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Reputation effects of nuclear accidents

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Abstract— Nuclear accidents act as a negative shock on the reputation of food products, even beyond contaminated areas. Reviewing the literature, we show how the reactions of consumers and producers when facing a nuclear crisis can amplify or mitigate the food crisis. We then detail a simple methodology to estimate the direct, indirect and induced effect of the reputation damage on the food sectors. We show that total economic losses could range between 10 to 100 billion euros, depending on the final demand drop scenarios. We further describe new research avenues relying on behavioral and experimental economic methods to mitigate the causality issue of the estimation of direct reputation effects.

Keywords— nuclear accident, reputation damage, food sectors

I. INTRODUCTION

Major accidents like the ones that took place in Chernobyl and Fukushima have economic consequences well beyond contaminated areas. The reputation of the country hit by a nuclear accident is severely impacted and the quality of its food products as well as the safety of domestic travels and tourism, are put into question.

To account for this negative reputational externality of nuclear accidents, the IRSN's nuclear risk economics laboratory coined the concept of *coût d'image* ("reputation cost") in 2013, when it published a report detailing an estimate of the total economic costs of serious and major accidents in France [1]. Reputation effects are defined as the economic losses in areas with low or no radioactive contamination, due to the decline in domestic consumption and exports caused by the damaged reputation of the region or the country affected by the nuclear accident.

From an economist's point of view, reputation costs are a collective reputation problem [2]. The nuclear accident acts as a negative shock on the collective reputation of a group, for instance all food producers in France, while the quality (degree of contamination) of only a small fraction of these products is actually concerned. Products that are too contaminated would have already been prohibited, on the basis of their level of radioactive contamination exceeding some official threshold¹.

However, information about radioactive contamination is imperfect (monitoring every single food product is often unfeasible) or not fully trusted, and official quality standards may be deemed too lenient [3]. Since most consumers cannot monitor food contamination by themselves, the reputation of all food producers is questioned. Reputation damage can also affect other sectors such as tourism and the nuclear industry. In this paper, we focus solely on the food sectors, but the reader should bear in mind that reputation effects have a wider scope.

Quantifying reputation costs is an arduous task because when a nuclear accident occurs, many areas of the economy are impacted at once, making hard to disentangle the pure reputation effect from a more standard indirect effect (e.g. non-contaminated areas suffering from the deterioration of macroeconomic conditions). Moreover, the (luckily) short list of nuclear accidents complicates the use of *ex post* econometric analyses. The contribution of this paper is two-fold: we first provide a simulation exercise meant to estimate *ex ante* the total economic cost associated to damaged reputation following a hypothetical major nuclear accident in France. Second, we emphasize how the behavioral economics literature can be useful to improve our estimates of reputation effects, by showing the results of a pilot experiment meant at anticipating populations' reactions when faced with a major nuclear accident.

The methodology of the *ex ante* simulation is similar to the one used in the IRSN report published in 2013 [1]. Yet, we update our calculations with 2018 data² and describe in more details the steps leading to the results. We consider a nuclear accident of a similar magnitude as Fukushima that could take place in any one of the Nuclear Power Plants (NPPs) in France. We build our estimation upon four scenarios to account for more or less strong behavioral reactions of the French population (domestic consumption and restaurant attendance) and foreigners (exports of food products). In particular, we show results for two short (3 years) and two long (9 years) reputation crises, varying the magnitude of the initial drop in demand. We base our calibration on a detailed comparison of the reputation damage following the Fukushima accident, questioning its generalization to the case of France. We

¹ See for example directive 2013/59/Euratom for European countries.

² The 2013 report used 2007 data.

complement this picture with information on non-nuclear food crises that occurred in Europe, such as the BSE crisis that affected the reputation of cattle in the 1980s and 1990s in Europe. Our estimation accounts for direct effects (impact on the food sectors), indirect effects (rippling effect on the economic activity along the supply chain) and induced effects (diminished economic activity caused by the declining wages in the food sectors, which deprive household consumption). We find that total reputation damage could range between 10 to 100 billion euros, with direct and indirect effects accounting for about 45% of the total each, and induced effect the remaining 10%. Depending on the selected scenario, from 25% (long scenarios) to 50% (short scenarios) of the losses would be incurred on the first year following the accident.

We acknowledge the limits of such simulation exercise, especially with respect to the calibration of the magnitude of the initial drop in final demand we could expect after a nuclear accident. We describe new research avenues to better calibrate the main parameters of our model, drawing on the behavioral economics literature and a pilot experiment we conducted in 2021, in collaboration with Hugo Mercier and Alicia Herrera-Masurel³. This experiment faces people with a hypothetical nuclear accident scenario and asks them to detail the potential reactions they could have, with minimal priming. Indeed, experiments of this type in the literature tend to make fear of food contamination very salient, a shortcoming we wanted to avoid. We argue that such methods could both improve our estimates and also provide a mean to test *ex ante* for the efficiency of mitigating policies.

II. RELATED LITERATURE

A. Assessment of the complete costs of nuclear accidents

This paper relates to the economic literature seeking to assess the economic cost of nuclear accidents with large radioactive releases in the environment (see [4] [5] for reviews). This literature focuses on the cost incurred in the most contaminated areas (for instance the ones subject to countermeasures). Most of these papers try to be as exhaustive as possible and so estimate a much larger range of consequences than we do in this paper. They evaluate health costs, agricultural losses due to local food restrictions, capital asset losses in the exclusion zone, cost of displaced population etc. Indirect consequences in non-contaminated areas are sometimes accounted for in the form of rippling effects on businesses that are either suppliers or buyers of firms located in contaminated areas [6]. Reputation damage in non-contaminated areas is one component of total nuclear accident costs, but is often neglected (except for [1]), for the lack of appropriate methodology available in the academic literature may yield too uncertain estimates. In 2000, the OECD considered those image costs to be “unquantifiable” [5]. We argue that progress can be made in this area, to avoid costing image effects at zero, which is the inevitable assumption made in all the works discarding such costs from their analyses.

B. Behavioral factors causing reputation effects

Reputation effects are a behavioral consequence of a nuclear accident, where economic agents answer sub-optimally⁴ to the news out of fear, a precautionary principle, belief in harmful rumors (*Fu-hyo* in Japanese) [7] or mistrust.

According to psychologists, fear of radioactive contamination is the result of evolution that endowed humans with a hypervigilant “behavioral immune system” to help avoiding harmful pathogens [8]. Psychological mechanisms activate a feeling of disgust to motivate people to stay away and avoid eating potentially infected food. It takes a lot of reasoning to go against repulsion and since this cognitive bias has proven so successful for evolution, it is deeply rooted. Mistrust may interact with disgust, but is also largely determined by official communication, media and social interactions, as we will see later [9] [10].

On top of disgust bias, humans also have a biased intuitive understanding of probabilities. The difference between a 1 out of 100 probability and 1 out of 1000 probability is often overlooked: people often make judgments as if those two probabilities were roughly the same. This cognitive bias called “denominator neglect” is explained by the fact that people tend to focus on the number of occurrences of bad events, such as getting a cancer due to ionizing radiations (one in this case), but fail to properly account for how large the sample is (100 or 1000 in our example) [11]. Moreover, they tend to overestimate the likelihood of low probability catastrophic risks, because they focus more on the badness of the outcome than on its actual probability of occurring (“probability neglect”) [12]. Hence, people tend to be more concerned about extraordinary but low probability risks (terrorism, airplane crashes) than statistically larger risks they face in their daily lives (car crashes) [12].

In the situation of a nuclear accident, it is then natural to expect an over-reaction of the population with respect to more ordinary risks. They might take more precaution to avoid radioactive contamination (extraordinary risk) than against pesticide risks (ordinary risk), keeping the likelihood of adverse health effect constant across both types of risk.

C. Lessons learnt from the Fukushima accident

1) Reputation in the Fukushima prefecture

The accident on the Fukushima Daiichi NPP in March 2011 showed that reputation damage can be large and long-lasting, especially on food products, for which reputational concerns are still felt ten years on, according to recent interviews with stakeholders in the Fukushima prefecture [3] and consumer surveys [13] [14] [15]. We can note that the NPP’s name, “Fukushima” could have been particularly detrimental in this case, since it refers to a whole prefecture, inhabited by almost 2 million individuals, and not simply a town as it is often the case in France.

Behavioral reactions to accident management policies from both consumers and producers amplified image costs. Crisis management policies in the aftermath of the accident

³ Hugo Mercier is a research scientist at CNRS (Institut Jean Nicod), Alicia Herrera-Masurel was a student of the master in cognitive sciences of the ENS. The IRSN used their services for the elaboration of the questionnaire, its implementation online, the recruitment of the subject pool and the collection of answers.

⁴ We understand optimality in a purely economic sense and this should not be taken as a normative judgment. We focus on the economic costs associated to this behavior, but we don’t quantify the potential psychological benefits for the population of taking such precautions.

involved provisional safety standards that came in the form of radiological contamination thresholds above which agricultural products cannot be consumed. In the weeks and months after the accident, the standards evolved several times to become more and more stringent, with a lowered contamination threshold and the addition of new food categories within the regulation scope⁵ [3] [7], implying that food products that were deemed safe earlier would now be forbidden. Moreover, food restrictions sometimes varied across prefectures and municipalities [3]. All these elements casted doubt on the quality of the products sold in Fukushima, and eroded consumers' trust, already well damaged by controversies over Japanese authorities' delimitation of contaminated areas [10]⁶. Food producers' attempted to restore trust by implementing even more restrictive unofficial standards to flag the quality of their products. On top of willingly discarding part of their production, several agricultural cooperatives in Fukushima invested in costly monitoring equipments to assess radiological contamination at every step of the food production process [3] [7].

2) Economic consequences

How do these behaviors translate into market consequences and economic damage? We could gauge reputational damage by its depressing effect on exports, market prices, quantities sold, profits, GDP, a plummeting number of active farms, etc. Interpreting these figures is hazardous, since in the case of the Fukushima nuclear accident, depressed economic activity in the food sectors stemmed from many factors, and reputation is only one of them. The accident on the NPP originated from an earthquake and a tsunami that hit the north-eastern region of Japan, damaging agricultural lands and capital. Besides, major nuclear accidents like Fukushima have disruptive and multiple consequences since they hit many sectors at the same time, thereby inducing rippling effects across sectors and regions of the economy. All these factors create a causality issue that is hard to overcome. Agricultural prices illustrate the difficulty to pin down reputation effects: while bad reputation and imports controls imposed by foreign countries drive prices down, the losses due to the destruction of contaminated products and the tsunami have inflationary effects by restricting supply. Hence, the resulting equilibrium price underestimates reputation effect.

Bearing these limits in mind, we can study some of these figures and interpret them as "net economic effects", mixing both reputation, food restrictions, disorganization of the supply chain and tsunami effects. Aruga [13] compiles data on the total annual value of production of several food products (rice, beef, mushroom, tuna, cucumbers etc.) and compares its evolution across prefectures. Clear differential trends can be observed for most food products: Fukushima was often a top seller in 2010 but fared worse than other prefectures in 2012. For instance, the Fukushima prefecture experienced a 30% drop in cucumbers production value between 2010 and 2012, while none of its cucumbers ever tested above contamination thresholds [13]. Exports of food products dropped by 7% over the first nine months of 2011 with respect to the same period

in 2010, with important disparities since livestock exports fell by 20% and rice by 62%⁷

3) Generalizing these results to France

How far can we go to generalize those numbers in the case of a major nuclear accident in France? On top of the causality issues described above, Japan and France's food sectors are dramatically different. While Japan is a net importer of agri-food products, France exports all around the world and the quality of its food products is renowned, especially for several flagship products such as its wine and cheese. Its exposure to reputation effect is probably larger. A major accident at one of the sites in the Rhône-Alpes region (Bugey, Saint-Alban, Cruas, Tricastin) or at a power plant on the western side of France (Chinon, Civaux, Blayais, Golfech) would affect France main exportable food categories (livestock, dairy products, crops and drinks), and potentially Bordeaux vineyards. An accident in the center of France (Saint Laurent, Dampierre, Belleville) would perhaps spare dairy products, but would strongly impact crops, meat and wine production. Finally, an accident on one of the sites of Gravelines, Penly, Paluel or Flamanville could be devastating for livestock products, especially if the winds blow from the North-East. For all these reasons we cannot solely rely on the Fukushima experience to quantify the potential effect of bad reputation of a major nuclear accident in France, we can also use data on experiences of non-nuclear food crises that occurred in France and in Europe.

D. Non-nuclear food crises

Non-nuclear food crises usually involve the discovery of pathogens in food products that could lead humans to develop diseases if consumed. Bovine spongiform encephalopathy (BSE), commonly known as the mad cow disease, hit several countries in Western Europe, including France, in 1996 and 2000. These food crises that dramatically damaged the reputation of cattle products is a typical example of food scares. They are characterized by a sharp initial decline in consumption followed by a gradual recovery, usually taking a year or more, depending on the duration of the crisis and the uncertainty surrounding food safety [16]. Table I provides example of several food crises and the associated drop in domestic consumptions and exports of the incriminated food products. The arguably most severe crisis was the BSE crisis that hit the UK sporadically in the 1980s and the 1990s with a spike in 1996. This crisis only concerned cattle products, and yet it costed to UK's public budget around £3.5 billion between 1996 and 1999 to alleviate its economic consequences [17].

We expect the drop in consumption attributed to reputational damage following a major nuclear crisis to be of similar magnitude but to last for a longer time period, because of the long-lasting nature of radioactive contamination. Moreover, we assume that the crisis would affect all food products simultaneously. We show in the next section how we derive the total economic cost associated with reputation damage, using the figures shown in Table I to calibrate our parameters.

⁵ See here for a list of all the updates on food restrictions: https://www.accessdata.fda.gov/cms_ia/importalert_621.html

⁶ This mistrust rose despite the fact that only 1.8% of all sampled food items were tested above radioactivity thresholds between March 19th, 2011 and March 31th, 2013 [28].

⁷ *Monthly Information on Imports and Exports Agricultural, Forestry and Fisheries Products*, International Department, Ministry of Agriculture, Forestry and Fisheries of Japan.

TABLE I.
ECONOMIC EFFECTS OF SOME NON-NUCLEAR FOOD CRISES

	<i>Disease</i>	<i>Drop in domestic consumption</i>	<i>Drop in exports</i>
UK, 1996 [16] [17]	BSE (cattle)	40% immediate drop, 20% drop first year, 10% second year, 5% third year ⁸	100% for about three years ⁹
France, 1996 [18]	BSE	20% drop the first three months and back to initial level 6 months later 10% decline overall on the first year	14% drop on the first year
France, 2000 [16] [18]	BSE	30%-35% back to normal one year later	40% initial drop and back to normal three years later
France, 2001 [18]	Foot-and-Mouth disease	23% initial drop and stabilization one year later	45% initial drop back to normal after a couple of months
France, 2005 [18]	H5N1 virus	8% drop the first two years and 5% drop the third year	
US, 2004 [19]	BSE	No drop in domestic consumption	18% initial drop

Note: Drops are estimated with respect to pre-crisis level. They only concern the incriminated food products and not the entire food sector.

III. EX ANTE ESTIMATION OF THE MAGNITUDE OF REPUTATION COSTS IN FRANCE

Broadly speaking, the total market losses¹⁰ associated to any kind of negative shock on the economy are equal to the difference between the GDP that the country would have had achieved in the absence of the shock and the GDP observed once the shock takes place. If the effect of the shock lasts several years, then the differences must be summed every year until GDP goes back to its pre-shock trend. Reputation costs on the food sectors are only one cost component among others generated by nuclear accidents. Therefore, we try to isolate the specific contribution of damaged reputation in total losses.¹¹

We carry out a simulation exercise, based on national account data, to roughly estimate what could be the direct, indirect and induced effects of reputation damage caused by a major nuclear accident in France. Direct costs refer to the drop

⁸ The BSE crisis spiked in 1996 but started already in the 1980's. The UK have experienced a downward trend in beef consumption since the 1980s but BSE was not the only reason. [30].

⁹ The export of UK beef and cattle was prohibited for 30 months. [29]

¹⁰ Non-market losses involve negative health effects, psychological and well-being losses that are not accounted for by market forces. They are beyond the scope of this study.

¹¹ You can refer to [1] and [4] for estimations of total market losses of serious and major nuclear accidents.

¹² We use gross value added throughout: it is equal to the sales revenues minus intermediate consumption.

¹³ To be more precise, GDP is equal to the sum of all gross value added + taxes on products (value added tax and specific taxes on tobacco and alcohol for instance) - subsidies on products. Taking taxes and subsidies into account would imply considering that the deprived activity also decreases the amount of taxes on products the State can levy. Taking taxes and subsidies into account would ask for a much more refined model with a proper modelling of

in value added¹² in the food sectors (agriculture sector, agri-food industry and restaurants) because of the decrease in demand for French food products. The sum of all the value added generated in France over a year is equal to GDP¹³. Indirect costs refer to the loss of value added in other sectors of the economy, because of the rippling repercussions throughout the supply chain following the initial shock impacting the food sectors. Farmers use intermediate goods and services in their production process (tractors, oil, electricity, etc.). If they face a decreasing demand for their products, they will adapt by producing less, and hence will buy less intermediate goods supplied by other sectors of the economy. Induced effects refer to the loss of activity induced by the decreasing consumption of households working in the food sectors. To face the consequences of reduced demand, the food sectors may be forced to lay off employees or cut wages, which in turn reduce employees' consumption of all goods and services. We detail the calculation steps of each cost in the next paragraphs.

A. Reputation effects scenarios

We build our estimations upon four reputation scenarios, two short-duration ones that only last three years (S1 and S2) and two long-duration ones that last nine years (S3 and S4), as described in Table II. We also vary the magnitude of the initial reaction to the accident (drop in final demand the first year after the accident), and assume a progressive attenuation path in the following years. Short scenarios can also be interpreted as being relevant for nuclear accidents with more limited radioactive releases or a favorable weather with winds blowing the radioactive plume offshore. A long scenario would fit a more dramatic accident, with higher radioactive releases or an unfavorable weather leading to larger contaminated areas. For each scenario, we attribute percentage decrease in final domestic consumption¹⁴ and exports for the agriculture sector¹⁵ and the agri-food industry¹⁶, and losses in the demand for restaurants¹⁷. All our estimations focus on losses on the French economy only and don't account for spillover effects on France trading partners through a decrease in demand for imported goods and services.

S1 assumes that only food exports are negatively impacted and that everything is back to normal after three years. S2 describes a stronger shock on exports and a small negative effect on final domestic consumption, both resorbed after three years. The last two scenarios, S3 and S4, are more intense and long-lasting shocks. In S4, both final domestic consumption and restaurants are impacted.

the governmental response to the crisis. We can imagine that the government could change taxes on product (decrease momentarily the value added tax to help the food sector) or increase its subsidies. These policies are not pure GDP losses since they feedback into the economy by fueling demand (fiscal multiplier). It is beyond the scope of this study to model such policy responses.

¹⁴ Final consumption includes both household consumption and consumption by the administration although the latter's weight is negligible. Since we focus on losses on the French economy only, we must subtract the value of final consumption of imported products to get final domestic consumption.

¹⁵ The agriculture sector is defined as the AZ category in INSEE's nomenclature (cultures, livestock, hunt and related services; forestry; fisheries).

¹⁶ The agri-food industry is defined as the CA category in INSEE's nomenclature (alimentary industries, beverage, tobacco industry).

¹⁷ INSEE category A88.56.

Overall, we expect stronger negative effects on exports than on domestic consumption for two reasons. First, foreign consumers are more likely to conclude that France as a whole was impacted, whereas domestic consumers may be more able to differentiate across regions. We would thus expect domestic consumers to substitute regional products within France and not necessarily rely more than usual on imported food. Since our simulation takes place at the national level, we cannot account for these regional effects. In practice, this would imply that the losses in the impacted region could be partially or fully compensated by more vigorous consumption of food products in other regions of France. Second, foreign countries can implement precautionary restrictions on exports out of radioactive concerns, as it has been and is still the case in Japan¹⁸.

TABLE II.
REPUTATION DAMAGE SCENARIOS: PERCENTAGE ANNUAL DROPS IN FINAL DEMAND BY SECTOR

	Agriculture et agri-food industries				Restaurants	
	Final domestic consumption		Exports			
<i>Short scenarios</i>	S1	S2	S1	S2	S1	S2
Year 1	0	5	10	20	0	0
Year 2	0	3	5	10	0	0
Year 3	0	1	2	4	0	0
<i>Long scenarios</i>	S3	S4	S3	S4	S3	S4
Year 1	0	10	20	30	0	5
Year 2	0	7	14	21	0	3
Year 3	0	5	10	16	0	3
Year 4	0	4	8	12	0	2
Year 5	0	3	6	9	0	2
Year 6	0	2	4	7	0	1
Year 7	0	2	3	5	0	1
Year 8	0	1	2	3	0	0
Year 9	0	0	1	1	0	0

Note: Assumed annual drop in final demand (in percentage) by scenarios, with respect to the pre-accident level. Reading: final domestic consumption is assumed to drop by 5% one year after the accident, relative to the pre-accident level, in the second scenario (S2). Then the economy slightly recovers with a 3% decline two years after the accident with respect to the pre-accident level, and finally a 1% drop in year 3. In year 4, final domestic consumption goes back to its pre-accident level (0% drop).

B. Data

All the data comes from INSEE's national account statistics for 2018¹⁹. We don't use more recent data to avoid polluting our results with the exceptional years of the Covid crisis. Using 2018 data amounts to assuming that the nuclear

accident took place at some date in that year. Older data would tend to underestimate the effect of a nuclear accident in the future, considering that the economy grows at a positive rate every year.

C. Direct effects

To estimate direct reputation effect, we assume that the decline in final demand described in Table II impacts in a proportional way the value added of each sector. We don't make any assumption about the channels of transmission of this demand shock, it could affect altogether prices, quantities sold and the firm could also adjust its production costs. We only consider that overall, total valued added will decline in the same proportion as final demand.

The shares of the agricultural sector and the agri-food industry have been fairly constant for the last ten years, stabilizing around 1.5% and 2% of GDP, respectively [20]. In 2018, the contribution to GDP (i.e. the value added) of each sector amounted to 39 and 43.3 billion euros, respectively. Restaurant services are not exportable, so we only focus on the loss in demand they may face domestically. Since we focus in this paper on reputation damage on the food sectors only (and not tourism), we follow [21] and assume that one third of restaurant activity should be attributed to tourism. Our analysis is carried out on the remaining two thirds, which contributed to GDP by 30.2 billion euros.

Since we don't know exactly what share of the value added of the agriculture sector and agri-food industry should be attributed to final domestic consumption on one hand or exports on the other hand, we assume that the respective contributions of final domestic consumption and exports are both equal to their relative proportion with respect to final demand.²⁰

To compute direct effects, we multiply for each scenario the annual drop in final demand compared to pre-accident values (in percentage terms) by the value added of each sector for each year following the accident. We sum up the losses over the years assuming a $r = 0.04$ discounting rate starting at year 1, so that losses reflect the discounted value of direct costs at the date of the accident (year 0)²¹. Summing over all directly impacted sectors²² indexed by i , the total discounted direct losses over T years, for an accident occurring at date t , are equal to:

$$Total\ discounted\ direct\ losses = \sum_{s=1}^T \sum_{l=1}^N \frac{Drop_{i,t+s} * VA_i}{(1+r)^s}$$

An underlying assumption is that the fundamentals of the economy remain the ones of 2018, and so VA_i is the value added of sector i in 2018²³. In particular, this implies that no other shock affects the food sectors so that variations in demand are entirely driven by the reputation effect caused by

¹⁸ <https://www.japantimes.co.jp/news/2021/03/09/business/311-food-exports/>

¹⁹ All the data can be freely accessed here: <https://www.insee.fr/fr/statistiques/4494218>

²⁰ For instance, if final domestic consumption accounts for 60% of final demand (and so exports for 40%), then we assume that the value added attributed to final domestic consumption is 60% of the total value added of the sector. This proportionality assumption is an approximation. We could imagine that products that are sold locally have a greater value added than products for exports because of the diminished transportation costs. In that case the value added contribution of final domestic consumption would be greater.

²¹ Following the recommendations of the Lebègue (2005) report [31]. Since we assume that reputation effects last at most 9 years and that most of the losses are supported within the first three years, our results are barely affected by the choice of a lower discount rate.

²² There are three elements for this sum over i : the final domestic consumption of the "agriculture and agri-food sector", exports of the "agriculture and agri-food sector" and the restaurants sector.

²³ Everything is computed with 2018 prices, so inflation is not driving the result upward.

the nuclear accident. We don't take into account any pre-existing upward or downward trend in the level of value added²⁴. This also implies that the structure of the economy is assumed to be unaffected by the nuclear accident.

Table III shows the results of our estimation. Direct losses range from 3.8 to 44.3 billion euros (S1 and S4). S2 and S3 display similar results (12.3 and 14.5 billion euros, respectively). These figures are interpreted as the direct business losses faced by the agriculture, agri-food industry and restaurants for either three (S1, S2) or nine (S3, S4) year-long crises.

TABLE III.
SIMULATED DISCOUNTED DIRECT, INDIRECT AND INDUCED COSTS FOR EACH SCENARIO, IN BILLION EUROS.

	S1	S2	S3	S4
Direct effect	3.8	12.3	14.5	44.3
Indirect effect	4.0	12.9	15.2	46.4
Induced effect	0.8	2.7	3.2	10.1
Total	8.6	28.0	32.9	100.8

Note: Results of our simulations for the 4 scenarios detailed in Table II. Discount rate = 4%. Costs are in constant 2018 billion euros. Reading: the estimated direct cost of the S1 scenario is 3.8 billion euros.

D. Indirect effects

We use input-output matrices of the national economy provided by INSEE²⁵ to compute the matrix of technical coefficients. This matrix tells us for each sector, how much intermediate consumptions of each one of the other sectors are needed to produce one unit of output. Thanks to this matrix, we can assess how a reduction in activity in the food sectors diffuses to the other sectors of the economy, through the reduced intermediate consumption of the food sectors. All sectors that are usually selling goods and services to the food sectors will be impacted in proportion to their contribution in the food production processes.

Hence, the indirect losses on a sector j due to the direct impact on sector i at year $t + 1$ will be equal to:

$$\text{Indirect losses}_{j,i,t+1} = \left(\frac{IC_{i,j}}{\text{output}_i} \right) * \text{direct losses}_{i,t+1}$$

Where $IC_{i,j}$ is the intermediate consumption of goods and services of sector j by the directly impacted sector i . The technical coefficient $\frac{IC_{i,j}}{\text{output}_i}$ thus corresponds to the share of goods and services of sector j required in the production process of sector i .

Input-output matrices enable to generalize this calculation to all sectors, assuming each time that three sectors face direct losses²⁶, and that all their suppliers are affected in proportion

of their respective contribution to the production processes of these three sectors. Firms sometimes use imported goods and services in their production process. This imported intermediate consumption is subtracted since we don't take indirect effects on trading partners into account.²⁷

Thus, the total indirect losses one year after the accident that occurred at time t are equal to:

$$\begin{aligned} \text{Indirect losses}_{t+1} = & \sum_{j=1}^N \left(\frac{IC_{agri,j}}{\text{output}_{agri}} \right) * \text{direct losses}_{t+1,agri} \\ & + \sum_{j=1}^N \left(\frac{IC_{agrifood,j}}{\text{output}_{agrifood}} \right) * \text{direct losses}_{t+1,agrifood} \\ & + \sum_{j=1}^N \left(\frac{IC_{restaurants,j}}{\text{output}_{restaurants}} \right) * \text{direct losses}_{t+1,restaurants} \end{aligned}$$

With $j = 1$ to N sectors in the economy²⁸.

Once we obtain the indirect effect for the first year, we compute the effect on the second year by considering that the indirect losses of the first year ripple once again across all sectors, as shown below:

$$\text{Indirect losses}_{t+2} = \sum_{i=1}^N \sum_{j=1}^N \left(\frac{IC_{i,j}}{\text{output}_i} \right) * \text{indirect losses}_{i,t+1}$$

Indirect losses will converge towards zero over the years. We also apply a 4% discount year starting at year 1 to compute the net present value of losses (at the time of the accident).

Table III shows that our estimated indirect costs range between 4 to 46.4 billion euros, with median estimations around 15 billion euros. Overall, indirect effects are roughly equal to direct ones.

E. Induced effects

Induced effects correspond to the decline in household consumption due to workers' wages cut and lost jobs in the directly impacted sectors. In 2018, wages paid to workers in the agriculture sector amounted to 10.1 billion euros, 26 billion euros in the agri-food sector and 18.9 billion euros in the restaurants sectors²⁹. How do firms' hardship translate into declining household consumption? An optimistic scenario would be that wages and jobs are maintained and that firms find another way to cope with the negative consequences of bad reputation. In that case, induced effects would be equal to zero. A pessimistic scenario could be that firms entirely adjust to the crisis by wages cuts and layoffs, and so the percentage losses on final demand hypothesized in Table II would fully apply and the total value of wages in those sectors would be decreased by those amounts year after year. Then, households' declining purchasing power could entirely pass on consumption (no decline in savings). We assume a mid-case

²⁴ This simplification assumption biases very slightly downward our results since the total value added of the food sector has a slight upward trend.

²⁵ <https://www.insee.fr/fr/statistiques/4494213?sommaire=4494218>

²⁶ The three sectors are agriculture, agri-food industry and restaurants. Restaurants fall into the "accommodation and restaurants" INSEE category, which means that the technical coefficients may be a bit distorted, especially if housing use different shares of intermediate consumptions from accommodation.

²⁷ We use the symmetrical input-output matrices for imports provided by INSEE. We use the most recent statistics available (2017). They show how

imported goods and services are used as intermediate consumption in the different sectors of the economy.

²⁸ The food sectors are included into these $N = 17$ sectors. This makes sense because farmers may indirectly suffer from the lack in demand faced by restaurants that buy their fresh products for instance.

²⁹ According to INSEE national account figures. Wages are defined as all cash payments or payments in kind made by employers to their employees. They include employers' social contributions.

scenario, where half of the direct losses described in Table II (in percentage terms) apply to wages in the aforementioned sectors. Total discounted induced losses then write as follows:

$$\text{Total discounted induced losses} = \sum_{s=1}^T \sum_{i=1}^N \frac{0.5 \text{Drop}_{i,t+s} * \text{wages}_t}{(1+r)^s}$$

Table III shows that induced costs would range between 0.8 and 10.1 billion euros, with median estimations around 3 billion euros.

Summing up all costs, we estimate that reputation effect on the food sector following a major nuclear accident could range between 8.6 and 100.8 billion euros, depending on the selected scenario. It may be hard for the reader to gauge the magnitude of such figures. Are they rather small or large? Could they be easily absorbed by the economy? It is tempting to compare these losses to GDP, but we should bear in mind that they would be supported on three years for S1 and S2 and nine years for S3 and S4. We can then conclude that reputation damage would account for 0.12% to 0.4% of a three-year GDP, and 0.15% to 0.47% of a nine-year GDP³⁰. But the economic burden will be the largest on the first year after the accident, since reputation damage has strong immediate effects that typically decrease more or less rapidly over time. We estimate that about 50% of the total losses would be incurred in the first year in short-duration scenarios, and 25% for long-duration scenarios³¹. In that case, the economic burden of reputation damage ranges between 0.17% and 1.1% of GDP in the first year following the nuclear accident. Given that economic growth has been between 1 and 2% for the last decade, we can conclude that reputation damage would probably not be sufficient in itself to lead to an economic recession, although it would constitute a serious negative shock on economic growth in the first year following the accident.³²

F. Caveats

This study is a simple approximation of the order of magnitude of the reputation damage caused by a major nuclear accident. The range of losses we estimate varies by a factor of 10, which is arguably large, but this should not come as a surprise given that there is no unique image cost estimate. Reputation damage will depend on the size of the nuclear accident (which can vary by an even larger factor within the category of major nuclear accidents)³³, crisis communication, mitigation policies, media portrayal of the accident, trust of the population, etc.

Nevertheless, we should acknowledge the main uncertainties underlying our model. The initial scenarios chosen in Table II are arguably one of the greatest sources of uncertainty and are based on non-nuclear food crises (Table I),

whose transposability can be questioned. Studying indirect effects by the use of input-output matrices also has its shortcomings. It implies a static representation of the economy thereby assuming that sectoral linkages are not affected by the nuclear accident. Moreover, our analysis is conducted at the national level, which blurs the likely region-dependent specificities of each reputation crisis. Further research could conduct regional analyses where reputation damage could depend on the precise location of the accident and the food products that are grown in this region. But refining the model to better account for indirect or induced effects is probably second order with respect to the issue of calibrating direct losses. Ideally, we would like to develop a methodology that estimates drops in final demand and makes explicit how the magnitude of such drops depend on the nuclear accident scenario (size of the accident), mitigating policies and the media environment. Behavioral economics tools can be a research avenue to achieve this goal. In the next section, we show the results of a pilot experiment that investigates the feasibility of this research direction and provides its methodological foundations.

IV. MAKING PROGRESS WITH BEHAVIORAL ECONOMICS

A. Behavioral economics and bad reputation

Another way to calibrate Table II is to use surveys and experiments to ask people how they reacted to the damaged reputation of food products after the Fukushima accident, or how they would react to hypothetical nuclear accident scenarios. In both cases, the questions can help measuring how final demand would decline should a nuclear accident happen in France. Moreover, by varying randomly the context of the scenario, we could test for the effect of mitigation policies, such as how countermeasures change people's opinion with respect to the reputation of food products.

A strand of the behavioral economics literature published experiments on the impact of the fear of radioactive contamination on food consumption behavior. Several papers used the stated preferences method to directly estimate the consumption preferences of people faced with potentially contaminated products. For instance, Aruga [14] estimates the willingness to accept buying food produced in the Fukushima prefecture after the 2011 nuclear accident. It thus estimates the minimum drop in price at which consumers are willing to accept a certain level of radioactive contamination in food produced in the Fukushima prefecture³⁴. Sawada et al. [22] survey 392 respondents in Tokyo about their beef consumption by varying the origin and the level of radioactivity of the food (contamination below permitted thresholds, below one tenth of the threshold, undetectable level of radioactivity). They show that 81% of the respondents declare that they would not eat beef from Fukushima as long as it has not been tested (33% would persist in refusing to eat

³⁰ GDP in 2018 (with 2018 prices) was equal to 2360 billion euros according to INSEE. Hence, if we assume no real economic growth (constant 2018 prices), a three-year GDP would be equal to 7080 billion euros and a nine-year GDP to 21,240 billion euros.

³¹ Our estimates give first-year reputation losses of 4.2, 13.5, 8.3 and 25.6 billion euros for S1, S2, S3 and S4, respectively.

³² This does not mean that a major nuclear accident would not lead to an economic recession in France. Answering this question would require to assess all the economic losses associated with the accident, not only reputation losses as we do here.

³³ Fukushima and Chernobyl are both major nuclear accident on the INES scale but Chernobyl contaminated a much larger area (13 000 km² with a Cs-137 contamination greater than 600 000 Bq/m²) than Fukushima (600 km² for the same contamination threshold).

See https://www.irsn.fr/FR/connaissances/Environnement/expertises-incident-accidents/comparaison-tchernobyl-fukushima/Documents/IRSN_conference-tchernobyl-fukushima_092012.pdf

³⁴ To be more precise, this estimates the demanded price. We would need to model supply in order to obtain the equilibrium price.

it even if the level of contamination was below the threshold). This article shows the importance of communicating on food testing policies. Peterson & Yamaura [23] assess changes in food consumption in a sample of 2500 Japanese. Respondents are asked to indicate how they had changed their Japanese food and seafood consumption habits after the Fukushima accident on a scale of -2 to +2 (0 = no change, -2 decreased significantly, -1 decreased, +1 increased, +2 increased significantly). Only 5 to 6% indicated that they had decreased (-1 or -2) their consumption. However, the question is not asked specifically about products from the Fukushima prefecture, but about Japanese domestic products as a whole. Therefore the results could underestimate the effect in the contaminated areas.

Regarding foreign demand, Lee et al. [24] show that 70% of respondents in a sample of 1,000 Koreans report that they do not want to purchase seafood from Japan, even if the level of radioactivity is undetectable. McKendree et al. [25] surveyed 1000 US consumers in 2011. 22% stated that the nuclear accident in Japan had impacted their food consumption habits.

Aruga [13] uses an online questionnaire, answered by nearly 7,000 Japanese, to estimate the percentage price reduction that would have to be applied to products near Fukushima (100 km away from the NPP), for the respondent to accept to consume that product rather than an identical substitute from a region located 300 km away from the accident site. This "willingness to accept" is estimated for several products (rice, apples, cucumbers, beef, pork, eggs and shiitake mushrooms). Overall, about 30% of consumers simply refuse to consume the product coming from a region near the NPP, even if the product was 60% cheaper (maximum discount available). Wakamatsu & Miyata [26] conduct a seafood consumption experiment on a sample of about 2000 Japanese in November 2015. Respondents are asked to choose between products differing by their price, origin, local label, and whether there is an ecolabel. They find that products from the Fukushima Prefecture are priced 94 yen cheaper than an identical domestic product. The adjacent prefectures (Miyagi and Ibaraki) are also affected with a decrease in value of 50 to 60 yen. The existence of a more local label than Fukushima Prefecture or an eco-label reduces reputation damage.

What conclusions could we draw from this literature? First, with the exception of Peterson & Yamaura [23], the estimated consumption drops are extremely large, often much larger than what the statistical series suggest (see Section II.C). Three effects are likely biasing upward the results. First, radioactive contamination concerns are made extremely salient in these experiments ("priming effect"). Second, there is no real stake in the decisions (people won't have to consume the food for real), and third, products are often assumed to be perfect substitutes. In reality, paying attention to the origin of each food item we buy is tedious and costly. Many people would probably not bother changing their food habits after a nuclear accident, or they would pay attention for a much shorter time period than what they would have thought initially. This idea is comforted by the results of retrospective surveys like Peterson & Yamaura [23] and McKendree et al. [25], which display more modest effects.

Despite these limits, we can clearly see the interest of such experiments. A well-designed experiment could solve the external validity issue of relying on Japanese data and non-nuclear crises to estimate the reputation effects of a nuclear accident in France. These tools are flexible and could allow to study the effect of communication, food labels and the dynamics of trust.

B. A pilot experiment on a hypothetical nuclear accident in France

Our ultimate goal is to estimate final demand drops with surveys using a two-step methodology, precisely meant to mitigate priming effects. After introducing a nuclear accident scenario, we would show a list of habits subjects could modify, or reactions they could have, in the aftermath of a nuclear accident. Changing food habits would be one of them. Then, we would ask questions meant to quantify those changes only to people that ticked that box. This experiment could be conducted on two samples: one representative of the French population (to evaluate how much they would substitute imported products for French products) and one on foreigners (to evaluate the decrease in exports).

We conducted a pilot experiment online³⁵ on a sample of 109 French subjects to test whether people understand well such kind of hypothetical nuclear accident scenarios and to come up with a complete list of reactions they could have. The other objectives of the experiment were to 1) evaluate how frequently precautions about food are raised by subjects, without being primed to do so; and 2) assess how the distance to the nuclear accident site and (reassuring) information about the health effect of ionizing radiations in weakly contaminated areas may affect their answers.

1) Experimental design

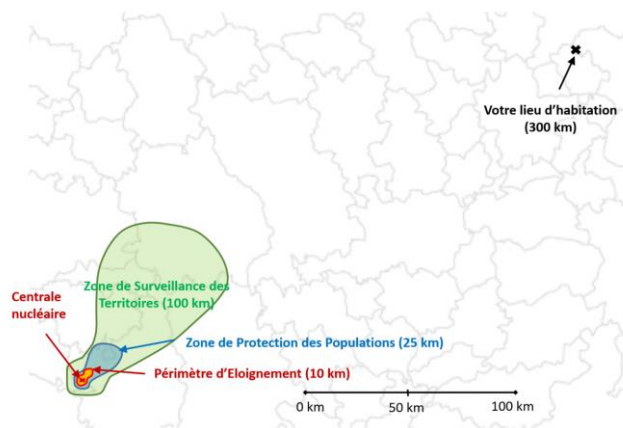
The experiment starts with the description of a nuclear accident whose severity and consequences are roughly those of the Fukushima accident. We don't give the precise location of the NPP, we only say that it took place in France three months ago.³⁶ The complete text of the scenario is available in Appendix VI.A. We illustrate the consequences of the accident using a map of the assumed contaminated zones that would take place in France according to the action plan detailed in the doctrine CODIRPA of 2012 [27], as in Fig. 1 and Fig. 2. The doctrine is outdated now, but since the new one is not yet published, we decided to stick to the 2012 version. Our respondents were then able to check that the action plan we detailed in the scenario was plausible because it was equivalent to the one accessible online.

We explain that three zones are delimited based on contamination levels: the Exclusion Zone where people had to be evacuated; the Population Protection Zone where contamination is too low to justify evacuation but still too high to let people consume locally grown food, and the Territory Surveillance Zone where contamination is even lower so that local food has been authorized after a first ban of three weeks to check that contamination levels were sufficiently low.

Fig. 1. Nuclear accident scenario – 300km distance

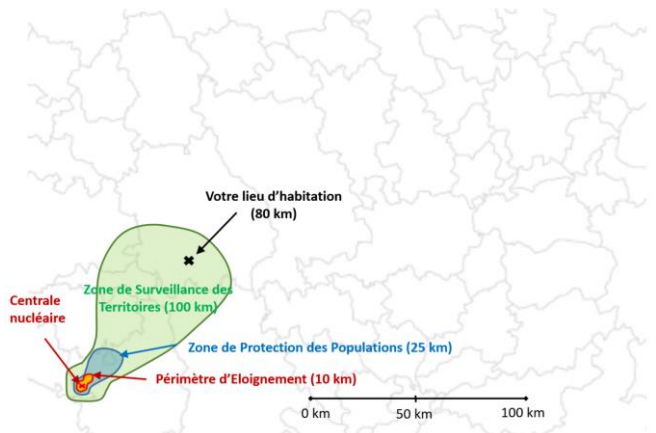
³⁵ The survey was elaborated on <https://www.qualtrics.com/fr/> and participants were recruited using <https://www.prolific.co/>. The socio-demographic characteristics of our sample can be found in Appendix VI.D.

³⁶ Our goal was to avoid having answers referring to the emergency phase.



Note: map shown to the subjects in the 300 km + information and 300 km + no information treatment groups.

Fig. 2. Nuclear accident scenario – 80km distance



Note: map shown to the subjects in the 80 km + information and 80 km + no information treatment groups.

We randomize two pieces of information subjects receive:

- The distance between their home and the accident site. It is either 300 km away (as shown on Fig. 1), or 80 km away, within the Territory Surveillance Zone (Fig. 2).³⁷
- Half of the sample got access to an additional screen after the nuclear accident description, with a (reassuring) message about the effect of ionizing radiations on health. The other half received no additional information.

The message is reassuring because we focus on the expected health effects in the Territory Surveillance Zone (the

³⁷ The scale of the picture remains the same in both situations, so that distances are represented identically across both treatment conditions. The areas boundaries in light grey are borrowed from a map of *intercommunalités* without matching scales so that the precise location of the NPP is undetermined.

³⁸ We keep the text voluntarily simple to avoid having people dropping out. Since the experiment is online, it is tempting for subjects to give up once explanations get too detailed or complex. To build this message, we used the fact that the effective dose in normal situations in France is on average 4.5 mSv (including medical exposition), and that the doctrine CODIRPA defines the Population Protection Zone as a zone in which an individual receives as

only contaminated area where our subjects might be living in our scenario), which has a much lower contamination level than the Exclusion Zone for instance. We explain in simple terms the concept of dose, and give orders of magnitudes and elements of comparison (see Appendix VI.B)³⁸.

Of course, in reality, people will be exposed to a much larger variety of discourses, some reassuring and some alarmists, from experts and non-experts, and they will have to come up with their own opinion to assess risks. We could not test the effect of a larger variety of messages in this pilot experiment since we only sampled 109 subjects. We nevertheless think that testing more systematically the effect of various messages, possibly with a time dimension, would be a promising research avenue, especially to study trust dynamics and the efficiency of official communications.³⁹

We randomize between-subject these two pieces of information and so our sample is divided in four roughly even groups:

1. 80 km + information on health effects (27 subjects)
2. 80 km + no additional information (26 subjects)
3. 300 km + information on health effects (28 subjects)
4. 300 km + no additional information (28 subjects)

The rest of the experiment contains the following steps:

- A set of open-ended questions meant to elicit potential behavioral changes, with minimal priming.
- True-False questions to assess subjects' understanding of the accidental scenario (see Appendix VI.C)
- Closed-ended questions to measure opinions and attitudes with respect to nuclear risk and nuclear energy.
- Question on socio-demographics characteristics.

Since this pilot experiment is a building block toward a larger and more comprehensive survey and is based on a small sample, the results shown here are only suggestive. We only interpret qualitative data and don't detail all participants' answers. We show results that could be useful to other researchers or experts interested in conducting similar experiments to anticipate people's reaction to disastrous events.

2) Understanding of the accidental scenario

To our knowledge, there is no other experiment detailing a hypothetical nuclear accident the way we do. All the papers surveyed in Section IV-A directly refer to the accident of Fukushima, a well-known event. This pilot experiment was

much as 10 mSv per year. There is no explicit dose threshold for the Territory Surveillance Zone, but the 10 mSv limit applies for this zone too since it must be less contaminated. The dose received by an abdomen scan is about 15 mSv.

All the figures come from:

https://www.irsn.fr/FR/Actualites_presse/Communiqués_et_dossiers_de_presse/Documents/IRSN_Rapport%20EXPOP_def.pdf

³⁹This could be done in the form of serious games played over longer time period, in the spirit of the "An Zero" app produced by Skill Lab (<https://anzero.eu/lapplication/>), but designed for the information people would get several months after the accident, instead of during the emergency phase.

thus also dedicated to test whether people understand well the details and implications of the scenario, as well as the information about the health effect of radioactivity. Their answers to the true-false test are reassuring, 83.3% of the subjects in the no-information treatment groups answer correctly to at least 3 questions out of 4, and 78% of the information treatment groups got at least 4 questions out of 6 correct.

3) Answers to the general open-ended question

After the introduction of the nuclear accident scenario, we ask a very general open question: *“We would like to know what would be your behavior in this situation, three months after the accident. Do you think that you would want to change your lifestyle or some of your habits with respect to your life before the accident?”*

As shown in Table IV, we read all the answers and classified them by categories to illustrate the variety of reactions people may have. We see that many of these reactions can potentially have economic consequences. Some refer to reputation damage, both in the food sector and also leisure and cultural activities, travels and tourism, but none of the 109 subjects declared that they would avoid going to restaurants in order to have a better control on the origin of the food. This indicates that direct effects on restaurants might be rather small, more in line with the first three scenarios of Section III.

TABLE IV.
LIST OF ANSWERS TO THE FIRST OPEN-ENDED QUESTION

	Avoid eating products that grow close to the NPP (the declared precautionary zone goes sometimes well beyond 100 km)
Food habits	Stop eating food from own vegetable garden
	Keep boycotting products for several months after they have been declared safe to eat
	Banning food products that capture radioactivity, such as mushrooms
	Consumption of canned goods
	Consumption of mineral water rather than tap water
	Buy less locally and prefer big stores
	Limit outdoor activities
Tourism and leisure	Avoid contaminated areas for leisure or culture
	Tourism abroad rather than in France
	Family vacations to get away for a few weeks until the radioactivity decreases
	Going to the sea or the mountains regularly to purify the body
Information acquisition	Search for information from multiple sources
	Increase frequency of news acquisition about the contamination levels
	Ask local farmers about the tests and monitoring they conduct on their products
	Acquisition of radioactivity monitoring devices
Lifestyle	Move away from the NPP
	More internet shopping
	Wear a mask when going outside
	Increase medical surveillance
Activism	Decrease own energy consumption
	Activism against nuclear power

Note: list summarizing all the types of answers subjects provided when answering to the first general open question of the pilot experiment.

Some answers are very detailed, and show how reputation damage could affect more certain products than others, especially products known for absorbing radioactivity, such as mushrooms:

“On a daily basis, I would be more vigilant when purchasing my fruits and vegetables, and pay attention to their production areas, and I would ban at least all the products coming from the surveillance zone, or even beyond, I would say within 200 km around the power plant. Same for the origin of my meats, charcuteries, mineral waters... For my leisure activities and as much as possible, I would try to avoid any travel in the radius of the surveillance zone of 100 km around the accident site. I would inform myself several times a week about the contamination/decontamination situation points produced after the accident. I would prohibit the consumption of foodstuffs more receptive to radioactive contamination (mushrooms, etc.).” (300 km+ information group)

And people often mention the presence of children as an important cause of drastic reaction:

“First, I would shop in a more distant area, and I would use water packs so I wouldn't use tap water anymore. If it is possible, I would take a few vacations with my family, in order to wait a bit, and see the future estimates. If this is not possible, I would think about a solution for the children of the household to go on a family vacation for the same reasons. Of course, we would not make any more walks around, only out of the area.” (80km + no information group)

“After 3 months, I would seriously consider moving, in order to get as far away as possible from the contamination zone. Furthermore, having young children, it would not be livable to stay near a radioactive zone. Moreover, our food habits will have to be reviewed, especially concerning the consumption of agricultural products.” (80 km + information group)

The official boundaries of contaminated areas (the three zones in this scenario) may also create anchoring effects that guide people's decisions to adapt to the event. The participants to the survey often detailed a zone-dependent behavior: *“I probably wouldn't go on vacations in the blue zone and I probably wouldn't be allowed in the red zone. However, I would probably go to the green zone if I had family there.”* (300 km+ information group).

We will see later that the information treatment successfully reduced subjects' precautions on average, but some individuals took our radioactivity health effect information with caution and sometimes skepticism: *“(…) Learning that the first year's dose only corresponds to a CT scan of the abdomen would have reassured me, but only if I could verify its veracity.”* (80 km+ information group).

4) Quantifying changes in food habits

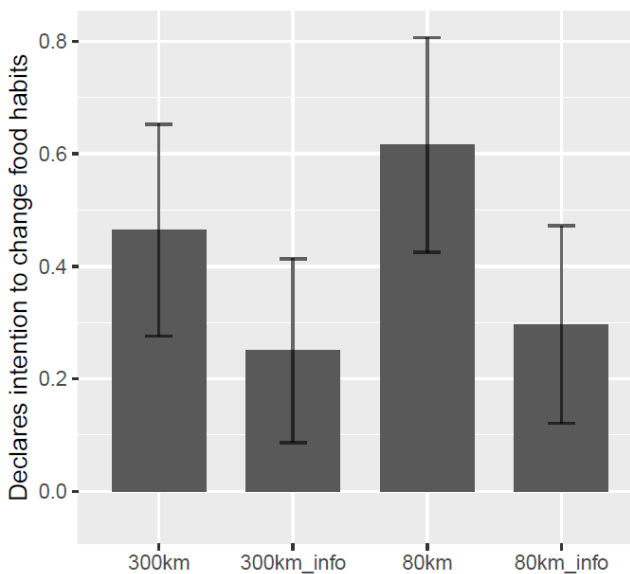
Then, we can quantify how frequent answers were with respect to behavior relevant to food reputation effects. Fig. 3 shows, by treatment groups, the share of people declaring in their answer to the first open-ended question that they would modify their food habits to avoid potentially contaminated foods. Even without specifically asking subjects about whether they will change their food consumption habits, about 40% of the subjects mention it in their answers. With our small sample, we cannot draw precise conclusions with respect to

cross-treatments averages, but it seems that the information treatment is working well to reduce the fear of ingesting contaminated food. About 30% of the subjects in the treatment groups that received information declare that they would modify their food consumption habits, while the same statistics goes up to about 50% in the no additional information groups.

The distance to the accident site does not significantly alter people's answers across treatment groups. When keeping information constant but varying distance, subjects tend to declare that they will change food habits in roughly similar magnitude (45 to 60% in the no information groups and 25 to 30% in the information groups). Nevertheless, the details of their answers show that the nature of the reactions differ depending on distance. People nearby the accident mostly declare that they will stop buying local food while people 300 km away declare that they would avoid purchasing food growing near the NPP. Overall, the 300 km distance is not sufficient for people to feel unconcerned.

The general conclusion of this pilot experiment is that the features of the design of the experiment, and in particular how strong priming is, are crucial to interpret the results. Experiments that have a much stronger priming effect than ours typically find that between 70-80% of the subjects refuse to buy food coming from potentially contaminated areas [22] [24].

Fig. 3. Share of people declaring that they would modify their food habits



Reading: about 60% of the subjects in the 80 km and no additional information treatment group declare having the intention to change their food habits three months after a hypothetical nuclear accident in France. Bars display 95% confidence intervals.

We cannot readily transpose the results shown in Fig. 3 to calibrate the annual percentage drops in final demand we showed in Table II. Another experiment with more precise questions to quantify changes in behavior (relying more often on exports for instance), is necessary. Moreover, this second experiment should be conducted on large samples of French individuals and also foreigners. This pilot is a first step

towards this goal, by providing a way to reduce the overestimation bias we identified in Section IV.A.

V. CONCLUSIONS

This paper defined the concept of reputation damage in the case of a nuclear accident and detailed a simple methodology based on national accounts data to estimate the magnitude of the economic losses it would generate. We argued that the magnitude of reputation damage should be larger in France than in Japan, given the importance of the French food sector and its world-renowned food products. We estimated that losses could fall within a 10 to 100 billion euros range. We argued that the greatest uncertainty in this kind of study comes from the calibration of the drops in final demand (domestic consumption and exports) following the event. We explained how behavioral experiments and surveys could be useful to come up with a new methodology to calibrate the main parameters of the model. We detailed the experimental design and some results of a pilot experiment we conducted as a first step toward this goal. More research is needed to overcome methodological issues that could arise with such kind of behavioral data, especially the caveat of priming effects that would tend to bias upward the estimates. Our study is limited to reputation effects on the food sector, but reputation problems could arise in other sectors, especially tourism, following a nuclear accident. A similar simulation exercise can be used to estimate the economic losses associated to this sector as well.

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APPENDIX

A. Accidental scenarios displayed in the pilot experiment

Imagine that an accident occurred three months ago at a nuclear power plant in France. The plant is indicated by the red cross on the map below, and your home is located

[Treatment residence 1] 80 kilometers from the plant, by the black cross.

[Treatment residence 2] 300 kilometers from the plant, outside the contaminated areas, by the black cross.

The accident caused a core meltdown and a significant release of radioactive materials into the environment. The accident was gradually brought under control and the releases were completely stopped after ten days.

The radioactive plume moved with the wind, and the radioactivity it contained diffused and diminished as it moved away from the plant.

Exclusion zone

To protect the population from the ambient contamination, it was necessary to evacuate people living up to 10 kilometers from the plant. This zone, called the Exclusion Zone, appears in orange on the map. 80,000 people living there were relocated outside this zone.

Population Protection Zone

Contamination beyond the Exclusion Zone is lower and does not justify evacuation, but agricultural products growing in the Population Protection Zone are considered too

contaminated to be consumed and their marketing is therefore prohibited. Cleaning and decontamination measures have been taken and are still in progress to reduce radioactivity. This zone, shown in blue on the map, extends to 25 kilometers from the accident site.

Territory Surveillance Zone

Finally, a third zone extends up to 100 km from the accident site, the Territory Surveillance Zone (in green on the map). The contamination is even lower there and does not justify special measures to protect the population. However, as a precautionary measure, the food produced there was initially banned from sale for three weeks. Checks on contamination levels then showed that they did not present a health hazard. They are therefore available for sale.

B. Information about the health effect of ionizing radiations

We will give you some information about radioactivity, its sources and effects.

Where does radioactivity come from?

In normal situations, we are all exposed to:

- Natural radioactivity: radioactivity naturally produced by the ground and the cosmos (we are subject to a higher exposure when we fly for example). This radiation is relatively weak.
- Radioactivity induced by human activity: typically, our exposure to this radioactivity comes from the use of radioactive products for medical imaging (e.g. X-rays), contamination due to atmospheric nuclear tests in the past, inhalation of tobacco smoke, etc.

What are the health effects?

Radioactivity absorbed by the body can cause cancer. The probability of developing cancer increases with the amount of radioactivity received, which is called the dose.

What doses do people living in the Territory Surveillance Zone receive?

In the case of the nuclear accident described above, the radioactive releases have at most doubled the dose received by the inhabitants of the Territory Surveillance Zone (in green on the map), compared to a normal situation. In this area, the dose received in the first year due to the accident is generally lower than the dose received during an abdominal scan. The exposure decreases gradually after the accident.

C. True-false comprehension test

[All treatments groups]

1. The nuclear accident took place two weeks ago (answer : false)
2. You live in the Territory Surveillance Zone (answer depends on treatment group)
3. Populations living in the Exclusion Zone have been evacuated and relocated (answer: true)

4. Agricultural products everywhere in France have been temporarily forbidden for consumption, and then progressively marketed again, once judged safe. (answer: false)

[Only information treatment groups]

5. The likelihood of developing a cancer increases with the radioactivity doses received by the body. (answer: true)
6. People living in the Territory Surveillance Zone receive on average an annual dose 10 times higher than the dose due to natural radioactivity (answer: false).

D. Socio-demographic characteristics of the sample

TABLE V.
SOCIO-DEMOGRAPHIC CHARACTERISTICS OF THE SUBJECTS OF THE PILOT EXPERIMENT

	Mean	Number of observations
Is female	0.50	109
Age	44.3	109
Is in a relationship	0.63	108
Has children	0.49	108
Has children under 10	0.30	53
Has a job	0.60	109
Education: Bachelor or more	0.45	109
Lives within 50km of a NPP (declarative)	0.12	104

Note: answers to socio-demographic questions at the end of the survey. The question about whether the respondent has children under 10 was only asked to people reporting having children. The number of observations is sometimes slightly below 109 when respondents refused to answer or did not know how to answer certain questions.