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Abstract

New plant engineering techniques (NPETs) may significantly improve both production and quality of foods. Some consumers and regulators around the world might be reluctant to accept such products and the global market penetration of these products may remain low. We develop a parsimonious economic model for R&D investment in food innovations to identify conditions under which NPET technology emerges in the 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 cost can reduce R&D investment in NPETs to suboptimal levels.

KEYWORDS

apple, food innovation, genome editing, new plant engineering techniques, trade, willingness to pay

JEL CLASSIFICATION

C91, D12, Q18, Q16, F14

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 & Wesseler, 2021). International trade in these products could enhance profit opportunities for producers and benefit consumers with access to improved goods and more choice.

Our paper analyses 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 analyse the welfare impact of NPETs regulatory and trade policy heterogeneity across countries.

1.1 | Research and development

Public investment in R&D provides 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 & Fuglie, 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 European Union (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 et al., 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) with 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 & 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

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

4–6 years (Alvarez et al., 2021). To date, GenEd has been used to improve traits such as flowering time and disease resistance in apples, though GenEd apples have not yet been commercialised (Ramirez-Torres et al., 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 programme funding, such as the programme at Washington State University for developing new apple varieties.

1.2 | Hurdles to innovation commercialisation

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

Consumer food choices are based on many factors, including price and quality (Lusk et al., 2011; Lusk & Marette, 2010). Consumer acceptance is uncertain, as some consumers dislike or distrust biotechnology, whereas other consumers value new attributes that may be brought about by NPETs (Beghin & Gustafson, 2021; Caputo et al., 2020; Lusk et al., 2005; Marette et al., 2021a). 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 foods (horizontal differentiation), 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 (Beghin & Gustafson, 2021; Caputo et al., 2020; Kolodinsky et al., 2019).

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 (Qaim, 2020; Sheldon, 2002). 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 (Anderson, 2010; De Faria & Wieck, 2015; Disdier & Fontagné, 2010; Sheldon, 2002). Heterogeneous regulations across borders, lack of transparency in the approval process, import bans, trade disputes, co-mingling issues, and traceability requirements are tangible problems facing NPETs.

The heterogeneous regulatory environment across borders is characterised 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, since 2020 USDA exempts certain modifications that could have been obtained with conventional breeding from additional regulation (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).

In contrast, the Court of Justice of the EU 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 Online Appendix A summarises the approaches implemented in the USA, 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).

The impact of regulatory heterogeneity on international trade has been extensively investigated in the trade literature. Regulatory heterogeneity tends to have detrimental trade effects, especially on exports from developing countries (Wilson & Abiola, 2003). Both trade margins (new trade at the extensive margin, deepening of existing trade at the intensive margin) can be affected. The impact on the extensive margin appears to be particularly strong, highlighting the fixed cost nature of matching different standards in destination markets (Foletti & Shingal, 2014). Interestingly, harmonisation of technical regulation within regional trade agreements facilitates trade among its members but negatively affects trade with external countries from the South (Disdier et al., 2015), echoing findings of Chen and Mattoo (2008) on regionalism and standard harmonisation.

The literature on asynchronous approvals of GMO is equally relevant to our analysis. Asynchronous approvals create regulatory heterogeneity. Several authors have analysed the impact of asynchronous approvals of GMOs and their impact on trade and welfare (De Faria & Wieck, 2015, 2016; Disdier & Fontagné, 2010), but without considering the interface between trade policy and innovation. However, a few investigations have analysed the impact of heterogeneous regulation across borders and its impact on biotech R&D. Oliveira et al. (2020) analysed the impact of technological change on bilateral trade of soybeans in the presence of unequal technology adoption of GMOs and heterogeneous regulations and acceptance in international consuming markets. Lapan and Moschini (2004) analysed the impact of introducing GM innovation in a two-country trade model, in which a GM product is a weakly inferior substitute for the non-GM product in the importing country and in which costly regulation may decrease trade and welfare. The innovation originates in a profit maximising sector producing the two products (conventional and GM). To our knowledge we are the first to formalise the interface between regulatory heterogeneity, R&D, trade and welfare in the NPETs context.

1.3 | Modelling 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. Our model application is a case study of a hypothetical development and introduction of improved apple varieties into domestic and/or international markets.[2] The application builds upon the results of two experimental surveys of consumers' preferences in France and the USA (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 values 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 at the average of the EU and US consumers. This is a reasonable 'middle of the road' 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) and the more accepting attitudes of US consumers.

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.[3]

The simulations lead to characterisation of countries' decisions to invest in R&D, depending on market opportunities (domestic and abroad), probability of R&D success, and sunk cost. 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 disincentivise R&D investment, slow or stop research, and even push research to other countries (European

[2]Apples are largely traded internationally. One-third of the US apple crop is exported each year with a value of $1 billion (Source: https://usapple.org/policy-priority/international-trade). In the EU, about 10% of the production is exported outside the EU and extra-EU imports of apples represent about 20% of total EU imports (Source: https://www.fruitlogistica.com/fruit-logistica/downloads-alle-sprachen/auf-einen-blick/european_statistics_handbook_2021.pdf).

[3]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.

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 commercialisation (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, Vigani et al. (2012) analysed 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 analyse 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 analyse 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 organised 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 organisation 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 we 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 (e.g. USA, EU, India, Brazil, China, etc.), but for simplicity, we limit our analysis such that the EU and the USA 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 commercialisation 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. It 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 standardised 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 A2, online, summarises 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 summarised 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.[4] The R&D process fails with probability $(1 - \lambda_{Ni})$. Uncertainty of Stage 1 is resolved at Stage 2. Sunk cost is 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 cost 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.[5] Countries may allow importation for food, feed, processing, transit or cultivation. For simplicity, we consider regulatory approval as 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.

In Stage 3, producers and consumers adjust 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 considerations, 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

[4]This setup is highly stylised to contrast two strategies (NPETS, no innovation) and their interface with regulatory heterogeneity and trade. In reality, multiple innovations can be considered (conventional breeding, GMO, multiple NPETs) and multiple agents can innovate.

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

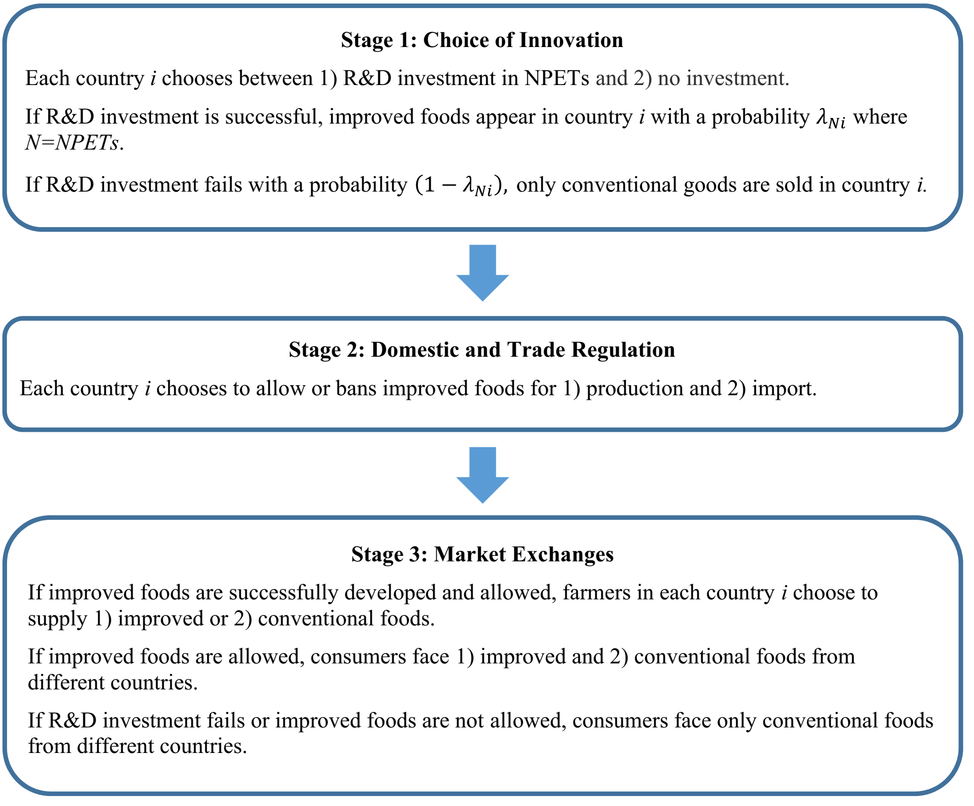

FIGURE 1 Stages of the model

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, either directly on their exports of improved foods, or through lower prices resulting from lower world demand for improved foods.

As we abstract from differentiation by country of origin, we model net trade of each type of food (conventional, improved) being traded. Any country can export its excess supply to fulfil the excess demand from other trading countries for the conventional or improved foods, and vice versa, can import to satisfy its excess demand. In each country, the two types of foods are imperfect substitutes through vertical differentiation and quality segmentation. Two world equilibrium conditions (sum of excess demands and supply summing to zero) allow us to solve for the two world equilibrium prices for the two food types. Both prices endogenously adjust depending on bans or authorisations of improved foods and the success of the R&D process.

For the purposes of this model, consumers in country $i=\{US, EU, RoW\}$ are informed about the technologies 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. 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 characterised by the uniformly distributed parameter $\theta \in [0, 1]$. A consumer who buys one unit of food of a quality k at a price p has an indirect utility equal to $\theta k - p$ (see Mussa & 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.

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

2.3.1 | Stage 3: Supply adjustment

The supply sector is derived from profit-maximising producers characterised by a quadratic profit function. Profits are increasing in apple prices and the profit function is convex in prices. Envelope theorem results provide the supply of each type of food as linear functions of own and cross prices. We restrict cross-price effects to be symmetric, negative and equal to minus half the geometric mean of own prices to impose convexity in prices. When the R&D process fails or when improved apples are not grown (such as in RoW), the profit function represents profit opportunities in the conventional apple sector alone.

Starting with foods in country i (i = EU, US) when both conventional and improved foods are produced and for prices (p_C, p_N), and assuming price-taker producers, the maximisation of profits leads to supplies of conventional and improved foods, q_{Ci} and q_{Ni}, $q_{Ci}(p_C, p_N) = a_{Ci} + b_{CCi}p_C + b_{CNi}p_N$, and $q_{Ni}(p_C, p_N) = a_{Ni} + b_{NNi}p_N + b_{CNi}p_C$. Their calibration is detailed in the next section.

If improved foods are not produced, either if the R&D process is not successful or just not undertaken (i = RoW), the supply of conventional foods is just $q_{Ci}(p_C) = a_{Ci} + b_{CCi}p_C$.

2.3.2 | Stage 3: Domestic demand and surpluses under different configurations

For a country i, demand depends on the type of 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 $\overline{\theta} = pc/k_i$ (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:

$$M_i \int_{\overline{\theta}}^{1} d\theta = Q_{Ci} = M_i\left(1 - pc/k_i\right). \tag{1}$$

The inverse demand in this first configuration is $p_C(Q_{ci}) = k_i\left(1 - \frac{Q_{Ci}}{M_i}\right)$. For any given price p_{C0}, the consumers' surplus is then $CS_{Ci}(pC0) = M_i \int_{pC0/k_i}^{1} (\theta k_i - pC0)\, d\theta$. Producers' profits are $\pi_{Ci}(p_{C0}) = a_{Ci}p_{C0} + 1/2 b_{CCi}p_{C0}^2$. Hence, welfare for any country i depends on consumers' welfare and farmers' profits. It is denoted W_0^i and equal to:

$$W_0^i = CS_{Ci}(pC0) + \pi_{Ci}(pC0). \tag{2}$$

Configuration 2. Improved foods are available with successful R&D investment (Stage 1) and authorisation (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 $\widetilde{\theta} = (p_N - p_c)/(k_{Ni} - k_i)$, where $\theta k_{Ni} - p_N = \theta k_i - p_c$. The parameter $\overline{\theta} = p_C/k_i$ 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 $\beta_i M_i \int_{\widetilde{\theta}}^{1} d\theta = Q_N = \beta_i M_i [1 - (p_N - p_c)/(k_{Ni} - k_i)]$ and the demand for low-quality food is $\beta_i M_i \int_{\overline{\theta}}^{\widetilde{\theta}} d\theta = Q_C = \beta_i M_i [(p_N - p_c)/(k_{Ni} - k_i) - p_C/k_i]$. 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 improved food leads to an increase in consumer surplus (observed through the comparison of consumer surplus under the improved food versus consumer surplus under conventional food).

Producers' profit comes from sales in markets for both conventional and improved foods. It is $\pi_{C\&Ni}(p_C, p_N) = a_{Ci} p_C + a_{Ni} pN + 1/2 (b_{CCi} p_C^2 + b_{NNi} p_N^2) + b_{CNi} p_N p_N$. Total welfare in country i, in this second case, is denoted W_N^i. It is:

$$W_N^i = CS_{CNi}(p_c, p_N) + CS_{Ci}(p_C) + \pi_{C\&Ni}(p_C, p_N). \quad (4)$$

2.3.3 | 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 to identify the impact on R&D investment.

2.3.4 | 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 realisation 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 borders 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 $\left(1-\lambda_{Ni}\right)$, leading to a welfare metric without an improved food. Sunk expenditures F_{Ni} are associated with R&D investment and regulatory authorisation 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:

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

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

3 | APPLICATION TO APPLES

We apply this 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 so 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., 2021a). Apples are popular and highly consumed fruits, and good for health. They are available everywhere, all year long, with a price segment that is not too large and relatively well known by consumers. Finally, apples are subject to many innovations, for example, to extend their preservation, improve their vitamin content, reinforce their taste. Our experimental results can be considered as representative of the general issue of NPETs innovation. During the experiment, successive rounds of information dealing with the browning process affecting apples, the traditional hybridisation process, and the GenEd technique were revealed to participants, and WTP were elicited after each message. The messages were relatively short but based on scientific publications and press releases.

A multiple-price list (payment card) was used for eliciting WTP of consumers for each product (conventional and new). During each round, participants were asked to choose whether (or not) they will buy the product 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 USA. For each price, participants checked either 'yes', 'no' or 'maybe' as their purchase intentions. Prices were representative of the range of prices observed in supermarkets at the time of the experiment, respectively in France and in the US Midwest. No apple was sold at the end of sessions, leading to a possible upward bias of WTP. For each round and each good, the WTP was determined by taking the highest price consumers were willing to pay (the highest 'Yes' checked off in the list). For participants who never replied 'yes' to each line of the multiple-price list, the selected WTP was equivalent to 0.

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 USA than in France. Moreover, in the USA, a few consumers give very high value to innovation (right part of the relevant curve). This group of accepting consumers facilitates the adoption of foods improved with NPETs, when information about the technology is provided.

The Mussa and Rosen (1978) framework with accepting consumers is tailored to the WTP structure in Figure 2. As accepting consumers (right part 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 part of the figure). These non-interested consumers are included 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 the EU. Then we take the average of the US and French consumers' values and apply them to consumers in the RoW. Given the reluctance of many French consumers for foods improved with NPETs, this approach is reasonable and sets the ROW within the bounds of the two estimated WTPs and shares.

3.2 | Calibrated supplies and demand for apples

The supply functions for conventional and improved apples are calibrated using own- and cross-price supply elasticities and the average quantity (and price) over a year. For the initial calibration, the price for new apples is unobserved and a 60% premium is assumed over the price of conventional apples. Own-price elasticities are based on Devadoss et al. (2009). Own slopes are first derived for both conventional and improved supplies. Then the symmetric cross-price response is derived by taking minus half of the geometric means of the own slopes ($b_{CNi} = b_{NCi} = -0.5\sqrt{(b_{CCi} b_{NNi})}$).[6]

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 $\frac{M_i}{k_i} = -\varepsilon_{Ci} Q_{Ci} / p_C$ and $Q_{Ci} = M_i\left(1 - p_C / k_i\right)$. Table 1 presents the parameters used for the calibration.[7]

[6]Sensitivity is undertaken around this constraint by scaling the cross-price up and down. We find that results are not sensitive to varying the magnitude of the cross-price effects.

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

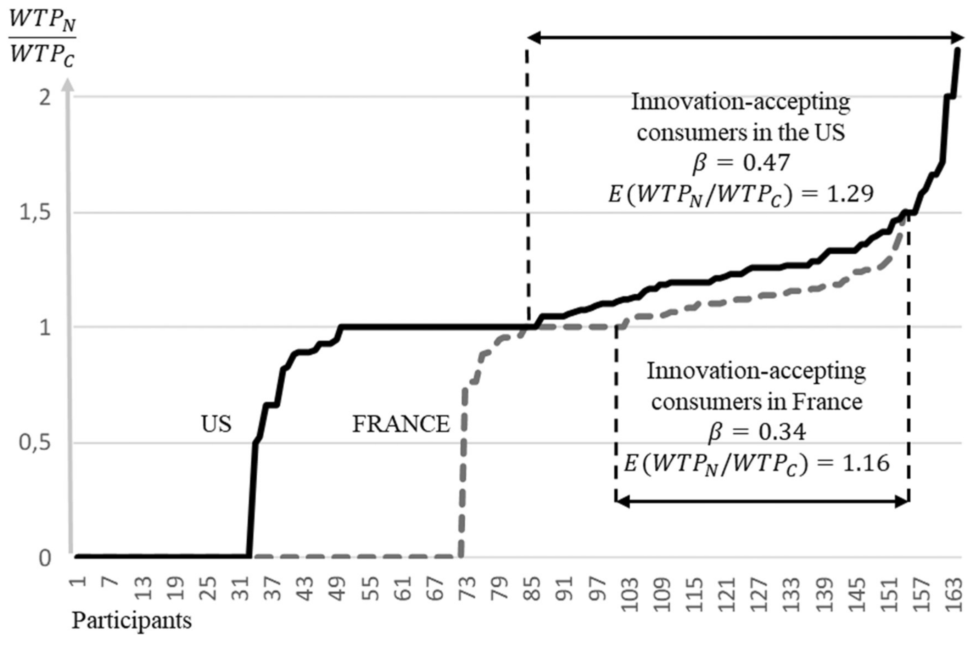

FIGURE 2 WTP expressed for improved apples relative to WTP expressed for conventional apples

Regarding the hypothetical improved apples, assumptions are made for both supply and demand sides. The decomposition of supply between conventional and improved apples is assumed as follows: the introduction of the improved apples in production reduces the supply of conventional apples one for one and we assume that 30% of the conventional production switch to supplying the new apples. After the initial calibration, all prices and quantities are fully endogenous and change depending on adjustments in regulation, probability of success in R&D and fixed cost of R&D.

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 equalised to the ratio of the inverse demands, and we can write the equality

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

leading to a value $k_{Ni} = k_i \times E\left(WTP_{N_i} / WTP_{C_i}\right)$ integrated in (3). 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 maximising welfares and leading to possible emergence of improved foods. Simulations are presented

TABLE 1 Parameters used for calibration

Country	Description	Values	Sources
US	Consumption, average 2017–19 (tons)	4,216,047	FAO
	Production, average 2017–19 (tons)	4,961,047	FAO
	Supply own-price elasticity	0.2	Devadoss et al. (2009)
	Demand own-price elasticity	−0.3	Devadoss et al. (2009)
EU	Consumption, average 2017–19 (tons)	11,483,049	FAO
	Production, average 2017–2019 (ton)	12,019,331	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 2017–19 (tons)	110,754,764	FAO
	Production, average 2017–19 (tons)	109,435,928	FAO
	Supply own-price elasticity[b]	0.37	Devadoss et al. (2009)
	Demand own-price elasticity[b]	−0.31	Devadoss et al. (2009)
	Average conventional apple price ($/kg) 2017–19 (3 regions)	(1.67 + 0.91 + 0.95)/3	FAO

[a]Average of elasticities in France, Germany, Italy and the Netherlands.

[b]Average of elasticities in Brazil, China, India, Middle East and Southeast Asia.

Source: FAO data: http://www.fao.org/faostat/en/#home. Data downloaded in June 2021.

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 dollars and reported on the y-axis.

We start with our first scenario, where the USA is the only country to potentially access improved foods, due to adequate R&D investment and favourable regulatory authorisations, 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 panel of the figure, these foods are allowed to be sold in all countries, while in the right panel, imports of these foods are banned in the EU and in the RoW.

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). The frontier is linear in the probability because a single country innovates. If improved foods emerge with certainty ($\lambda_N = 1$), the investment is socially desirable for a sunk cost (F_N) lower than US$1.907 billion, a significant amount. For relatively high values of per-unit of sunk cost F_N, there is no R&D investment by the USA 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,[8] 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 not optimal because of import bans on improved foods in the other markets. 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 at or above 1.799 billion (assuming that the new food emerges with certainty).

[8]This frontier is not shown to avoid clutter.

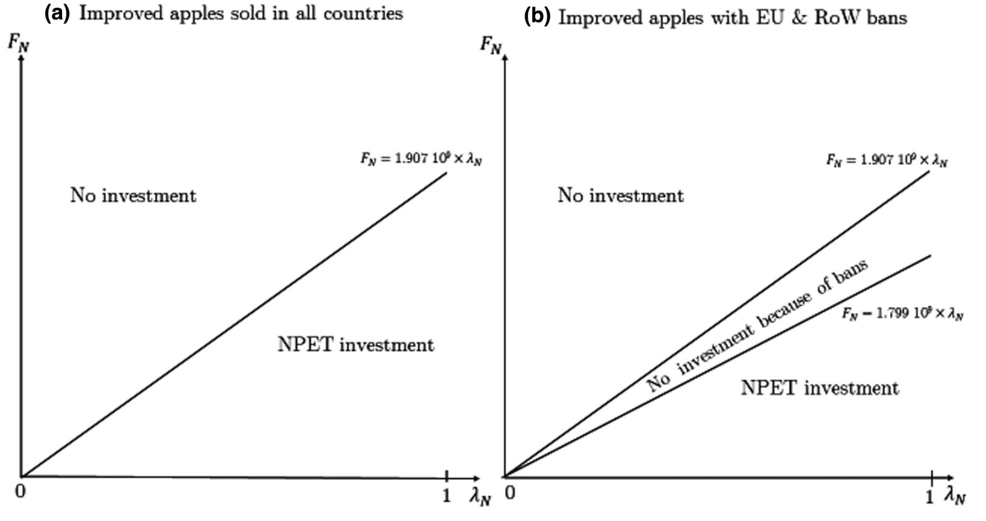

FIGURE 3 Scenario 1: R&D for improved foods accessible only for the USA

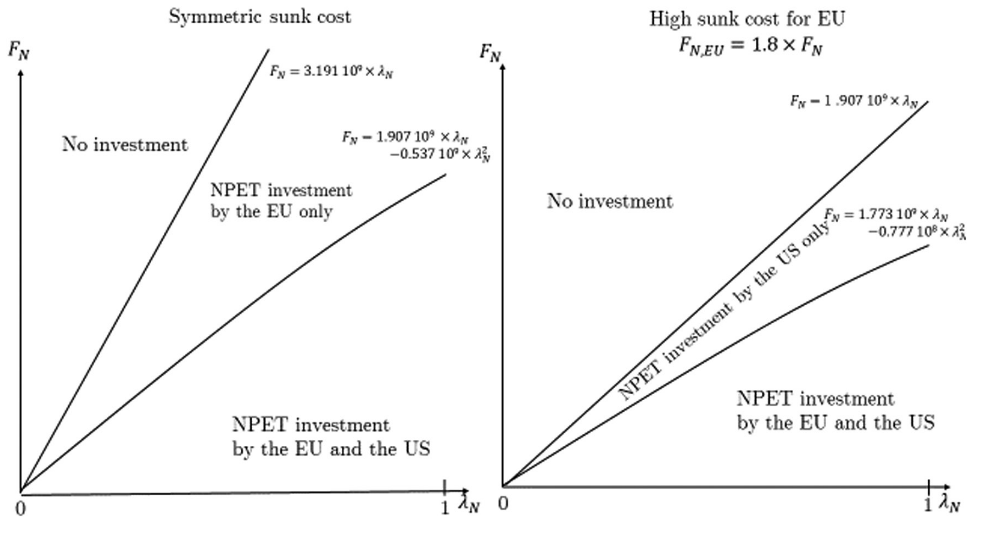

FIGURE 4 Scenario 2: R&D investment accessible for both the EU and the USA

In sum, Figure 3 characterises country choice in R&D investment, which depends on market opportunities at home and abroad, the probability of R&D success, as well as the sunk cost of R&D and its spread over markets. R&D investment is deterred by import bans on improved foods outside the investing country.

Scenario 2 introduces a new competitor in the production of improved foods. The EU is now able to invest into R&D for improved foods and produce foods improved with NPETs and export such products worldwide. This second scenario assumes all three regions allow the consumption of improved foods generated with NPETS. R&D investment decisions by the USA and the EU are reported in Figure 4. Symmetric sunk costs (F_N) in the USA and in the EU are shown in the left panel of the figure. In the right panel, the EU R&D cost is assumed to be 80% higher than in the US. As shown in the left panel of Figure 4, R&D investment is optimal for both countries for relatively low levels of sunk cost, normalised by output. The lowest frontier is quadratic in probabilities because two countries invest and the probability of success is, consequently, squared.

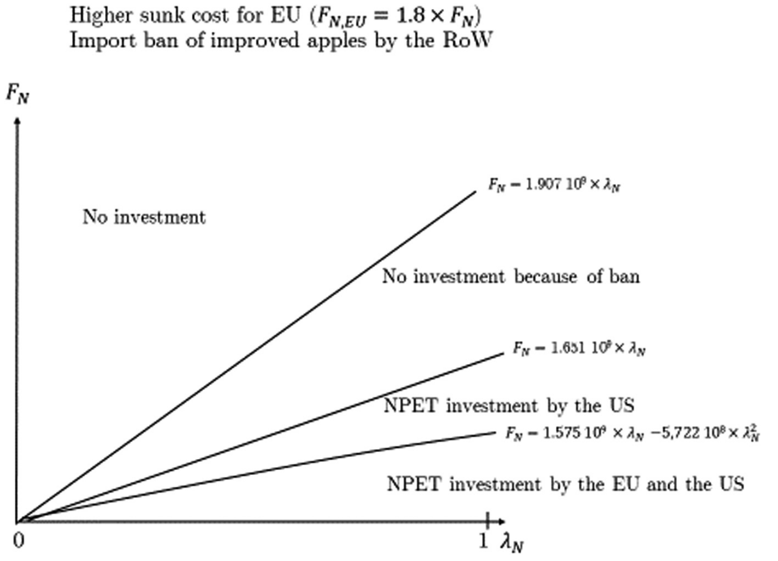

FIGURE 5 Scenario 3: Investment accessible for both the EU and the USA, import ban in RoW

Because the apple market is larger in the EU than in the USA, the profits and surpluses linked to the introduction of improved apples are bigger in the EU, leading to more possibilities for covering higher sunk cost compared to the USA (left panel of Figure 4). For relatively high sunk cost, the USA eventually exits the production of improved apples and the EU remains the only partner investing R&D funds in improved apples. Finally, for high values of per-unit sunk cost, there is no R&D investment anywhere and improved foods do not emerge.

On the right panel of Figure 4, sunk cost is assumed to be 80% higher in the EU due to higher regulatory costs. In this case, the USA becomes the only country investing in R&D for medium values of sunk cost. The separating frontier between no NPET investment by any country and some investment by the USA ($F_N = 1.907\ 10^9 \lambda_N$)[9] indicates reduced opportunities to see improved apples emerge relative to the situation with symmetric sunk cost ($F_N = 3.191\ 10^9\ \lambda_N$), which is relevant for the EU investment in R&D, since the USA has ceased to invest in that zone of the graph.

Scenario 3 considers the impact of an import ban by the RoW. It further assumes that both the EU and the USA have access to the innovation technology with a higher sunk cost for the EU (as in the right panel of Figure 4). However, results are robust to different assumptions (e.g., EU sunk cost similar to those in the USA). The import ban modifies the incentive for innovating, since potential profits from exporting improved foods to the RoW disappear. Compared to the right panel of Figure 4, frontiers pivot downward in Figure 5. They imply some decreased ranges in R&D investment undertaken by the US and the EU respectively.

For low values of sunk cost F_N, both countries invest in R&D. For medium values of sunk cost F_N, only the US invests in R&D, while both countries invested. For high values of sunk cost F_N, there is no R&D investment, while the US was previously investing (Figure 4). The import ban is directly responsible for the absence of investment because of the reduced profitability. It is detrimental for the world welfare inclusive of all profits and surpluses. Hence, a ban in a third country can deter the emergence of improved foods in countries contemplating the R&D investment in these foods. This deterrence effect on R&D is different from the standard case in the NTM literature. The standard NTM literature focuses on the NTM's potential

[9] $F_N = 1.907\ 10^9 \lambda_N$ is also shown in Figure 3a when the USA is the only country investing in R&D.

protective impact on existing output in a domestic market of the country issuing the ban, as well as on the anti-protective effect on foreign exporters competing for that market and the resulting trade deterrence (UNCTAD, 2018).

3.4 | Robustness

We investigated the robustness of this model and its outcomes and implications by considering variations in supply and demand price elasticities, share of production going to improved apples in the initial calibration, and asymmetric fixed cost of R&D. As long as the model converges with interior solutions for the demands for improved apples, policy implications are unaltered. Hence, we focus on conditions under which these demands reach corners. The model converges to interior solutions without issue under various configurations when both the US and the EU supply improved apples and under different policy configurations in the RoW (ban/no ban). This holds for variations in elasticities (with halving, and doubling them) and for variations in the initial share of apples going to improved apples (20 to 30% or higher).

When the USA is the only producer of improved apples and when we increase demand and supply elasticities, demand for improved apples eventually reaches a corner in the rest of the world. An interior solution is reached with a 50% increase in elasticities. When the elasticities are doubled, the corner is reached. The corner implies that an import ban on improved apples in the RoW would not have any impact on the emergence of improved apples. The corner originates from the demand elasticities. When doubling the supply-price responses but leaving demand elasticities unchanged, the model converges to an interior solution. Similarly, doubling the price elasticities for EU demands when the USA is the only producer of improved apples, the model reaches a corner in the EU demand for improved apples.

In addition, when the US is the only producer of improved apples, lowering the initial share of improved apples in total production eventually leads to a corner in the demand for improved apples in the RoW (below a share of 27%). These conditions do not arise when both the EU and US produce improved apples. Finally, changing assumptions on the symmetry of the fixed cost of R&D affects the location of the frontiers but the policy implications remain unaltered.

4 | DISCUSSION AND CONCLUSIONS

This paper emphasises 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.

Our 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 cost, 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 cost 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 harmonisation or reciprocity would be ways to open borders for these improved foods.

Our analysis is based on ex-ante simulations. Of course, an ex-post analysis, once GenEd products are available on the market, is needed to validate the simulation results. Recent developments in the trade literature suggest new tests applicable even in the presence of other unobserved shocks that may affect the economic environment (Adao et al., 2022). The combination between quantitative trade models and this new testing procedure represents a new and promising area of research.

Despite these limitations and those resulting from the simple setup (stylised WTP elicitations and industrial organisation 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 harmonisation 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. Second, for characterising 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.

Third, we considered just one period of exchanges. Several periods of exchanges with different probabilities of success for R&D investment could be considered, 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 foods are introduced. In addition, countries may simultaneously invest in R&D for different technologies and products in order to boost chances of innovations and larger sunk cost.

Other extensions could consider situations with or without consumer information about the technology. Countries or producers could decide whether to further inform consumers about the process of innovation, 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. Regarding the relationship between the sunk cost F_N and the probability of success λ_N (namely development of an improved food), we could assume that the sunk cost is endogenous as a quadratic function of the probability of success as is classically assumed in industrial organisation. However, this relationship between these two parameters is hard to characterise empirically and nothing simple can be concluded. The success depends on many parameters such as the sunk investment in the lab and the wages of skilled researchers. The sunk cost F_N and the probabilities λ_N could be evaluated with interviews, questionnaires and financial analyses.

All these proposed extensions could be considered to undertake more elaborate cost–benefit analyses of NPETs regulations and their impacts on trade.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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