Disaster cost assessment: A case study of the potential economic impact of a nuclear accident affecting Ireland

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Abstract
We present a method for assessing the economic costs of disasters with relatively low data requirements, complementing existing methods of disaster cost assessment, such as input-output (IO) analysis and computable general equilibrium (CGE) models. The approach draws on the diffusion literature that provides insights into the temporal evolution of phenomena such as the adoption of technological innovations, which often occur via non-linear pathways. An appealing feature of the methodology is the ability to quickly conduct analysis of multiple hypothetical scenarios through the use of the same dataset. The methodology is demonstrated in a case study examining the economic impact of a hypothetical nuclear accident in northwest Europe on the Irish economy with four disaster scenarios of increasing severity. The scenario results can help inform policy makers and emergency planners who may wish to estimate costs in the wake of a disaster as well as aid planning and mitigation strategies.

Keywords: economic costs, cost assessment, emergency planning

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1. Introduction

There are many incidents which can be classified as a disaster, ranging from natural occurrences like earthquakes, hurricanes and floods to man made events such as war, oil spills and nuclear plant incidents. Each disaster is a unique event, occurring in different locations around the world with varying scale and impact. The infrequent nature of these events makes it difficult for policy makers and emergency planners to measure their impact and to devise safeguards which will minimize potential losses.

Policy makers and emergency planners may wish to quantify the economic impact of disasters as it can help to determine the merit of investing in preventative measures which may help to reduce or negate the impact of a disaster. An example of this might be deciding to upgrade homes to endure severe storms or upgrading a nuclear plant with additional safety measures. In the USA, every $1 spend by government on preparedness (such as flood control projects or the hazard mitigation grant) is worth $15 in terms of the future damage it mitigates (Healy and Malhotra, 2009). In addition to assessing the value of emergency preparedness investments, similar research could help determine whether regions or nations should sign up to international treaties which compensate countries in the event of a large scale incident. For example, there are a number of international treaties and conventions concerning nuclear emergencies, remediation and liabilities.[1] These treaties and conventions act as an insurance policy for countries in the event of a nuclear incident. From a policy perspective, recent incidents like the nuclear incident at the Fukushima Daiichi plant in Japan have increased the focus on being a signatory to such conventions (McRae, 2011). Therefore policy makers and emergency planners who bear responsibility for emergency preparedness decision making would benefit from a method of quantifying the economic costs of disasters, in particular when assessing the net benefit of becoming a signatory of such conventions.

In many instances, research has attempted to assess costs in the aftermath of disasters. Research into the 2004 Indian Ocean Earthquake (which resulted in a tsunami) in Sri Lanka estimated total losses in the region of $1 billion, with financial costs of rebuilding estimated around $1.5 billion (Bandara and Naranpanawa, 2007). Hurricane Katrina in 2005 was estimated to have resulted in direct losses valued at $107 billion, and total costs estimated at $149 billion (Hallegatte, 2008). Other work has estimated the value of damaged property due to nuclear incidents, such as those at Three Mile Island ($2.4 billion) and Chernobyl ($6.7 billion) (Sovacool, 2008). More recently, attempts have been made to provide preliminary estimates of economic impacts due to the nuclear incident at the Fukushimi Daiichi plant in 2011 (Bachev and Ito, 2013; McGinnity et al., 2012). Common among all of these studies is the admission that no approach perfectly captures all costs, and it is particularly difficult to assess the costs over time as data may be quite unreliable. Some studies also attempt to forecast costs in the event of a hypothetical incident. Pascucci-Cahen and Patrick (2012) estimate the economic impact in France resulting from a range of hypothetical incidents at a French nuclear power plant. They estimate the economic impact to the French economy in the range of e120–e430 billion. Li et al. (2013) estimates an imbalanced economic recovery process following a hypothetical flood scenario in London in the year 2020. They find that the London economy would recover within 70 months with labour, capital and final demand the main constraints which distort economic balance and recovery.

Quantification of the economic impact of a disaster has been attempted through different methodological approaches, such as input-output (IO) analysis, computable general equilibrium (CGE) models and econometric methods. Each approach has different strengths and weaknesses, data requirements and modelling assumptions. In certain cases the required data and assumptions make analysis difficult, in particular when modelling events as infrequent and irregular as disasters. When studying the impacts of the ten day ban on air traffic during the 2010 Eyjafjallajökull ash cloud incident, Lee et al. (2012) note how measuring the economic impact of such high impact, low probability ("HILP") events are challenging from a preparation and cost calculation perspective. In addition to the issue of imperfect cost measurement, West and Lenze (1994) suggest that more sophisticated impact models require more precise numerical data, which is an issue when economic data is limited (Smithers and Smit, 1997), especially in developing countries (Okuyama, 2008).

The application of input-output (IO) models to study disasters dates back to bombing studies during World War II (Rose and Guha, 2004). It is considered a relatively simple tool for modelling disasters and accounts for the economic linkages between sectors of an economy. The IO methodology has been used to answer questions such as the economic impact of earthquakes (Cochrane et al. (1974), Wilson (1982)), floods (Van Der Veen and Logtmeijer, 2005) and hurricanes (Hallegatte, 2008). Although the IO framework is often favoured because of its relative simplicity and its ease of modification, it has the drawback that the economic linkages are fixed in the model and there are no behavioural responses which might be unrealistic as a disaster may change the structure of the economy (Rose and Guha, 2004). This rigidity would lead to a mis-measurement of the size of impacts. For example, the single value for final demand in an IO framework does not capture the effects of a range of recovery scenarios (Ellson et al., 1984). Despite these limitations, researchers have attempted to extend the basic IO framework to address these issues, such as the integration of more flexible imports in order to study the shortage of regional inputs in the event of a disaster (Cochrane, 1997).

Computable general equilibrium (CGE) models are theory based models with parameters drawn from the literature that are typically calibrated to a single years' data. These have been used to model disasters, including the cost of earthquakes (Rose and Guha, 2004), water service disruptions (Rose and Liao, 2005) and road and rail traffic disruptions (Tsuchiya et al., 2007). The CGE approach by explicitly modelling the behavioural relationships in the economy is a more sophisticated approach compared to the IO models as it features the ability to incorporate input and output substitutions, features a non-linear structure, is able to respond to price changes and can explicitly handle a supply constraint. However, the drawback of CGE models is that estimates for the required parameters may not be available, which means that particularly in developing countries they can be viewed more as theoretical models than empirical models and it is difficult to verify the accuracy of their prediction over time. Another problem with CGE models is the assumption of rational optimizing behaviour, which could be considered unrealistic under disaster conditions.

Econometric models have also been used to model the economic impact of disasters. These models are data intensive and produce statistical forecasts based on potential scenarios through the use of historical data, as in Ellson et al. (1984). One weakness of this approach is that it is unable to easily distinguish between direct effects (as a result of the potential incident) and higher-order (indirect) effects on wider sectors of the economy (Rose and Guha, 2004). Additionally, the time series nature of data used in econometric models appears to be a poor fit for modelling disasters, as they are events which occur with a very low probability and feature a very high impact. Ellson et al. (1984) find that earthquakes in the USA are not out of line with other economic shocks and cyclical fluctuations. Other work using econometric models has relied on data of previous disasters to help forecast the expected cost of future potential disasters in Argentina (Freeman et al., 2002) and Mexico (Cardenas et al., 2007). But the significant variation of event types and impacts means that such forecasts constitute only a general indication of potential impacts.

This paper aims to complement existing methods by introducing a methodology which can be applied to provide order of magnitude estimates of costs in the event of a disaster. This approach draws on the diffusion literature which provides insights into the temporal evolution of phenomena such as the adoption of innovations, where a product launches at a particular point in time and grows in popularity and usage. Importantly, the time path of diffusion processes has been found to be non-linear. In contrast the impacts of events are often assumed to follow a linear path, or are assumed to be constant up to a point in time or indeed include no explicit assumption regarding the time path of impacts. In reality it is likely that disaster impacts are likely to follow a path where costs will dissipate in a non-linear way over time back to pre-incident levels of activity. Our approach entails estimating the nature and size of the impacts of an event and to use the insights from the diffusion literature to model the time path of these impacts. This approach has the advantage that it requires few assumptions and has light data requirements but more explicitly links the size and nature of the event to the size and duration of impacts over time, which is usually not well specified in other methodologies. Despite its simplicity the method generates results that can serve as a rule of thumb to help inform policy makers and emergency planners who may wish to estimate costs in the wake of a disaster or forecast costs for hypothetical events.

Diffusion has been studied in the growth of cell phone subscriptions (Yamakawa et al., 2013), forecasts of future vehicle energy demand in China (Wu et al., 2014) and even to study media coverage after disasters (Wei et al., 2009). Some of the earliest research into diffusion was used to study biological and economic growth (Gompertz, 1825; Prescott, 1922; Winsor, 1932). Diffusion typically features a slow initial growth, followed by a period of strong growth and ending with slower growth towards an asymptotic maximum. Yamakawa et al. (2013) finds the Gompertz growth function to be a more suitable specification than the logistic function to model the diffusion of cell phone subscriptions in Peru when forecasting the level of future subscriptions. Wei et al. (2009) finds the same function to be suitable for modelling the development of news stories following a disaster, where there are few reports immediately after an incident, followed by a a sharp increase with slower growth leading to an asymptote.

This research follows Yin et al. (2003), which adapts the traditional Gompertz function to handle recovery within a finite duration (as opposed asymptotic recovery in the basic Gompertz function). We suggest how this specification could be used as a complementary modelling approach that can be applied to certain aspects of disasters. It is presented as a computationally intuitive tool that could provide added insight for policy makers and emergency planners, especially when paired with other techniques (such as IO analysis). Section 2 explains the modelling approach in detail, while Section 3 features a case study of the economic cost of a hypothetical nuclear incident in north west Europe on the Republic of Ireland, where longer term losses are estimated and the wider economic impact is calculated.

2. Methodology

The first step in the methodology is to identify the type of impacts within the main sectors affected, which encompass direct costs and losses as well as potentially negative sentiment, which one might term reputational losses. These losses may arise as a direct consequence of a natural disaster (e.g. a harvest is lost due to a flood) or due to perceived effects (e.g. not purchasing a product from a country that had a nuclear incident even if it is certified to be safe). The scale of these losses will depend on the size and severity of the disaster, which will impact on the length of time over which the effects will occur.

A determinate growth function, which is often used in diffusion research, is proposed as a mechanism to estimate temporal dimension of the losses after a disaster. This provides a more realistic approximation of the time path of impacts compared to a linear decay or a single step function. This approach complements other techniques, such as IO or CGE modelling as these can be used to estimate the indirect effects on the economy. This methodology may be of interest to policy makers and emergency planners as it produces an estimate of costs for a broad range of incidents with relatively light data requirements and few functional assumptions.

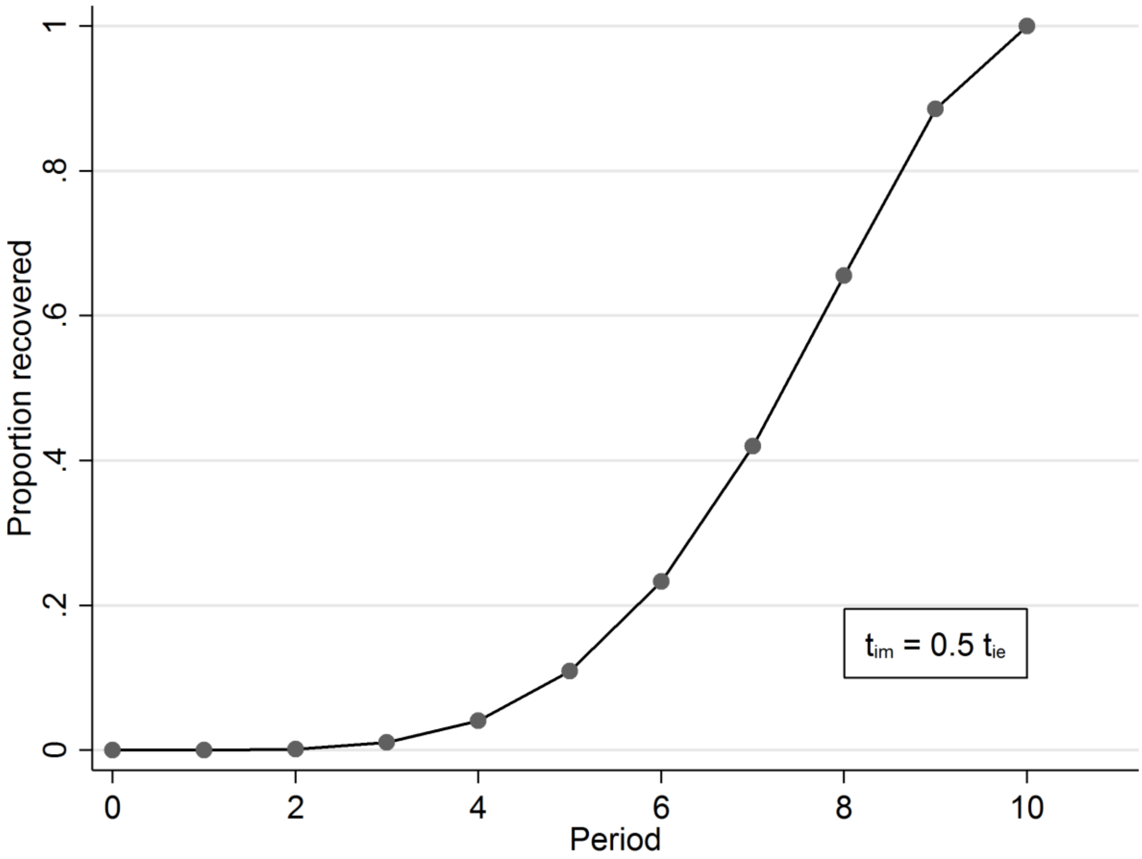
The conventional ‘S’-shaped curve (See Figure 1) is used to model situations where there is an initial period of slow growth followed by a very strong growth which eventually slows down as the function reaches an asymptotic maximum. Although it has been used to model the diffusion of new technologies, the pattern could also reflect the process following a disaster:

- A slow recovery in the short term after the event as responses are determined
- Stronger recovery in the medium term as recovery policies begin to take hold
- In the long term the rate of recovery plateaus as much of the recovery has been achieved

We follow the approach of Yin et al. (2003), who modify the standard Gompertz function for a finite time frame and (more importantly) to reach full recovery within this period. This determinate growth function begins at zero and recovers to its pre-event value by the end of a specified duration. An important aspect of this is the feature of full recovery within a specified time frame, which allows scenarios with fixed end points to be studied, which is easier for researchers to apply and present. Figure 1 graphically depicts a loss which recovers to the pre-incident value after ten

periods.

Figure 1: Determinate growth function (Source: authors)

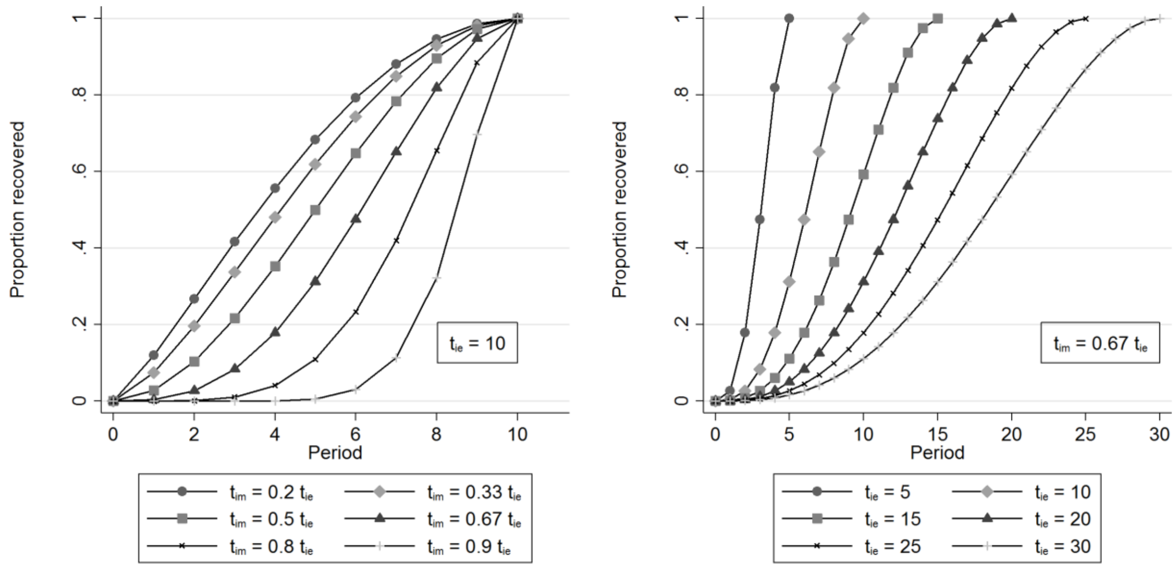


We wish to model recovery in a deterministic manner, which charts a smooth pathway to recovery after an incident and recovery is fully achieved within a determinate time frame. In reality, recovery is unlikely to be smooth or monotonically increasing, but the smooth s-shaped path is likely to be a close approximation of the actual path and thus provides an order of magnitude estimate of costs. Following Yin et al. (2003), the proportional recovery of losses for a particular sector industry i in time period t, such that $0 \leq \lambda_{it} \leq 1$. The calculation of λ_{it} is given by equation 1, where the proportional loss at any time compared to the pre-incident value is $1 - \lambda_{it}$.

$$\lambda_{it} = \left(1 + \frac{t_{ie} - t_i}{t_{ie} - t_{im}}\right) \left(\frac{t_i}{t_{ie}}\right)^{\frac{t_{ie}}{t_{ie} - t_{im}}} \tag{1}$$

Where t_{ie} is the period when the loss is fully recovered and t_{im} is the inflection point near the centre of the 'S'-shaped curve. To estimate the loss for each period t we need to specify these two parameters. The value of t_{ie} will depend on the incident and sector being studied and t_{im} the inflection point can take on different values depending on the nature of the incident, determining how quickly recovery occurs. Figure 2 illustrates varying levels of t_{im} (the inflection point) and t_{ie} (the duration) respectively. The parameter t_{ie}, which is the time period when losses are fully recovered, varies across scenarios and by economic sector (or product) and must be specified by the analyst. The parameter (t_{im}) can also be specified by the analyst. For our purposes we specify it to be a fixed proportion of the impact duration across all sectors and scenarios such that $t_{im} = (2/3)t_{ie}$.

Figure 2: Determinate growth function - Varying t_{im}, varying t_{ie} (Source: authors)



Certain assumptions regarding the initial loss in value at the onset of the incident are required in every scenario. An example of this would be an initial sudden fall in tourist numbers in the immediate wake of an aeroplane-related incident. Due to the incident, there is a sudden sharp fall in activity which then begins to recover. The level of initial loss, R_{i1}, is assumed to be a some fraction, α_i, of the total value of pre-incident activity V_i. In the case where $\alpha_i = 1$, economic activity in that particular area of interest recovers from a post-incident base of zero.

$$R_{i1} = \alpha_i V_i \qquad 0 \leq \alpha_i \leq 1, \text{t=1} \tag{2}$$

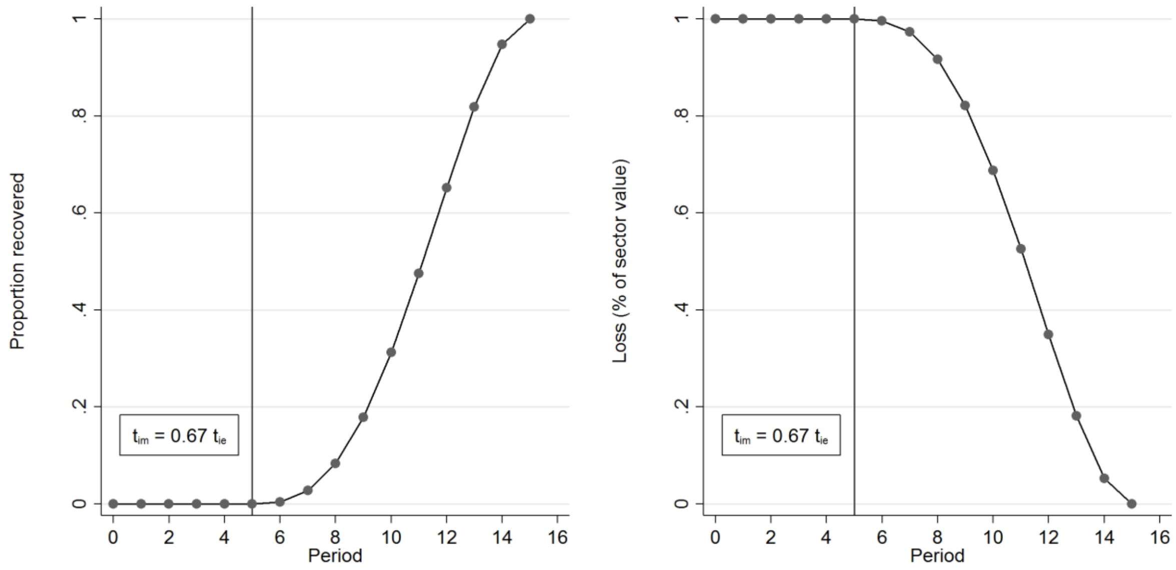
To calculate sector i's loss in subsequent periods we apply the recovery curve (equation 1) to the post-incident level of activity. Losses are calculated as $(1 - \lambda_{it})$ multiplied by the value of the loss in the initial period after the incident R_{i1}. This is represented by equation 3.

$$R_{it} = (1 - \lambda_{it})\, R_{i1} \qquad \text{t} > 1 \tag{3}$$

2.1. Delayed start of recovery

In some situations, the beginning of recovery may be delayed for a number of periods after the incident in question. An example of this is where imports from a disaster areas a prohibited. In equation 3, the time index $\text{t} = 1$ begins in the first period after the trade restriction on produce has been rescinded and activity begins to recover from a base of zero. For each period the restriction is in place, the value lost is assumed equal to V_i. Recovery begins after the restriction is lifted, with losses declining until recovery is fully achieved. For example, recovery might begin from a base of zero following the lifting of trade restrictions but full recovery is not immediate due to competition in the market or persistent reputational damage from trade restrictions making recovery to pre-incident levels more challenging. Figure 3 illustrates recovery (and loss) for a ten period recovery, with a restriction on exported produce in place for the first five periods. In this example, full recovery is achieved after fifteen periods (the sum of the restriction duration and the assumed recovery duration) and we assume the point of inflection to be $t_{im} = (2/3)t_{ie} = 6.67$ years.

Figure 3: Determinate growth function - Delayed recovery and loss (Source: authors)



2.2. Indirect economic impacts

If the focus of a study is on the impact in specific sectors of the economy, there are likely to be indirect impacts on the wider economy. For example, modelling losses in the agriculture sector has wider implications for sectors of the economy with which it interacts (such as farm machinery). Thus, a reduction in gross output produced in a sector reduces the demand for intermediate inputs purchased from within the sector and from other sectors. Input-output (IO) tables give a detailed picture of the transactions of all goods and services by industries and final consumers in the economy in a single year, building on interdependencies within sectors of the economy. The IO method generates and utilises a multiplier which helps show the impact of a one unit change in the output of that sector on total output in the economy.[2]

2.3. Summary of methodology

This section has outlined the methodology which is used for estimating certain economic costs in the event of a natural or man-made disaster. By specifying the initial drop in activity (α_i), the inflection point of recovery (t_{im}) and the duration of recovery (t_{ie}) policy makers and emergency planners can obtain an estimate of the cost of an incident. Although each event is unique, previous research can help inform the range of values for these parameters. Table 1 provides a brief summary of the parameters discussed and provides an example of the data which would be required in order to carry out this analysis. Section 3 presents a demonstration of the methodology for the case of a hypothetical nuclear event in north-west Europe on the Republic of Ireland, considering a range of scenarios with economic impacts across a number of sectors.

Table 1: Summary of parameters

Parameter	Detail	Data Source
V_i	Sector specific	Latest economic data (one year) for sector of interest
t_{ie}	Incident and sector specific	Review literature of similar incidents for duration
t_{im}	Incident specific	Review literature of similar incidents for rate of recovery
α_i	Incident and sector specific	Review similar incidents, sectors to determine the level of initial loss

3. Case Study

This case study aims to estimate the impact on the Irish economy of a hypothetical nuclear accident at a facility abroad in north-western Europe, for four different scenarios. The scenarios were designed around varying levels of radiological contamination within Ireland occurring during times of the year when its impact is likely to be greatest. The scenarios are not intended to represent an accident at any particular location; rather they serve as an estimate of the potential scale of economic impacts associated with an accident. While an accident in north-western Europe may have an impact on Ireland, accidents at much further distance could also have an impact, as was the case with Chernobyl. The level of impact will depend not only on the location of the accident, but also on the scale and type of accident, as well as the prevailing weather conditions.

In addition to providing an overview of assumptions regarding the impact of the event, we discuss the reasoning behind the selection of parameter values before discussing results across three areas: agriculture, exports and tourism. These areas were chosen as being potentially the most adversely effected in the event of a hypothetical nuclear incident. Although the risk of a nuclear accident may be small, this case study can provide an indicative value of the cost it would impose on Ireland's economy.

3.1. Scenario overview

We consider three types of cost - Direct Cost, Direct Loss and Reputational Loss. Direct costs are incurred as a direct result of the nuclear incident. In this study direct costs accrue where additional testing and monitoring must occur as a result of the incident. Direct losses accrue as the result of produce that loses value as a direct result of the nuclear incident. An example of this is the value of lost exports which are not exported due to the prohibition by other countries on imports of Irish produce in the wake of an incident. Reputational losses are different to direct costs and losses as they are hypothetical in nature and represent losses due to reputational harm. For example, if an incident is expected to have an impact on tourism levels, the expected expenditure of tourists who change their plans and travel elsewhere are counted as a reputational loss for the location in question. Reputational losses arise for tourism and exports which are foregone as a result of the nuclear incident and are modelled using the determinate growth function using publicly available data. For the purpose of this exercise, direct costs and losses are similar in nature and distinctly different from reputational losses. For this reason, they are combined and referred to as direct loss throughout.

Four scenarios are considered in this case study as follows:

- Scenario 1 is assumed to be an event where there is a nuclear incident in north-western Europe, but there is no radiological impact on Ireland

- Scenario 2 assumes that a hypothetical nuclear accident in north-western Europe leads to some low-level environmental contamination in Ireland
- Scenario 3 assumes a nuclear accident that leads to moderate environmental contamination in the Republic of Ireland
- Scenario 4 assumes a nuclear accident that leads to high levels of radiological contamination in the Republic of Ireland.

3.1.1. Data

The data used for this study has been obtained from publicly available national accounts data in the Republic of Ireland. Unless specified otherwise, we have used published data sources and where possible rely on the most recent data published by the Central Statistics Office (CSO). For detailed enterprise specific data on the agriculture sector we use the Teagasc 2013 National Farm Survey.[3] Costs and losses are discounted to the base period using a discount rate of 5%, which is the recommended rate for the evaluation of publically funded investments.[4]

3.2. Parameter specification

When attempting to specify the model parameters we reviewed literature of other disasters similar to a nuclear accident in north-western Europe. Given the unique nature each event, we were unable to find a suitable precedent to inform estimates of losses for the Irish case, especially when studying other nuclear incidents at Three Mile Island, Chernobyl and the Fukushima Daiichi plant facility. The extent and scale of these accidents within their own countries are disproportionally large compared to potential damages that might arise in Ireland. The lack of suitable data underscores the appeal of this method, which could provide an estimate of costs for decision makers in countries that have no historical precedent for such incidents.

3.2.1. Parameter α_i

In the absence of suitable historical precedent for Ireland, we reviewed literature on food and tourism crises, which are reported in Tables 2 and 3, to inform the value of α_i, the sector-specific initial loss in value.

Table 2: Literature on food scares

Source	Country	Crisis	Food	Peak to trough % change in demand
Philippidis and Hubbard (2005)	UK	BSE	Beef/Mutton/lamb Other meats	-72% in quantity -45% in quantity
Ishida et al. (2010)	Japan	BSE Avian Flu	Beef Chicken	-50% in quantity -25% in quantity
McCluskey et al. (2005)	Japan	BSE	Beef	-70% in value
Latouche et al. (1998)	France	Steroids	Veal	-40% in quantity
Niewczas, M. (2014)	Poland	Food Scares	Food	-30% in quantity
Carter and Smith (2007)	USA	GMO	Corn	-7% in price

In the context of a nuclear incident, we posit that consumers' perceptions of potential health impacts, irrespective of their accuracy, will be closer to the perceived risks associated with Bovine spongiform encephalopathy (BSE) contaminated beef than the other food scares listed. We assume that the assumed response in demand will be roughly the mid-point of the three BSE estimates in Table 2, i.e. $\alpha_{agri} = 0.6$, which is the initial drop in consumption from which recovery must begin. Incidents of terrorism, war and natural disasters might be useful for informing the value of $\alpha_{tourism}$. Some of the values of lost tourism in Table 3 are relatively low, possibly reflecting the view there will not be a major impact. We view the response of consumers to news of airborne diseases, such as the outbreak of the SARS virus would best approximate the consumer response in a nuclear incident. Mao et al. (2010) notes that there was a 90% decline in recreational tourist arrivals from the USA to Taiwan after the outbreak of the SARS virus. For this reason we assume $\alpha_{tourism} = 0.9$. Based on expert guidance, the value of $\alpha_{exports}$ has been set equal to one as it is expected that in the case of an incident, an importing country prohibits imports from countries affected by an incident. After the duration of the ban, recovery begins from an initial base of zero.

Table 3: Literature on tourism crises

Source	Tourist Origin	Tourist Destination	Crisis	Impact
Enders and Sandler (1991)	USA	Europe	Terrorism	54% cancelled reservations
D'Amore and Anuza (1986)	USA	Overseas	Terrorism	79% avoid international travel
Stafford et al. (2009)		Ireland	Terrorism	32% would postpone trip
Mc Kercher and Hui (2004)	Hong Kong		Terrorism	39% changed travel plans
Ioannides & Apostolopoulos (1999)	Overseas	Cyprus	War	-18% arrivals
Mao et al. (2010)	Japan Hong Kong USA	Taiwan	SARS	-98% arrivals n/a -90% arrivals
Huang et al. (2008)	Overseas	Taiwan	Earthquake	-15% arrivals
Mazzocchi & Montini (2001)		Italy	Earthquake	-50% arrivals

3.2.2. Parameter t_{ie}

As mentioned previously, the parameter t_{ie} (the period when losses are fully recovered) varies across incidents and economic sectors. Although there is often is a lack of information to inform the value of this parameter, previous research provides different estimates of the duration of losses caused by particular incidents. One example where the same type of incident lead to different results is studied by Mendoza et al. (2012), who found that tourist numbers fully recovered within 4 months of an earthquake in China. However, Guo and Xiong (2011) found for a different earthquake that tourism had not recovered after 10 months. For our case study, we established suitable values for t_{ie} based on expert guidance, the severity of each scenario and the area in question (agriculture, exports, tourism).

This methodology is able to specify scenarios where full recovery is achieved within a finite duration. The values of t_{ie} varied across each of the four scenarios under investigation. For hypothetical events, the ability to specify the duration of potential impacts is appealing for the purpose of forecasting and also for the decision making process of evaluating the net benefit of alternative policies (such as becoming a signatory to relevant international conventions). By varying t_{ie}, planners are able to generate results for multiple hypothetical scenarios using the same data. This helps to provide a range of possible outcomes in the event where impacts may potentially be long lasting.

Table 4 details the assumed duration and severity of impacts and how they vary across each scenario. The values have been drafted based on expert advice and by studying prior research. For this analysis we have assumed that radiological depositions are uniform across the country, without any regional variations. Accordingly, the scenario analysis undertaken here is at national level.

Table 4: Assumed values of t_{ie}

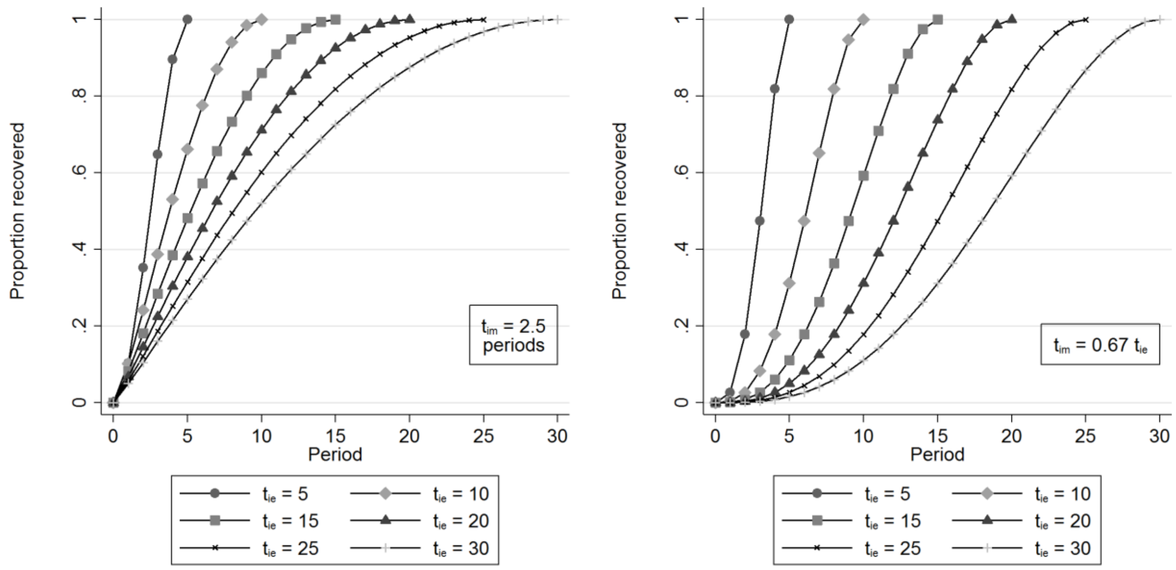
Date:	**Scenario 1** Mid-May	**Scenario 2** Mid-May	**Scenario 3** Early February	**Scenario 4** Mid-May
Radiological Impact	None	Minimal	Substantial	Severe
Advice for people to remain indoors	-	-	-	2 days
Loss of working days	-	-	-	3 days
Advice to keep livestock indoors	2days	4 days	8 weeks	-
Food/Environment Monitoring	2 weeks	9 months	10 years	30 years
Export Certification	-	7 years	10 years	60 years
Food import restrictions from Ireland				
- EU	2 weeks	9 months	1 year	3 years
- Non-EU	2 weeks	9 months	5 years	15 years
Duration of reputational damage				
Tourism	6 months	1 year	6 years	15 years
Post EU import restriction	6 months	1 year	2 years	6 years
Domestic consumers	6 months	1 year	2 years	6 years
Post non-EU import restriction	6 months	1 year	10 years	15 years

3.2.3. Parameter t_{im}

Studies of product diffusion suggest that values of t_{im} are generally larger than (1/2) t_{ie} (Gutiérrez et al., 2005; Dergiades and Dasilas, 2010; Kaldasch, 2011; Yamakawa et al., 2013). For the case study of a nuclear incident we set $t_{im} = 2/3\ t_{ie}$. This rule is applied across all scenarios and will result in a pattern of recovery which begins very slowly at first, followed by a very strong phase of growth before slowing towards full recovery. Qualitatively, an incident would potentially result in a short term halt in activity with a longer-than-usual initial period of recovery, potentially hindered by factors such as reduced tourism or trade restrictions on Irish produce. For simplicity, we assume t_{im} is a fixed proportion of t_{ie} across all areas of the economy.

Figure 4 illustrates the impact of assuming t_{im} is a fixed proportion of tie, rather than a duration which does not depend on t_{ie}. The left hand side of Figure 4 assumes that t_{im} = 2:5 periods with varying end points t_{ie}. This is compared to the right hand side of Figure 4, which shows $t_{im} = 2/3\ t_{ie}$. As t_{ie} increases in this case, t_{im} also increases, resulting in the inflection point of recovery occurring at a later period. As the duration of costs may differ across sectors within the same scenario, we assume that t_{im} is a fixed proportion of t_{ie} across all sectors and scenarios..

Figure 4: Determinate growth function - Fixed t_{im} = 2:5 , $t_{im} = 2/3\ t_{ie}$ (Source: authors)



3.3. Results

This section outlines the potential economic impacts of the four nuclear accident scenarios. Our methodological approach has been conservative in terms of the scope of impacts and only focuses on a number of specified impacts. It is important to note that any potential accident would also include wider losses to society, which are beyond the scope of this particular study. As mentioned in Section 3.1, we discuss direct and reputational losses, with the understanding that direct losses incorporate direct costs and losses. Table 5 provides a summary of the estimated decline in tourists visiting Ireland for each scenario, while Table 6 provides an overview of the anticipated costs in each scenario.

Table 5: Expected decline in international tourist visitors, million (Source: authors)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
UK	0.9	1.8	9.5	23.7
Rest of Europe	0.8	1.5	8.0	20.0
Rest of World	0.5	1.0	5.2	12.9
Total (million)	2.2	4.3	22.7	56.6

Table 6: Detailed scenario estimated costs (Source: authors)

	Scenario 1 (€m)		Scenario 2 (€m)		Scenario 3 (€m)		Scenario 4 (€m)	
	Direct Loss	Rep. Loss	Direct Loss	Rep. Loss	Direct Loss	Rep. Loss	Direct Loss	Rep. Loss
Tourism								
UK	-	423	-	846	-	4,125	-	9,003
Rest of Europe	-	356	-	712	-	3,468	-	7,571
Rest of World	-	230	-	461	-	2,245	-	4,899
Agriculture	-	-	-	-	1,963	-	5,138	-
Monitoring & certification costs	-	-	6	-	1,460	-	4,311	-
Exports								
Livestock & animal feed	-	220	480	418	1,550	1,494	3,895	1,904
Meat, dairy, seafood	-	1,956	2,273	3,727	13,800	13,297	34,659	17,902
Cereals, fruit & vegetables	-	209	458	399	1,478	1,424	3,712	1,917
Other food, goods	-	747	1,631	1,422	5,265	5,074	13,224	6,830
Total	**-**	**4,141**	**6,842**	**7,991**	**25,516**	**31,127**	**64,939**	**50,026**

Note: Rep. Loss = Reputational loss

3.3.1. Scenario 1

Scenario 1 is assumed to be an event where there is no radiological impact on Ireland. Consequently, there are no significant direct costs or losses to Ireland. It is assumed that the nuclear accident would generate significant media attention and because of Ireland's proximity to the accident site a perception that Ireland is contaminated. Reputational losses are assumed to occur with respect to food exports and tourism. For instance, it is reasonable to assume that international food markets will source product from suppliers further distant from the accident site and tourists are likely to travel to other destinations.

In the case of tourism we project a loss of over 2 million visitors, approximately 40% from the UK, and 35% from elsewhere in Europe. The associated loss in tourism revenue is e1 billion, with reputational losses in Ireland's export markets projected to be €3.1 billion. Meat and dairy produce account for 57% of the lost value. In this scenario it is assumed that losses are short-lived and markets recover to pre-accident levels within 6 months.

3.3.2. Scenario 2

Scenario 2 assumes that a hypothetical nuclear accident leads to some low-level environmental contamination in Ireland. In this event, food controls and agriculture protective actions are put in place for several days until it is proven that the levels of radioactive contamination are very low, are of no health concern and do not warrant any protective actions. Similar to Scenario 1, global media attention covering the accident is likely to be significant, leading to a perception that Ireland is highly contaminated. It is also likely that additional health costs will arise, as people engage with the health services to ensure that they have not been adversely affected. An assessment of additional health costs are not considered here.

As contamination occurs there are direct costs associated with this accident scenario, such as additional radiation monitoring. As contamination levels are very low these costs are primarily confined to laboratory and monitoring costs without any requirement to implement radiation remediation actions. These costs are estimated to be just over €6 million. This scenario assumes that there will be a restriction on imports from Ireland for 9 months, which results in direct losses to food and other exporters. The effect of the trade restriction extends beyond the period of the import restriction itself, as it takes time to recover market share. In this scenario we assume that the reputational losses associated with the import restriction are recovered within one subsequent year. Table 6 reports the direct export losses associated with the import restriction and also the subsequent reputational losses, totalling almost €13 billion. It is expected that there will be about 4 million fewer tourist visitors (See Table 5) because of the accident with an associated loss in revenue of roughly €2 billion.

3.3.3. Scenario 3

Scenario 3 assumes a nuclear accident that leads to moderate environmental contamination in the Republic of Ireland. In this scenario, the levels of contamination are found to warrant food controls and agriculture protective actions for a number of months, as without them food would not comply with EU regulations on radioactivity content. No protective actions for people, such as recommendations on staying indoors, are assumed necessary. Another aspect in which this scenario differs from the others is that the timing of the accident is assumed at the start of February. With the majority of animals indoors the direct impact on livestock is minimal but pastures will be contaminated. At this time winter feedstuffs will be in short supply and farmers will find it difficult and expensive to source uncontaminated feedstuffs for their animals.

Although this scenario assumes that there are no protective actions necessary for people and that the food controls and agriculture protective actions will prevent long term health risks, there are likely to be substantial additional health costs as the perception of a radiological risk will mean that people are likely to engage more frequently with the health services than would otherwise be the case. Just as in scenario 2, an assessment of additional health costs has not been undertaken in this paper.

Scenario 3 is the first case where there are significant impacts in the agriculture sector. Unlike export and tourism losses, it is important to note that these costs are not modelled using the determinate growth function, rather they are estimated by calculating the annual value over the assumed horizon for each cost in this scenario. Due to the level of contamination, plus the associated uncertainty, we assume that outdoor fruit and vegetable crops, as well as tillage are lost for the year. The value of the lost production is just less than €2 billion, as shown in Table 6. Production in subsequent years is expected to resume. Additional costs related to radiation sample testing, monitoring and remediation measures are estimated to cost an additional €1.46 billion, reflecting increased duration and scale of environmental monitoring, sample testing and expansion of laboratory operations to accommodate increased testing demands.

Due to radiation contamination, Irish produce will incur considerable losses in export markets, both direct losses due to import restriction and also reputational losses. For this scenario we assume that the EU will prohibit imports of Irish produce for one year, whereas other international markets impose 5 year restrictions. Reputational losses continue after the import restrictions are rescinded, 2 years for EU markets and 10 years for international markets. Table 6 lists the losses across the production categories with the total export losses in excess of €43 billion. In total there are almost 23 million fewer international tourist visitors to the country over a 6 year horizon. Over 6 years the total discounted loss in the tourism sector is almost €10 billion, as reported in Table 6.

3.3.4. Scenario 4

Scenario 4 assumes a situation where high levels of nuclear contamination would be economically catastrophic for Ireland and particularly so for the food sector. In this scenario, concerns for the health of the population become a primary focus. Levels of contamination are such to warrant food controls and agriculture protective actions for a number of years after the accident, as without them food would not comply with EU regulations on radioactivity content. International demand for Irish produce will collapse, while animal production systems need to start over. The cost of such a scenario is far from being just economic or financial, as it will have a substantial cost on societal well being. However, we focus on a narrow range of economic costs.

As in scenario 3, although food controls and other protective actions should prevent long term health risks it is likely that the perception of a radiological risk will mean more engagement with the health services than would otherwise be the case. It is difficult to assess either the level of additional health service engagement or its associated cost but it likely to be quite substantial. As is the case in scenario 2 and 3, estimates of the additional health costs under this scenario are beyond the scope of this study.

The impact of such high levels of contamination will also be long-lived. For example, our scenario assumes that additional radiation monitoring and product certification will continue for 60 years after the accident, which alone will cost almost €50 million. Other direct costs are listed in Table 6. Similar to scenario 3 the cost of disposal of contaminated material is not included. It is also likely that in this scenario (and to a lesser extent in scenario 3) that there may be substantial outward migration and capital withdrawal from the economy. Significant emigration and wealth shocks could have a substantial impact on the productive capacity and aggregate demand within the economy causing a serious fiscal-erosion of the tax base. The magnitude of such impacts has not been assessed.

Agricultural production is essentially lost in the first three years after an accident. The scenario assumes that EU markets will open to Irish produce after that time but that it will take a further 12 years before international markets open up to Irish produce. We have assumed that the duration of reputational losses are 6 and 15 years for the EU and Non-EU, respectively. The total value of loss of export markets is some €84 billion, with meat, dairy and seafood produce accounting for over €50 billion, as shown in Table 6.

3.3.5. Indirect impact

We also see how modelling reputational losses complements traditional input-output analysis. The wider economic impact increases in magnitude the more severe the hypothetical scenario is. Based on the IO multiplier, we estimate that indirect losses in the Irish economy would range from €287 million in scenario 1 to €44 billion in scenario 4. This is a significant figure and underscores the additional information that modelling reputational losses can have on the estimates of such an event.

3.3.6. Tourism impact

In addition to the financial impact of an event for each scenario, we also estimate the number of tourists which would not travel to Ireland after an incident. Table 5 shows that the fall in incoming tourists ranges from 2.2 million passengers to 56.6 million in the most severe scenario, with the largest loss being in visitors from the UK. Table 6 provides estimates of the financial losses to the Irish economy ranging from e1 billion to €21.5 billion respectively.

3.4. Discussion

Across each of the four scenarios we have assessed some of the potentially larger economic impacts of a nuclear accident. It has not been possible to assess all the impacts and from that perspective the figures presented here should be considered as conservative lower bound estimates. This is particularly the case for scenarios 3 and 4. The figures are intended to be illustrative of the scale of potential losses for accidents of varying severity rather than quantify a definitive loss resulting from an accident of very low probability with an uncertain outcome. In particular, certain impacts and costs are unique to that of a nuclear accident and would not be appropriate in studies of other disasters. It is important to highlight the contribution of the determinate growth function modelling technique in helping to provide a more conservative estimate of costs for decision makers. The scale of losses in this study are quite large, with the discounted cost of the most severe scenario being roughly equal to the annual GDP of the Irish economy (Nominal GDP was €174.8bn in 2013). We consider our estimation approach to be quite conservative, in particular as certain costs (such as additional healthcare expenditure) have not been included. For this reason, we feel that the actual level of impact is likely to be greater for each scenario. While the estimated impacts are reported here as discounted net present values the pathway of annual costs can easily be reported also, which may have relevance for emergency planners. The analysis in this case study serves to aid planning and mitigation strategies for decision makers. For example, such analysis could inform government on matters relating to nuclear liability, safety and security, particularly when deciding to become a signatory to international treaties and conventions which provide reimbursement in such an event.

Table 7 summarises the scale of losses across the four scenarios, combining the direct agricultural, tourism, export and wider resulting economic impacts. Two points are immediately striking. A hypothetical nuclear accident in north-western Europe could potentially have a severe impact on the economy; the discounted cost of the most severe accident scenario is in the order of €159 billion. The second point is that where a nuclear accident does occur but with no radiological deposition occurring on Ireland there is still a substantial though more manageable economic impact, which is particularly highlighted by the estimates for scenario 1 and 2 (€4.4 and €18.3 billion respectively).

Table 7: Summary of losses

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Direct Loss (€bn)	-	6.8	25.5	64.9
Reputational Loss (€bn)	4.1	8.0	31.1	50.0
Indirect Losses (IO) (€bn)	0.3	3.5	22.6	44.4
Total	**4.4**	**18.3**	**79.3**	**159.3**

4. Conclusion

A number of different methodological approaches, such as input-output (IO) analysis, computable general equilibrium (CGE) models and econometric methods are frequently used to estimate the economic impact of disaster events. Each approach has different strengths and weaknesses but data requirements make analysis difficult in many instances, in particular when modelling events as infrequent and irregular as disasters. The approach presented in this paper complements existing methods by introducing a methodology which can be applied to provide order of magnitude estimates of costs in the event of a disaster. The approach developed has the advantage that it requires few assumptions and has light data requirements but more explicitly links the size and nature of the event to the size and duration of impacts over time, which is usually not well specified in other methodologies. Despite its simplicity, the method generates results that can serve as a rule of thumb to help inform policy makers and emergency planners who may wish to estimate costs in the wake of a disaster or forecast costs for hypothetical events.

The methodology draws on the approach often used to study technology diffusion and applies it to the study of disasters, as they are events which are similar in the development of their impact over time. An applied case study is presented to illustrate findings and how this methodology complements existing techniques, such as IO analysis. The methodology presented in this paper is appealing due to the ability to quickly conduct analysis of multiple hypothetical scenarios through the use of the same dataset.

The case study in this paper is intended to be illustrative of the scale of impacts and does not purport to be an exhaustive assessment of all potential effects and guidance which would be experienced in the event of an accident. We have taken a conservative approach by focusing on the direct impacts within three key areas: agriculture, exports and tourism. Results represent lower bound estimates of the potential economic impacts for each of the scenarios examined. For instance, the analysis has not attempted to estimate the costs associated with disposal of contaminated or condemned materials, as well as any losses or additional healthcare costs, or wealth or migration flows that might arise in the event of such an accident.

[1] Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960 (the “Paris Convention”); Convention of 31 January 1963 Supplementary to the Paris Convention of 29 July 1960 (the “Brussels Supplementary Convention”); Convention on Civil Liability for Nuclear Damage of 21 May 1963 (the “Vienna Convention”); Joint Protocol Relating to the Application of the Vienna Convention and Paris Convention; Protocol to Amend the Vienna Convention (the “1997 Amending Protocol”); Convention on Supplementary Compensation for Nuclear Damage (the “Compensation Convention”)

[2] See Miller and Blair (2009) for a detailed treatment of Input-output analysis and Rose et al. (1997) for an application of IO tables to assess the impact of an earthquake.

[3] See https://www.teagasc.ie/rural-economy/rural-economy/national-farm-survey/

[4] For Ireland, see http://www.per.gov.ie/en/project-discount-inflation-rates/

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