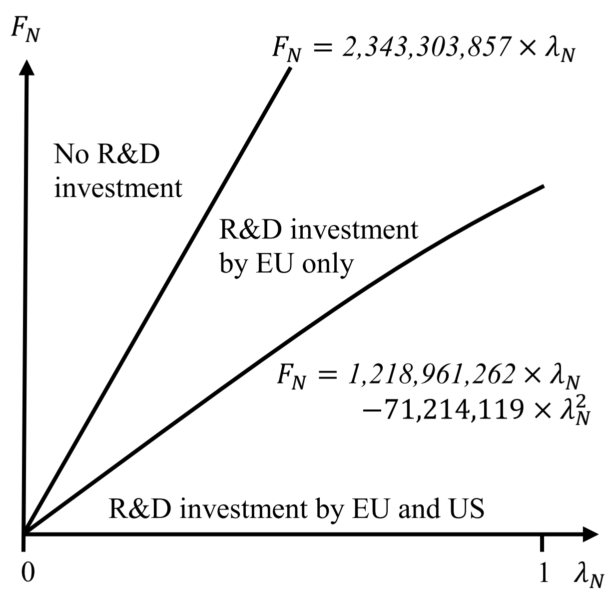
[5] This frontier is not represented for avoiding any cluttering.

apples are bigger in the EU, leading to more possibilities for covering higher sunk costs compared to the US. Even if sunk costs remain moderate, the US benefits from imports of improved apples from the EU. Finally, for relatively high values of per-unit sunk costs, there is no R&D investment anywhere and improved foods do not emerge.

On the right side of Figure 4, sunk costs are assumed to be higher in the EU due to higher regulatory costs. In this case, the US becomes the only country investing in R&D for medium values of sunk costs. Scenario 3 considers the impact of an import ban by the RoW. Figure 5 starts from the right side of Figure 4 with a high sunk cost for the EU, but results are robust for other scenarios. The import ban by the RoW leads to the absence of many improved foods and prevents possible profits for farmers in the US and the EU. As a consequence, the import ban modifies the incentive for innovating, since gross profits from exporting improved foods to the RoW disappear. Compared to the right side of Figure 4, frontiers pivot downward in Figure 5, implying some changes in R&D investment.

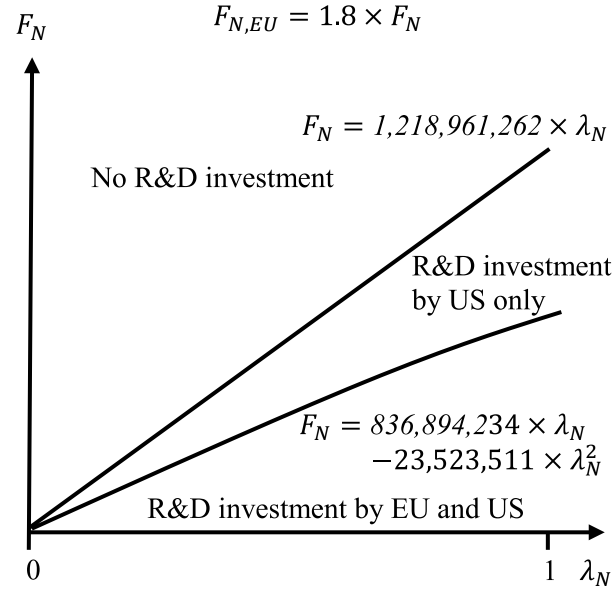
Figure 4. Scenario 2: innovation technology accessible for the US and the EU

4a. Similar sunk costs



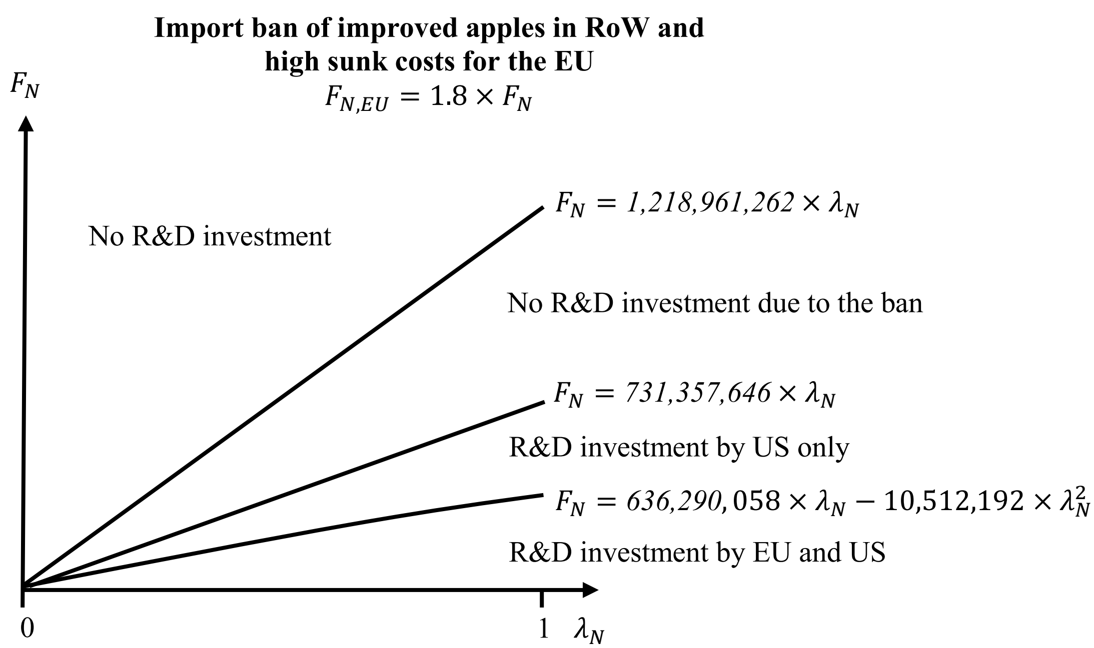
4b. High sunk costs for EU

$F_{N,EU} = 1.8 \times F_N$



For low values of sunk costs F_N in Figure 5, both countries invest in R&D as in the right side of Figure 4. For medium values of sunk costs F_N in Figure 5, only the US invests in R&D, while both countries invested in Figure 4 (below the locus F_N=836,894,234$\lambda_N - 23{,}523{,}511\lambda_N^2$). For high values of sunk costs F_N in Figure 5, there is no R&D investment, while the US was previously investing in Figure 4. The import ban is directly responsible for the absence of investment. The import ban and the related absence of profitability deters investment for high values of sunk costs, which is detrimental for the world welfare inclusive of all profits and surpluses. Note that such a ban by the RoW of improved foods deters R&D investment and deters the emergence of improved foods in other countries. This deterrence effect on R&D is different from the standard case in the NTM literature, which focuses on the NTM's potential protective impact on existing output in a domestic market of the country issuing the ban, and anti-protective effect on foreign exporters competing for that market and the resulting trade deterrence.

Figure 5. Scenario 3: improved foods allowed in the US and the EU, import bans in RoW



4. Discussion and conclusions

This paper emphasizes the important role of consumer preference, along with R&D investment and uncertainty of R&D success, in the context of trade and regulatory policies which may vary across countries.

The simulation results suggest that R&D investment for foods improved with NPETs (using GenEd apples as a case study) may be impeded by import bans for relatively high values of sunk costs, even though it would be optimal to make investment decisions based on global welfare, inclusive of all countries' welfares (by a global social planner). The issue of scale to spread R&D sunk costs is instrumental. Scale can be present in the domestic market (the case of the EU apple market), but is more easily attainable with international trade, especially for smaller countries. Hence, defining a clear regulatory process which allows for production and consumption is instrumental for the success of foods improved with NPETs. Regulatory harmonization or reciprocity would be ways to open borders for these improved foods.

Despite limitations resulting from the simple setup (stylized WTP elicitations and industrial organization approaches), our methodology can be expanded and replicated to assist in international discussions such as bilateral trade negotiations. Obviously, the framework would apply to other innovative technologies, including other NPETs for which regulatory certainty or harmonization are lacking.

Beyond this, our analysis could accommodate alternative situations using the following extensions. First, our analysis abstracts from supply chains. We could integrate cost functions for retailers and seed industries. Different models could help determine profits using demand calibrated with price elasticities, or experimental results for characteristics influencing demand (Marette et al., 2008). Alternative to this profit characterization, checkoff program funding and marketing orders that bring together farmers and research organizations could be studied with a per-unit paid by farmers for financing R&D and the resulting impacts on the price of apples.

Second, for characterizing consumers' preferences, the paper used a model of vertical differentiation à la Mussa and Rosen (1978) under perfect information about product characteristics. A configuration à la Akerlof (1970) with imperfect information about characteristics could be integrated into the analysis. In addition, an alternative setup taking into account social benefits from an increase of product diversity related to trade could be considered via a constant elasticity of substitution (CES) function à la Dixit and Stiglitz (1977), which is extensively used in trade economics. This specification could be tailored to the apple market, encompassing many varieties (e.g., Gala, Red Delicious, Fuji, Honeycrisp) being close to horizontal-differentiation models. Eventually, Anderson et al. (2012) offer a possibility to combine vertical and horizontal differentiation characteristics with their logit specification as a kind of meta-model of product differentiation. These specifications could enrich but complicate the analysis.

Third, we considered just one period of exchanges. Several periods of exchanges with different probabilities of success for R&D investment could be envisaged, boosting the overall probability of success but bringing time-discounting of future benefits. In a dynamic context, consumers may update their preferences and WTP when improved apples are introduced. After a certain adaptation, particularly if consumers could observe the safety and quality of the improved apples, consumers may revise their WTP for improved apples upwards, making market penetration easier than in our simulations. Consumers who discount innovations may also update their WTP for improved apples upward. Moreover, WTP may be evaluated differently, e.g., with field experiments in supermarkets when the improved apples are introduced and sold. In addition, countries may simultaneously invest in R&D for different technologies and products in order to boost chances of innovations and larger sunk costs.

Other extensions could consider setups with or without consumer information about the technology. Countries or producers could decide whether or not to further inform consumers about the process of innovation, by incurring additional cost, such as through an information campaign or a product label. These costs could be included in a cost-benefit analysis accounting for R&D and market adjustments. Finally, the sunk costs F_N and the probabilities λ_N could be evaluated with interviews, questionnaires, and financial analyses. These evaluations could increase the credibility of any *ex ante* analysis searching to define the social benefit related to foods improved with NPETs or other technologies.

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Appendices (not intended for publication)

Table A.1. US, EU and RoW approaches for foods improved with NPETs

Stage	US	EU	Rest of World
Public R&D investment	Multiple federal agencies and other public organizations invest in R&D for foods improved with NPETs	Multiple agencies and other public organizations in the EU and in individual member countries invest in R&D for improved foods with NPETs	Highly variable, but some countries provide significant investment in R&D for foods improved with NPETs
Domestic policy	US Dept of Agriculture excludes from regulation certain products that could be created through conventional breeding; other US regulatory agencies are updating their policies	Foods improved with NPETs are currently regulated as GMO, with limited approvals of products for domestic use; Switzerland has a total ban on GMO production	Domestic policy is variable and still being developed in many countries; some countries exempt from regulation certain foods improved with GenEd
Trade policy	Accepts imports of foods improved with NPETs that are approved for domestic use	Foods improved with NPETs are regulated as GMO, with limited imports	Some countries allow products for import but not domestic production
Domestic production	Farmer choice depends on domestic approvals	Farmer choice limited due to lack of approvals	Farmer choice is highly variable, with production in progress in some countries
Consumer	National labeling scheme for biotechnology in foods excludes those that could be created through conventional breeding or that lack detectable proteins and DNA; third party "non-GMO" labels may define foods improved with NPETs as GMO for the purposes of labeling	Third party "non-GMO" labels may define foods improved with NPETs as GMO for the purposes of labeling	Third party "non-GMO" labels may define foods improved with NPETs as GMO for the purposes of labeling

Table A.2. Decisions about foods improved with NPETs by various economic agents

Stage	Choice 1	Choice 2
Public R&D investment (independent)	Country invests in R&D for foods improved with NPETs	Country does not invest in R&D for foods improved with NPETs
Domestic policy (independent)	Country allows domestic production and consumption of improved foods	Country does not allow domestic production or consumption of improved foods
Trade policy (independent)	Country accepts imports of improved foods	Country does not accept imports of improved foods
Domestic production (dependent on domestic policy)	Farmers grow improved foods	Farmers grow conventional foods
Consumer choice (dependent on trade policy OR domestic policy and farmer production)	Consumers buy improved foods	Consumers buy conventional foods