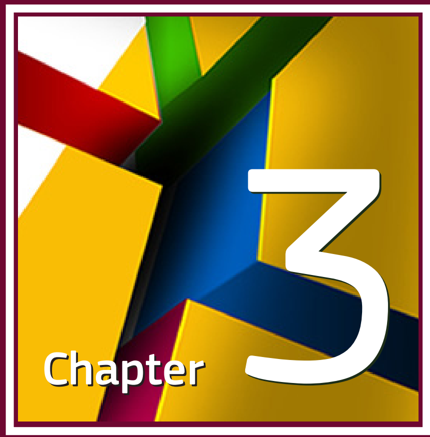

Assets at risk and potential impacts

3.3

Economic sectors

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3.3 Economic sectors

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3.3 Economic sectors

Introduction

Natural hazards are a major threat to sustainable development, economic stability and growth, territorial cohesion, and community resilience. According to the estimates of the European Environment Agency, the economic damage due to only natural hazard risks in the EU amounted to more than EUR 557 billion ([1]) in 1980–2017, mostly triggered by extreme weather and climate-related events whose frequencies and/or intensities are expected to increase as a result of human-induced climate change. The bulk of this damage was caused by relatively few low-probability, high-impact hazard events.

These estimates account only for the direct economic damages to physical assets only and omit often significant indirect economic losses generated by slow-onset hazards, spillover effects and indirect costs from the disruption of social networks, economic flows and ecosystem services. As a result of neglected attention to disaster risk impacts in the past, it is not easy to portray the spatial and temporal patterns of disaster damage and losses with reasonable precision.

The Sendai framework for disaster risk reduction 2015–2030 (UN, 2015) emphasised multi-hazard, inclusive, science-based and risk-informed decision-making, and laid down priorities for action and policy targets. The policy targets include a commitment to substantial reduction of economic damage. A sound understanding of risk does not only imply accounting for past damage and losses. Model-based economic risk assessment has been propelled by high-performance computing, large-scale hazard and disaster loss/impact models, and high-resolution exposure datasets of the Copernicus Earth observation programme.

A better understanding of natural hazard risk and ensuing economic losses is important for coordinating responses to shocks and crises within the European Economic and Monetary Union (Aizenman et al., 2013; Ureche-Rangau and Burietz, 2013). In the absence of financial protection tools for coping with disasters, the incidence of major disasters in several EU Member States may exacerbate economic imbalances and deteriorate credit ratings (Mysiak and Perez-Blanco, 2015).

This subchapter reviews the methods and models used, recent advances, and challenges in analysing disaster damage and losses in residential, agricultural and industrial sectors. Gross fixed capital formation in residential housing sector amounts to 5 % of gross domestic product (GDP) in the EU-27 (Eurostat, 2020). Housing statistics and prices are important indicators of living conditions and therefore regularly collected by national statistical offices and Eurostat. The characteristics of residential building stocks are surveyed by statistical censuses, and those of residential built-up areas can also be obtained from very high-resolution remote sensing data (e.g. European Settlement Map (Sabo et al, 2019; European Commission, 2020). Housing prices are sensitive to past experiences of risk and availability of insurance coverage. Insurance premiums determined at actuarial risk pricing, on the other hand, are a function of a property's hazard exposure.

The agricultural sector contributes around 1.1 % of the EU's GDP but manages almost 40 % of the EU's total land area and represents an important employment opportunity for the rural population. Agriculture is heavily exposed to weather- and climate-related hazards (storms, droughts, floods, heat and hail), other risks such as pests and diseases, and market volatility. Assessments of economic impacts of water scarcity or droughts may be based on statistical, crop growth and/or Ricardian land price models. The econometric models exploit the historical covariation between yields and weather on an annual or more frequent basis to infer the effect of climate variability and change (e.g. Schlenker and Roberts, 2011). The Ricardian method assumes that agricultural land rents reflect the expected productivity of agriculture (Moore and Lobell, 2014; Van Passel et al., 2017).

Hazard-induced disruptions of energy supply or industrial production set off supply and demand shocks that affect regional economies in and beyond the areas directly affected by the disasters. The damage to tangible productive assets is equivalent to losses caused by disruption of production networks (Rose, 2004). The demand for liquid capital may increase its price; the level of fiscal consolidation and perceived trustworthiness play a role. Efforts to restore productive and non-productive capital losses generate new demand and change consumption patterns, which may lead to changes in prices, trade levels and fiscal revenues. These effects can be modelled by input–output, computable general equilibrium, social accounting matrix and econometric models.

([1]) EU-28 Member States as in 2018 (including the United Kingdom), European Free Trade Association countries and Turkey, based on the NatCatService of Munich Re, estimated for the European Environmental Agency and Eurostat climate change indicators.

3.3.1 Residential sector

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1 Importance of the residential sector

Residential buildings constitute one of the main types of assets exposed to natural hazards, with a relatively high economic value. Residential construction contributed to 4.4 % of EU gross domestic product (GDP) in 2018. The total built-up residential area in the EU is more than 200 000 km^2. Natural hazards may result in damage to buildings and reduction in their market value. For instance, the price of houses in the north of the Netherlands dropped by almost 4 % for every percentage point increase in peak ground velocity due to induced seismic activity (Duran, 2017), while the price of houses within a 100-year floodplain is reduced by 4.6 % after a flood, and requires 5 to 7 years to recover (Beltrán et al., 2018).

Residential buildings are also important for the safety and quality of life of citizens; therefore, they are essential for achieving the Sustainable Development Goal 11 for inclusive, safe, resilient and sustainable cities as well as the targets of the Sendai framework for disaster risk reduction (UNISDR, 2015a) to reduce the number of affected people by disasters and direct economic losses. Residential buildings are the target of EU policies for risk prevention and mitigation. The Union Civil Protection Mechanism encourages measures to promote resilience at building level, whereas Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive) requires the assessment of the risk to assets and humans, as the basis for risk mitigation.

This section examines the impact of floods, landslides, earthquakes, tsunamis and volcanic eruptions on the residential sector. Other hazards, e.g. technological and human-made ones, are excluded, while the impact on people is discussed in subchapter 3.2.

2 Assessment of the potential damage and losses

Similar models and methodologies are used to assess damage to buildings due to different natural hazards. Harmonised and high-quality data on building features and damage, available at different geographical levels, are key to calibrate models in a multi-hazard perspective.

2.1 Methodologies for impact assessment

Models of hazard, vulnerability and the distribution of exposed buildings are used to estimate damage and losses (e.g. Casagli et al., 2017; Cloke et al., 2017; Loughlin et al., 2017; Papadopoulos et al., 2017; Silva et al., 2017). Scenario-driven approaches estimate the impact of specific events, while probabilistic ones consider the probability of occurrence of all possible events that may affect a site, and a probabilistic estimation of damage and losses, including relevant uncertainties. Depending on the purpose, there are different methodologies; there is no single one that is fit for all purposes.

'Hazard' refers to processes and phenomena that have the potential to cause damage. It is characterised by its temporal likelihood (i.e. return period), spatial likelihood and magnitude or intensity, such as extent of affected area, depth and duration of floods, peak ground acceleration and displacement for earthquakes, velocity and mass for landslides, or density and thickness of volcanic deposits. Hazard scenario can be defined as the maximum probable/credible or historical event or an event with a given return period and magnitude.

2.2 Taxonomies

A taxonomy is used to categorise buildings into classes, taking into account the characteristics relevant to assessing the impact of hazards (e.g. Fotopoulou et al., 2013; Zuccaro and De Gregorio, 2013; Du et al., 2014; Pitilakis et al., 2014a; Zhang et al., 2016; Silva et al., 2018). As Table 1 illustrates, the technical literature indicates that the same building attributes, such as year of construction, number of floors, construction material and system, are important to characterise the vulnerability of buildings exposed to different hazards. There is a clear need to better understand the response of structural and non-structural elements to different hazards (see for example Mavrouli and Corominas, 2010). Taxonomies may be expanded to include additional information and define more detailed typologies. However, the data for all attributes are not easy to collect (if available at all) at the local, regional or national level.

Table 1*. Building characteristics that are used to assess the vulnerability to natural hazards* ***Source****: Authors.*

Characteristic	Earthquake	Flood	Landslide	Tsunami	Volcanic eruption
Number of floors	X	X	X	X	X
Construction material	X	X	X	X	X
Year of construction or design code level	X	X	X	X	X
Load-bearing structural system	X	X	X	X	X
Level of maintenance	X	X	X		X
Height above ground	X	X		X	X
Irregularity in geometry and resistance	X		X	X	X
Presence and type of claddings	X	X		X	X
Number and type of openings	X	X	X	X	X
Presence of domestic plants		X			
Geometry and structure of roof					X

2.3 Exposure data

'Exposure' refers to the buildings present in hazard-prone areas. The most basic sources of information on building exposure, albeit not fully harmonised across countries, are the cadastres and national housing censuses that are performed regularly and may furnish an exhaustive picture of the housing stock. Open community-based web geographical information systems (GISs), such as OpenStreetMap, are becoming available and used to identify exposed buildings. Such information, however, often does not include important attributes, e.g. roof pitch or openings as a percentage of wall area, for studying risk under natural hazards. Cadastral and census data could be integrated with spatial information from the geodatabases that are becoming freely available from local authorities and contain such attributes as location, use, year of construction, level of maintenance and number of floors. Improved exposure data may be obtained by combining census data and data collected on site (e.g. Cacace et al., 2018).

Exposure data for buildings located in earthquake-prone regions were collected initially for a few European cities, often at a high level of geographic disaggregation. Later, inventories providing the population or fractions of building types at national, regional or local level were developed (Jaiswal et al., 2010; Crowley et al., 2012, 2018; Gamba, 2014; Zuccaro et al., 2015). However, these datasets typically exclude some of the attributes that affect buildings' response to other hazards. Exposure to floods and landslides relates to the number (or total surface/volume) of buildings present in the affected areas and their monetary value. Real estate market value or reconstruction costs are used and values can be depreciated to take into account the age of the assets (Merz et al., 2010). Very few studies have collected specific exposure data for tsunami hazards. Census, land cover or socioeconomic data are mainly adopted to quantify the number of people and assets within potential tsunami inundation areas (e.g. Grezio et al., 2012; Løvholt et al., 2014). For volcanic risk analysis at local level, e.g. Vesuvius, Campi Flegrei and Ischia in Italy and Santorini in Greece, exposure data for ordinary buildings are collected by in situ surveys and combined with census information (Zuccaro et al., 2018a; Zuccaro and De Gregorio, 2019).

2.4 Vulnerability models

Vulnerability represents the susceptibility of an element at risk of being adversely affected by a hazardous event. The vulnerability of buildings is commonly modelled using fragility functions, which give the probability that, for a given hazard intensity, structures of a certain typology will exceed various damage levels. Empirical fragility functions are based on observed damage data from past events, numerical ones are based on numerical simulations of varying degrees of sophistication and hybrid ones combine numerical analyses with observed and/or experimental data (e.g. Spence et al. 2004a,b, 2005; Quan Luna et al., 2011; Mavrouli and Corominas, 2010; Pitilakis et al., 2014a; Yepes-Estrada et al., 2016; Charvet et al., 2017; Park et al., 2017). Uncertainties in damage estimates originate from the variability of the hazard characteristics, geometric and material parameters of the buildings, type of structural model and analysis, resistance models, definition of damage states, etc.

Fewer than a handful of numerical tsunami fragility functions exist in the literature. This is due to a general lack of understanding of tsunami inundation processes and flow interaction with the built environment, and of how to implement tsunami loads into structural analysis software (Rossetto et al., 2018). The past few years have seen an increase in research activity with laboratory experiments (e.g. Foster et al., 2017) and structural analysis approaches (e.g. Petrone et al., 2017).

When insufficient data are available or the scope of the study requires it, vulnerability indices and matrices may be employed (e.g. Papathoma and Dominey-Howes, 2003; Vicente et al., 2011; Hu et al., 2012; Jakob et al., 2012; Kappes et al., 2012; Dall'Osso et al., 2016; Kang and Kim, 2016). Vulnerability indices are composed of a weighted combination of indicators that represent aspects of the building, the site or socioeconomic features that contribute to the vulnerability of an asset or area. Comparison of vulnerability index values across geographical areas allows the ranking of their relative vulnerability.

While most studies estimate vulnerability of buildings as separate entities, in reality they represent elements within a highly interconnected territorial system. Systemic vulnerability is assessed by characterising the physical vulnerability and functional interdependencies between buildings with different occupancy, lifelines and transport infrastructure (Pascale et al., 2010; Pitilakis et al., 2014b; Mota de Sá et al., 2016; Zuccaro and De Gregorio, 2019). Such an approach can identify areas of greater risk, and support better emergency and spatial planning. Adaptive simulation, data mining and artificial intelligence techniques of surrogate modelling or meta-modelling, combined with health monitoring of buildings, offer possibilities of improving models (Zio, 2018).

The approach depends on the scope, context and temporal and spatial scales of analysis (Sterlacchini et al., 2014; Schneiderbauer et al., 2017). As housing characteristics vary between countries, transferability of vulnerability models is a challenge; integrating multiple methods may help a better understanding of vulnerability (Papathoma-Köhle et al., 2017) and estimation of uncertainty.

2.5 Loss modelling

Damage-to-loss models are obtained by correlating observed damage with repair costs, or are based on expert judgement or analytical models (Martins et al., 2016; De Martino et al., 2017; FEMA, 2018). The economic impact of disasters includes the costs of reconstruction, evacuation, clean-up, loss of contents, etc., and requires complex modelling (Zuccaro et al., 2013). A new generation of models based on statistical approaches, machine learning algorithms and in-depth description of damage mechanisms has emerged in the last decade (e.g. Dottori et al., 2016; Zio, 2018). They account for a large number of hazard and vulnerability parameters, and outperform simple data-driven models. All types of models need sufficiently large and detailed loss datasets to be calibrated. Data-driven models also need to be validated for different contexts.

2.6 Risk metrics

Direct losses in residential buildings mean the monetary value of physical damage and costs for cleaning, repair, demolition, etc. Indirect loss includes costs occurring as a consequence of direct loss, e.g. decrease in market value or evacuation costs. These metrics may be expressed as loss exceedance curves (probability that various levels of loss will be exceeded), average annualised losses or average annualised loss ratios (FEMA, 2017). This last is useful to compare the relative risk across different regions, since it is normalised by the replacement or market value. 'Intangible damage' refers to consequences that cannot be evaluated in monetary terms, such as loss of memorabilia

3 Assessment of the impact after an event

Knowledge from ex post damage assessment may improve the efficiency of preparedness, response, recovery and mitigation measures, at both the individual and community levels. Standardisation of methods and procedures for ex post damage collection and recording would benefit from being set at the EU level.

3.1 Post-event collection of damage and loss data

Data collected in the aftermath of disasters are the basis for tailoring risk mitigation strategies, both after an event (e.g. for identifying priorities for intervention and guiding compensation) and before an event (e.g. to support preventative measures) (Ballio et al., 2015). For instance, the extensive review of flood impacts done by Pitt (2008) after the 2007 floods in England served to improve policies and techniques of flood risk management in the United Kingdom in the following years (United Kingdom, Government, n.d.).

The standardising of disaster damage data collection has been constantly advocated so that consistent and reliable data can be provided to public administrations, scientists and practitioners. Promoting improvements in the knowledge base for disaster loss management, including loss databases, is a key priority at both international and EU levels (e.g. Sendai framework for disaster risk reduction, EU disaster prevention framework, EU Solidarity Fund, green paper on insurance of natural and man-made disasters, and Floods Directive). Accordingly, an EU working group was created to support and encourage Member States to build a process for loss data collection and recording. According to the guidelines it provided (De Groeve et al., 2013, 2014, 2015), in order to optimise required efforts, the process should guarantee the multi-usability of collected data; in detail, it should consider all exposed sectors, and data must be collected at relevant time intervals to capture direct and indirect losses, regarding both observed damage and its explicative variables, and in the finest possible detail. In fact, most of the available procedures for ex post damage assessment are still sector- and hazard-specific, hampering the harmonisation process desired at international level.

Concerning the residential sector, procedures for the post-earthquake survey of damage are the most developed (Khazai et al., 2014; FEMA, 2018). Several countries have established inspection forms, primarily to assess the safety of buildings in the aftermath of a disaster, but also to support the implementation of short-term countermeasures, and estimate compensation and reconstruction costs (García and Cardona, 2003; ATC, 2005a,b; Anagnostopoulos and Moretti, 2006a,b; Baggio, et al., 2007; NZSEE, 2009; Santos, 2011; Roldán et al., 2013; Cruz et al., 2014). It must be stressed, however, that, whereas detailed damage data are collected, losses are usually reported as total economic losses, limiting the possibility of understanding damage mechanisms, improving risk models, etc.

Figure 1. *Destroyed (red) and highly damaged (orange) buildings in Amatrice, 25 August 2016.*
Source: *extracted from Copernicus Emergency Management Service, 2016. ©EU, 2016*

Tsunami damage survey procedures are traditionally focused on the evaluation of tsunami intensity rather than impacts (e.g. Rossetto et al., 2007). Still, new approaches are emerging. For example, on the occasion of the 2010 Chile earthquake and tsunami, the International Tsunami Information Centre developed a questionnaire to collect information on structural performance as well as general tsunami impacts (UNESCO, 2010), although aggregated over an area.

More recently, following the 2011 great east Japan tsunami, Japan's Ministry of Land, Infrastructure and Transportation developed a damage scale for the evaluation of tsunami damage to residential buildings (MLIT, n.d.). An unprecedented amount of detailed disaggregated damage data was collected (Tohoku Earthquake Tsunami Joint Survey Group, 2011) and then adopted for numerous empirical fragility studies (e.g. Suppasri et al., 2012; Macabuag et al., 2016). A particular complication arises in the assessment of damage in areas affected first by earthquake and then by tsunami inundation. Unless there is evidence of the damage due to the earthquake before the tsunami hit, it is almost impossible to attribute the final damage state to one of the two hazards. To adopt a consistent evaluation of damage, the UK Earthquake Engineering Field Investigation Team and Indonesian Tsunami and Disaster Mitigation Research Centre proposed a damage scale capable of capturing damage mechanisms under both earthquakes and tsunami (EEFIT-TDMRC, 2019).

Numerous databases and digital catalogues on landslides and their consequences have been compiled at regional, national and multinational scales in recent years and used for disaster relief, research and economic purposes (e.g. CNR, n.d.). Procedures for collecting building damage data after landslides have been proposed by Papathoma-Köhle et al. (2017) and Del Soldato et al. (2017). The "LANDslides and Floods National Database (LAND-deFeND)" (Napolitano et al., 2018) allows the storing of physical, geographical and socioeconomic data on geohydrological hazards and their consequences with different levels of detail (from local to regional events). There are not many procedures for post-flood damage assessment, basically owing to the limited need to evaluate the safety of buildings after such events.

A questionnaire developed after the 2002 Elbe flood in Germany (Thieken et al., 2005) addressed several topics: flood warning, precautionary and emergency measures, flood impact, contamination and cleaning up, characteristics of the affected households and related losses, flood experience and recovery, and socioeconomic characteristics of residents. Still, the survey was conceived mainly with research objectives, to capture information to improve capabilities to forecast damage. Collected data are stored in the German flood damage database (Kreibich et al., 2017) and have been used for empirical studies on flood damage to residential buildings (e.g. Thieken et al., 2007, 2008; Merz et al., 2013). In Italy, the Reliable Instruments for Post-event Damage Assessment (RISPOSTA) procedure (Berni et al., 2017) was developed to survey flood damage to buildings, and more generally to all exposed elements, in a multi-usability perspective (see the case study on the Umbria floods below).

Disaster loss data are available from a number of sources (e.g. CRED, n.d.; Munich Re, n.d.; Swiss Re, n.d.; UNDRR, n.d.), including the Copernicus Emergency service (European Commission, 2016), which uses satellite and aerial images to map damage after disasters, as shown in Figure 1 for the 2016 Amatrice earthquake. A comprehensive picture of available tools for disaster data collection, storing and reporting can be found at the Risk Data Hub (DRMKC, n.d.), developed by the European Commission Disaster Risk Management Knowledge Centre. The Risk Data Hub is a web-based GIS tool to access and share curated risk data, tools and methodologies at local, regional, national and European levels and covers a variety of natural hazards that may affect the residential sector, namely flood, forest fire, earthquake, volcano, landslide, subsidence and cyclone.

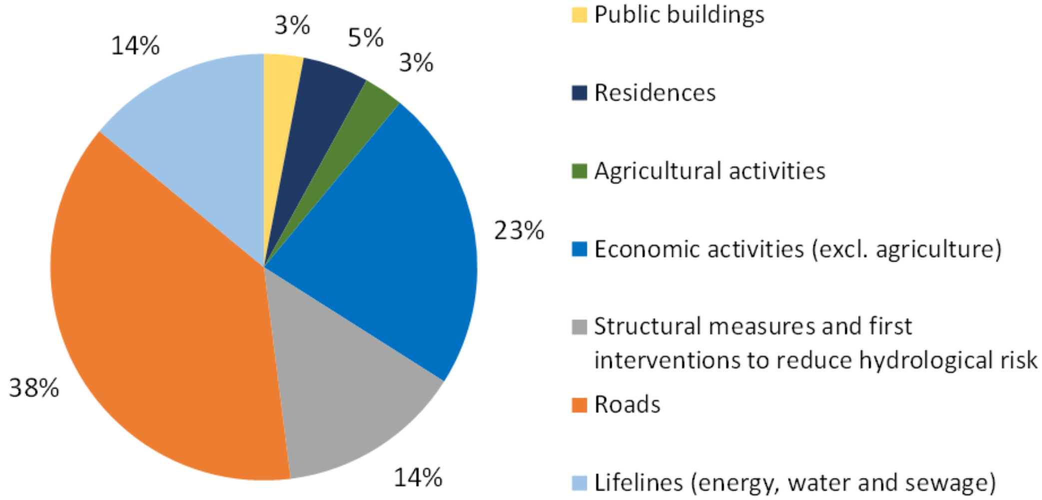
3.2 Case study: the Umbria flood in 2012

Context

In November 2012, a severe flood occurred in the Umbria region (central Italy) after a widespread, high-intensity storm. Flooding occurred with different features throughout the region, assuming the typical characteristics of riverine or flash floods. Out of 92 municipalities, 58 were affected. The total losses amounted to EUR 115 million, corresponding to 0.6 % of the regional GDP. After the event, a data collection campaign was performed by Politecnico di Milano, with the support of the regional civil protection, the main objective being to understand the damage and its causes, to identify criticalities and priorities for intervention. Data for the post-damage assessment were mostly acquired from local authorities and utility companies, which collect such information for the purpose of compensation. Damage to the residential and industrial/commercial sectors was surveyed in the field (Menoni et al., 2016).

Figure 2 shows the distribution of losses among the different sectors. As regards physical damage to the residential sector, collected data were analysed in terms of both damage and its explicative variables, as key information for the understanding of damage mechanisms and causes. In particular, the following aspects were investigated: structural and non-structural damage, water depth, velocity, sediment and contaminant loads at building locations, exposure/vulnerability of the buildings (materials, presence of basement, year of construction, etc.) and mitigation actions taken by owners before or during the event. The analysis highlighted that the most damaged component of buildings is plaster. Windows and doors were only damaged in long-lasting or high-velocity floods. Floors were usually not damaged, except where materials were not waterproof (e.g. wood). Domestic electrical plants were affected in most cases. Contents (furniture, appliances, etc.) were generally lost, apart from those cases in which people were able to move them to a safer place after receiving flood warnings (Menoni et al., 2016).

Figure 2: *Distribution of losses among the different sectors after the 2012 flood in Umbria.* ***Source***: *Menoni et al., 2016.*



Besides repairing damage, costs were related to cleaning up and to the civil protection assisting evacuees. As regards cleaning, the number of person-days declared by private residents varied between 1 and 30, depending on the damage suffered by the building. In total, 95 families (about 300 people) needed to be evacuated because houses were not habitable or accessible, for between 2 and 7 days, at a total cost for the civil protection of about EUR 150 000. Finally, the loss of memorabilia has been highlighted as significant intangible damage by most people living in damaged buildings (Politecnico di Milano e Regione Umbria, 2015; Menoni et al., 2016).

Lessons learned

The most important outputs of the campaign for disaster risk management were the following.The collection of very detailed data on damage and its explicative variables for 52 residential buildings and 10 industrial/commercial buildings. Data on residential buildings were used for:

- carrying out a cost-benefit analysis of flood proofing and construction of flood barriers versus relocation, leading to important recommendations on how to reduce the vulnerability of buildings (IDEA Project – Deliverable D4, 2016), a procedure that can be easily applied to other areas;

- analysing damage mechanisms in support of the development of In-depth Synthetic Model for Flood Damage Estimation (INSYDE), an expert-based model for the estimation of flood damage to residential buildings, validated for the Italian context, but transferable to other regions (Dottori et al., 2016; Molinari and Scorzini, 2017).

  - The development of the RISPOSTA procedure (Ballio et al., 2015; Berni et al., 2017) for the collection of damage/loss data to all exposed sectors after flood events. In particular, specific forms were created for field surveys of residential and industrial buildings (see Table 2), filling a gap in the current state of the art. RISPOSTA is now embedded into Umbria's emergency management regulations.

  - A model to assess event scenarios (Menoni et al., 2016) that offers a more comprehensive overview of the different types of damage that may affect communities and territories as a consequence of floods, and facilitates the understanding of causes of damage and its mitigation by reducing pre-event vulnerabilities. In particular, the model supports (a) loss accounting and damage compensation at different spatial scales, (b) forensic investigation in support of the recovery phase and (c) validation and calibration of improved damage and risk models. The model was applied to develop the complete event scenarios of the 2012 and 2013 floods in Umbria (Politecnico di Milano and Regione Umbria, 2015, 2018). The application of such a common model facilitates comparison between events, geographical regions and times.

Gaps and challenges

The experience highlights that the appropriate implementation of available risk management tools is the main challenge for the prevention of flood damage to residential buildings. A first issue regards promoting the adoption of floodproofing measures or the construction of flood barriers (both identified by the cost–benefit analysis as effective). This can be done with public financial aid (e.g. incentives, subsidies, loans), by including requirements in building codes for flood-prone areas, by reducing insurance premiums for owners adopting virtuous behaviours and by increasing public risk awareness.

A second issue relates to the use of flood damage models (such as INSYDE) for the identification of risk mitigation strategies. The limited availability of the required data, their complex formulation and the high uncertainty of their results prevent the implementation of such tools by decision-makers. The research community needs to make efforts to develop more usable but still reliable tools and to support decision-makers in dealing with uncertainty. To this end, a simplified and user-friendly version of INSYDE has been developed and validated in the Flood-IMPAT+ (an Integrated Meso & micro scale Procedure to Assess Territorial flood risk) project (Galliani et al. 2020).

The last challenge regards the prioritisation of strategies to mitigate the impact of flood events. Procedures such as RISPOSTA re-engineer the whole process to provide a standardised framework for collecting damage and loss data in the aftermath of flood events, optimise time and effort needed, improve the quality of data and produce analytical reports of damage. Wider use and reuse of damage data are permitted when they are collected in a systematic way, in line with the Sendai framework (UNISDR, 2015a). RISPOSTA proved effective in the 2012 floods in Umbria, reaching a good level of commitment by private and public stakeholders.

Table 2. *Information collected in RISPOSTA by means of the forms for damage to residential buildings* ***Source****: Molinari et al., 2014.*

Form	Section	Description
A: General information	1. General information	Building location
	2. Building features	Typology, period of construction, structure, footprint area, elevation, etc. to characterise exposure and vulnerability
	3. Flood event	Water depth and velocity, duration, sediment and contaminant loads to characterise stress on the buildings
	4. Damage description	Identification of affected parts of the building: number of housing units, attached buildings, common areas
B. Damage to housing unit (for every unit in the building)	1. General information	Identification of property, affected floors, residents
	2. Damage to affected floor X (for every affected floor in the unit)	Full characterisation of exposure, vulnerability, location and stress on floor X Direct damage, e.g. to coating, plaster, windows, doors, contents Indirect damage: loss of usability, clean-up cost Mitigation actions
C. Damage to common areas	1. General information	Description of affected floors
	2. Damage to affected floor X (for every affected floor in the common area)	Same as section B.2
D. Damage to attached building (for every attached building)	1. General information	Building location, identification of property
	2. Building features	Same as section A.2
	3. Flood event	Same as section A.3
	4. Damage description	Same as section A.4

4 From single to multi-hazard risk assessment

Multi-hazard risk assessment supports more effective disaster resilience strategies and better allocation of resources. Assessment methods should make use of harmonised models to provide results with comparable metrics, enabling the prioritisation of interventions.

Tackling natural and man-made hazards (including cascading effects) in a holistic way is essential to improve the resilience of the built environment and effectively allocate resources for risk mitigation. Such an approach allows the integration of multipurpose disaster risk reduction (DRR) and climate change adaptation (CCA) measures in the planning of new developments, urban regeneration and retrofitting buildings, to address in a coherent way the Sustainable Development Goals, the objectives of the 2015 Paris Agreement and the priorities of the Sendai Framework. The different backgrounds of the disaster risk and climate change domains have limited so far the establishment of an integrated methodological approach to DRR and CCA. Still, the recent path set by the Intergovernmental Panel on Climate Change (IPCC, 2014) reconciles climate risk assessment with the scientific framework in the field of risk science and theory of decisions (since UNDRO, 1980). Adopting this framework in a multi-hazard perspective means standardising hazard characterisation, exposure and vulnerability analysis methods (Marzocchi et al., 2009; Kappes et al., 2012; Garcia-Aristizabal et al., 2013), considering the similarities illustrated in Table 1. From this perspective, the following recommendations are derived from several past European research projects.

1. Define the time and spatial frames for the analysis. The probability of disastrous events from multiple hazard sources over the residential building's life (50–100 years, considering new design or retrofit) defines at the same time the potential expected damage and the type of DRR/CCA measures to implement to reduce losses. The spatial extension of the analysis can be hazard driven or exposure/vulnerability driven. In the first case, the multi-hazard characterisation gives information on the expected extent of the areas potentially affected (e.g. local for climate extremes, local to regional for earthquakes, supra-regional for volcanic eruptions), thus determining the areas to include in the analysis. In the second case, considerations such as administrative jurisdictions, planning domains and specific retrofitting programmes can guide the definition of spatial extent, in relation to the purpose of the assessment (e.g. assessing the multi-risk conditions of all residential buildings in a region, to determine tax incentives for DRR/CCA).

2. Hazard characterisation needs to be performed by experts in the specific field, deriving different events' probabilities of occurrence, magnitude, time and spatial extension, considering the future impact of climate change. Cascading effects analysis requires to determine the probability of hazard transitions within possible chains of events (Zuccaro et al., 2018a).

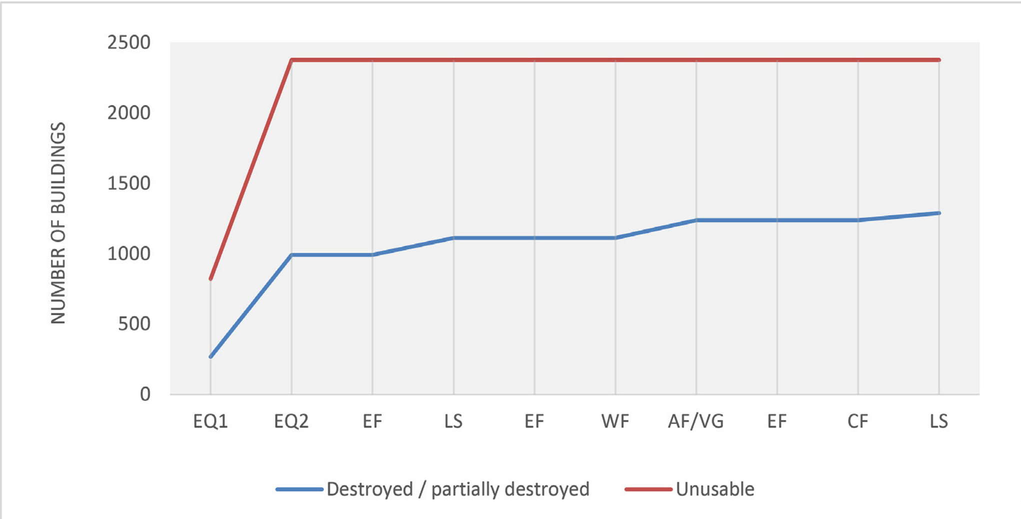
3. Exposure assessment must include the collection of all relevant (georeferenced) information in relation to the vulnerability of buildings considered in the analysis, including their geometric, typological, morphological, construction and performance features. This phase can take advantage of harmonised datasets, which must be promoted in the future, including by benefiting from significant innovations in the field of satellite surveys and big data analytics.

4. Vulnerability analysis represents the crucial step to build a reliable and flexible multi-hazard damage model. Multi-hazard vulnerability assessment for residential buildings must integrate the different characteristics that determine vulnerability to specific hazards, e.g. combining them in multi-hazard vulnerability classes or treating them as dynamic vulnerability in cases of cascading effects (Zuccaro et al., 2018a). Few studies have assessed the vulnerability of buildings in a multi-hazard context (Kappes et al., 2012) and

even fewer the changes in vulnerability due to the dynamic nature of the damaging process (El Moussaoui et al., 2017; Zschau, 2017), mainly because of the limited knowledge of process interactions and the scarcity of observed damage data, and then because of model limitations. However, there is room for improvement, as many of the vulnerability features are common to all hazards (subsection 2.2 above).

5. Risk assessment. Given the diversity of potential impacts of multiple hazards on the exposed elements, a major aspect to consider in multi-risk assessment is the need to develop common damage metrics across the different hazards considered. This allows (1) implementation of risk analyses and indexes able to provide a synthesised view of the hazards affecting a given location, (2) quantification of the expected impacts of single events, to compare the expected losses (Grünthal et al., 2006) from different hazards with the same return period, and (3) calculation of the cumulative damage from cascading effect scenarios on selected elements at risk (Junttila and Zuccaro, 2017), as shown in Figure 3. The output of such analyses enables the identification of DRR/CCA priorities, by means of multi-criteria or cost–benefit analysis tools (Garcia-Aristizabal et al., 2015; Zschau, 2017).

Figure 3. *Cumulative damage on buildings due to a Sub-Plinian eruption in Nea Kameni, Santorini island.* ***Source****: Junttila and Zuccaro (2017).*
Note*: AF, ashfall; CF, failure of the communication network; EF, failure of the energy distribution system; EQ, earthquake; LS, landslide; VG, volcanic gas emission; WF, failure of the water supply system.*



5 Disaster risk prevention

Risk prevention is key to mitigate negative consequences of natural hazards. Building codes that are effectively implemented, incorporate state-of-the-art knowledge and consider the impact of climate change are instrumental to reduce disaster losses. Insurance should be promoted to decrease the economic and social impact of disasters.

5.1 Risk insurance

Risk insurance is a means to transfer risk, provide compensation for damage, incentivise risk reduction measures and shorten recovery time (Mysiak et al., 2017). Insurance schemes for residential buildings have been introduced and redesigned in earthquake-prone countries after major disasters (Ranghieri and Ishiwatari, 2014; Başbuğ-Erkan and Yilmaz, 2015; CCS, n.d.; CEA, n.d.; EQC, n.d.) and similarly for floods (CCR, n.d.; CCS, n.d.; FEMA, n.d.; Flood Re, n.d.). Governments, private insurers and public–private partnerships offer policies that cover damage to buildings and contents, emergency repairs and reconstruction, but their potential for mitigation has not been fully exploited (Kousky, 2019). Insurance is obligatory in certain cases, e.g. for real estate sales and new homeowners in Turkey, and often risk-related premium rates are offered (i.e. depending on the hazard at the location of the building and the type of construction), with discounts for joint policies or for hazard-resistant buildings.

Despite being affordable, insurance is not widely used: the annual premium is 3 ‰ of the insured amount in Tokyo, but fewer than 40 % of households in Japan are insured for earthquake (Ranghieri and Ishiwatari, 2014). The number of policies is higher in areas of higher hazard, and it increases after major events, though many policies are not renewed (Başbuğ-Erkan and Yilmaz, 2015). Nonetheless, risk perception and damage of residential properties after disasters lower market values and increase insurance premiums (e.g. Nakagawa et al., 2009; Beltrán et al., 2018; Ortega and Taspınar, 2018).

Low-income households are less willing to purchase insurance, even after major disasters (Naoi et al., 2012), and affordable public insurance may have the detrimental effect of encouraging further development of risk-prone areas, where premiums would otherwise be very high. Moreover, middle- and high-income households abandon properties in high-risk areas without appropriate or affordable insurance, which are subsequently rented by low-income or otherwise marginalised social groups, leading to social segregation and possibly the creation of ghettos. These processes may be rather quick, and urban planning plays a pivotal role.

5.2 Building codes and standards

Over the years, developed countries have successfully implemented effective regulatory frameworks and codes for the safety of the built environment. In fact, in the last decade they have experienced 47 % of all disasters globally, but have accounted for only 7 % of disaster-related fatalities (UNISDR, 2015b). On the other hand, low- and middle-income countries have not been able to carry out such reforms, and many experience recurring human and economic losses each time a disaster hits (World Bank, 2018). There are valuable lessons that can be adapted to the needs of developing countries (see Box 1).

Risk-informed and affordable standards for the design and construction of buildings, e.g. the Eurocodes (Eurocodes, n.d.), that incorporate state-of-the-art scientific and technical knowledge have proven to be effective and cost-efficient measures to mitigate disasters and build back better after major events. Equally important is a regulatory system that is incrementally improved over time and takes into account the needs of disadvantaged segments of the population (World Bank, 2015, 2018). This is also recognised in Priority 3 of the Sendai framework (UNISDR, 2015a), which encourages the revision and development of building codes, focusing on the local context and the capacity for implementation and enforcement.

Given the long working-life and economic value of buildings, it is essential that they are resilient to the future impacts of changing climate (European Commission, 2013). In this context, adaptation of structural design to climate change is a key aspect to be considered in construction standards, at least for new structures, as intended for the second generation of the Eurocodes.

BOX 1

Building safely to avoid damages

Building codes have contributed to making Japan one of the world's most earthquake-resilient countries, as they were incrementally improved and continually incorporated lessons learned from disaster experiences (World Bank, 2018). Indeed, 97 % of buildings that collapsed during the 1995 Kobe earthquake had been built with old codes, while those that complied with the most updated ones accounted for only 3 % (World Bank, 2015). In 2003 two earthquakes were recorded in Paso Robles (California) and Bam (Iran): the death toll in Paso Robles was 2 as opposed to more than 40 000 in Bam (Kenny, 2009). Similarly, the extent of damage and collapse of buildings during the two 2017 earthquakes in Mexico confirmed that structures built in accordance with anti-seismic codes can better withstand ground-shaking events (Swiss Re, 2018)

6 Conclusions and key messages

Policymakers

Despite the significant scientific advances and the experience gained after past disasters, the application of mitigation measures is still insufficient. The implementation of building codes that incorporate state-of-the-art knowledge and consider the impact of climate change should be promoted by policymakers along with insurance schemes to decrease the economic and social impact of disasters. To this end, it is important also to promote behavioural drivers for individual protection, in order to encourage citizens in the adoption of virtuous behaviours.

Scientists

Models and methods for assessing the impact of natural hazards on residential buildings are conceptually similar but have reached different levels of sophistication. Furthermore, many of the parameters that affect the vulnerability of buildings are common to various hazards. There is therefore an opportunity for scientists to share the fragmented hazard-specific knowledge and for developing methods for multi-risk assessment to increase the efficiency of integrated mitigation actions. Such methods also require the definition of common metrics, spatial and temporal scales, and assessment thresholds across hazards.

Policymakers, practitioners and scientists

The ageing building stock and society's need for resilience – i.e. minimum disruption of activities and services, and speedy recovery after a disaster – call for new technical solutions and policy tools. The lack of harmonised, good-quality data on exposure and observed damage remains a major gap. To improve our capacity to assess and reduce losses, new developments are needed in the use of innovative and disruptive technologies (e.g. satellite and remote sensing, nature-based solutions, machine learning and artificial intelligence) for collecting data, monitoring the condition of assets, and developing dynamic models and tools for real-time decision-making (Zio, 2018; Zuccaro et al., 2018b). In this respect, shared effort by practitioners, scientists and policymakers is welcome.

3.3.2 Agriculture

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1 Introduction

Agriculture is a key socioeconomic sector of the EU, employing about 9.7 million people and with a regular labour force of 20.5 million (many people help on farms without being employed; Eurostat, 2019). Some 10.5 million farms manage 47 % of the total land area of the EU, most of them (96 %) being family farms and 66 % being smaller than 5 ha (Eurostat, 2019). However, 51.6 % of the total EU agricultural economic output is produced by just 2.9 % of farms (classified as agricultural enterprises). Crop and animal production contribute nearly equal shares (56.3 % versus 43.7 %) to the total agricultural economic output (European Commission, 2019). The former mainly comprises vegetables and horticulture, cereals, fruits and wine, while the animal output mainly consists of meat, milk and eggs (European Commission, 2019).

In the EU, 28 % of the population lives in rural areas, with large differences between the Member States (from 0.3 % in Malta to 56 % in Lithuania; Eurostat, 2019). The number of farms has been steadily decreasing in recent years (with estimated losses of up to 4.2 million farms since 2005; Eurostat, 2019); but the amount of land used for agriculture has remained almost unchanged. Land abandonment, however, driven by agroclimatic-environmental and socioeconomic conditions, represents a potential problem for 11 % of the EU's agricultural land (mainly arable, pasture and permanent crops) in the coming decade (Perpiña Castillo et al., 2018). The agriculture sector faces many risks associated with climate variability and extremes, pests and diseases, market volatility, socioeconomic crises and shocks. Unfavourable climate conditions, extreme weather and climate events (such as storms, droughts, floods, frost, heat and cold waves) have severe impacts on agriculture (see for example Lesk et al., 2016; Zampieri et al., 2017; Webber et al., 2018; Chavas et al., 2019), e.g. on crop yield, soil erosion, livestock production and infrastructure.

The frequency and severity of extreme events have increased, and this increase is projected to continue in the coming decades as a result of global warming (see for example Toreti et al., 2013, 2019a; Russo et al., 2014; Alfieri et al., 2015, 2017). Drought as severe as in 2018 and heatwaves as intense as in 2003 could become common occurrences by mid-century (Russo et al., 2014; Toreti et al., 2019a). Extreme precipitation events could intensify by more than 30 % in some areas of Europe (Toreti et al., 2013).

At the same time the world's population is expected to grow to 9.7 billion by 2050 (UN, 2019), increasing agricultural demand and changing nutritional patterns (e.g. Tilman et al., 2011; Davis et al., 2016; FAO, 2017; Gouel and Guimbard, 2019). Therefore, it is essential to study and better understand natural hazards and their impacts on the agriculture sector.

The impacts of climate change, variability and extremes are and will be uneven across regions and countries. Although elevated atmospheric CO_2 concentration and warmer climate conditions during the growing season may bring positive effects (especially in countries in mid-northern latitudes; Ciscar et al., 2018; FAO, 2018), concurrent and recurrent extremes may offset them and induce heavy losses as well as higher interannual variability. The 2018 drought in Europe is an example of such an event (Toreti et al., 2019a). The impacts of extreme events can be amplified (in terms of losses and damages), in particular in production systems that are not ready to cope with them. Examples are systems characterised by low levels of agro-management (Zampieri et al., 2020; Webber et al., 2014); lack of diversification (Lin, 2011); and lack of integration between production of crops, crops and forests (Altieri et al., 2015; Lin, 2011). Optimal and sustainable management practices, technological innovations and effective sectoral adaptation strategies can reduce the impacts of unfavourable climate conditions and extremes. The sensitivity of each crop and region is different, and so are the mitigation and adaptation strategies needed. Farmers represent a key component of the system for identifying and applying optimal solutions. However, there exist different levels of intervention and different actors to be taken into account. Assessing comprehensively the impacts and risks of climate change is a complex and challenging task addressed by various modelling approaches (which differ in tool availability, state of the art, open issues, etc.) involving the agriculture, climate, economic and hydrological sectors. Statistical approaches, crop growth models of varying complexity, economic partial and general equilibrium models, and agent-based models are all used.

The agriculture sector is not only affected by climate and socioeconomic conditions; it also affects the climate system and the environment. About 10 % of the EU's greenhouse gas emissions come from agriculture (EEA, 2019), and unsustainable practices can induce soil, air and water pollution as well as loss of biodiversity and habitat fragmentation (see for example EEA, 2019; Leip et al., 2015).

2 Risks and impacts

Climate extremes occurring locally and in other producing regions of the world, emerging and re-emerging diseases, and socioeconomic crisis and shocks affect agriculture, causing direct and indirect losses and damage.

The agriculture sector is exposed and vulnerable to weather and climate extremes. These events, especially when they occur during critical periods (e.g. around crop anthesis), can lead to severe losses and damages. Several studies have shown, for instance, how heat stress can affect agriculture systems, causing, for instance, yield losses (e.g. Zampieri et al., 2017; Fontana et al., 2015; Rezaei et al., 2015), and dairy and beef cattle mortality (e.g. Polsky et al., 2017; Morignat et al., 2015; Vitali et al., 2015). Drought events also severely affect the entire agriculture sector, triggering crop losses and problems for livestock (e.g. Stahl et al., 2016). Around the world, heat stress and drought have been responsible for 9–10 % reductions in national cereal production (Lesk et al., 2016) and for more than 40 % of wheat yield interannual variability (Zampieri et al., 2017). Heat waves such as those of 2003 in Europe, occurring during the crop-flowering/grain-filling period, have been shown to be associated, for instance, with durum wheat losses in the main Italian production areas, with yield reductions at the province scale reaching – 52 % (Fontana et al., 2015). The 2015 drought event also caused severe impacts on crop production and livestock farming, with, for example, production losses of potatoes reaching – 21 % in Poland and Czechia.

On the other hand, excessive wet conditions, heavy precipitation events and floods can have serious consequences by inducing crop yield and livestock losses, fatalities and injuries, damages to infrastructure and machinery (e.g. Bremond et al., 2013; Klaus et al., 2016; Mäkinen et al., 2018). Flood damage to livestock has been poorly investigated so far (Bremond et al., 2013). The limited available evidence of past events (e.g. Posthumus et al., 2009; Gaviglio et al., 2020) suggests that flood damage to livestock is mainly indirect, as animals' death and injuries can be avoided by livestock evacuation, if early warning is supplied.

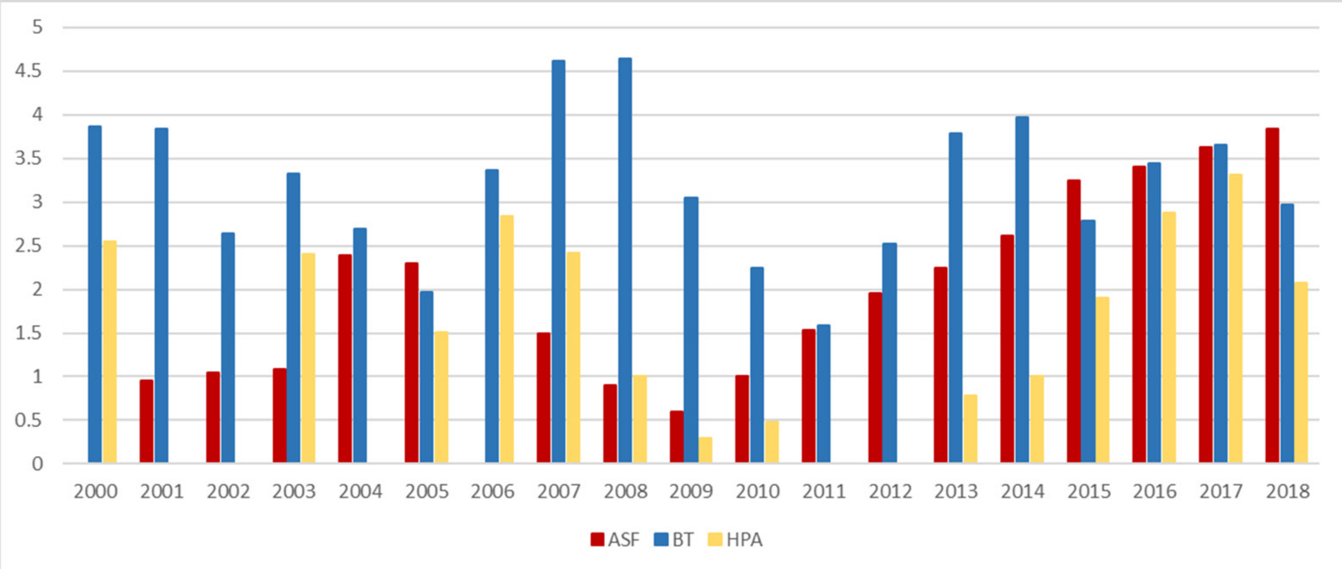
Indirect damage mostly consists in reduction in production quantity (e.g. reduction in milk production) and quality (e.g. reduction in milk quality or meat quality), due to reduction in, or change in quality of, food (due to flooding of crops and stocks); spreading of diseases and infections caused by inappropriate living conditions during the flood or the evacuation phase; and the stress suffered by the animals. Indirect damage is also linked to increased costs for farmers due to additional veterinary treatments, killing of injured or ill animals, carcass disposal and replacement of lost animals. Indirect damage to livestock can manifest even several months after the occurrence of a flood event. In the case of dairy farms, especially, the recovery time can follow the growth of the animals from the birth to the productive time, usually between 2 and 3 years.

A comprehensive assessment of losses and disasters in the entire agricultural sector attributable to weather and climate extremes does not exist, although spot assessments have been performed. This gap clearly has a negative influence on sectoral policies.

The emergence and re-emergence of livestock diseases (Figure 1), despite the better management of endemic ones, are also a serious concern, as they are influenced by evolving socioeconomic factors (e.g. ecosystem changes, agro-management practices, movement of goods, animals and people) as well as climate change (Perry et al., 2013).

Clearly not all risks and impacts are covered by this section. Other risks are, for instance, related to socioeconomic conditions, crises and shocks, e.g. input and output price volatility and spikes, economic well-being and stability, demographic structure, public infrastructure, natural resource dependence, and shocks induced by climate and weather extremes elsewhere (Chatzopoulos et al., 2020; Toreti et al., 2019b).

Figure 1. *Animal disease outbreaks (in logarithmic scale) in the EU, 2000–2018*
Source*: Data from the EU Animal Disease Notification System (European Commission, n.d.-a).*
Note*: ASF, African swine fever; BT, blue tongue; HPA, highly pathogenic avian influenza.*



3 Risk management tools

Several tools and strategies exist to manage the risk to agriculture. Damage prevention and compensation measures, ad hoc emergency aid, direct support, regulation and insurance are all available, although their use and level of implementation are not homogeneous. Farm-level specific management practices should be also better explored and encouraged.

The EU's agricultural policy is mainly driven by the common agricultural policy (CAP), which aims to support farmers, productivity and rural areas, contribute to climate change mitigation objectives, encourage environmental care, and promote sustainable development and growth. The CAP is managed and funded at the EU level and takes action on income support, market and rural development measures. Income support mainly consists of basic direct payments (based on hectares farmed), greening payments (for climate and environmental friendly practices) and young farmers' payments. Market measures are used to deal with threats posed by difficult market situations (e.g. a sudden price drop), while rural measures can be used for specific regional needs and challenges in rural areas.

In general, risk management policies and strategies in agriculture include several alternative/complementary strategies, such as hard engineering, soft engineering, information and awareness campaigns, regulations and the development of risk management tools, e.g. crop insurance, mutual funds and ex post disaster aid. Several of these policies act as a first stage of damage prevention, i.e. they aim to reduce vulnerability in exposed areas and thus limit potential damage. Supporting, for instance, the adoption and use of sectoral decision support systems integrated with targeted climate services (e.g. providing relevant climate information) contributes to significantly reducing vulnerability and increasing preparedness and awareness, thus triggering a positive feedback loop. In the context of climate change adaptation, three categories of measures have been identified (EEA, 2013): grey (relying on technology and engineering), green (based on nature) and soft (influencing human behaviour and governance).

Hard engineering solutions, such as the construction of dykes to prevent flooding, have been commonly used as an obvious way to prevent damages. Yet, despite the historical success of hard engineering solutions in harnessing the potential of the environment for economic growth, there is increasing awareness that they may not be enough to cope with growing risk. For example, water works in closed basins with inelastic supply can increase supply only marginally and at high, often disproportionate, costs, thus reducing the cost-effectiveness of the policy. Hard engineering solutions (and associated policies) may also introduce perverse incentives towards higher exposure that amplify economic damage when natural catastrophes hit. For example, flood protection infrastructures may work as an incentive for economic development in exposed areas, thus increasing the value of the assets at risk and the (economic) damage when flood events with high return periods hit. On the other hand, modernisation of irrigation infrastructure, which increases yield and profit per unit of water withdrawn, can incentivise a higher consumption rate and aggravate water depletion and related environmental problems (Grafton et al., 2018). Finally, budgetary constraints also represent a barrier to the further development of hard engineering solutions. Consequently, the cost of additional hard engineering projects often exceeds the economic benefits, constraining policy-makers to rely on other policy instruments.

Soft engineering solutions, such as rehabilitation of natural water retention measures, aim to integrate anthropic agricultural activities with natural processes and systems to enhance resilience. Under some circumstances, they may offer a low-maintenance and low-cost investment strategy compared with hard engineering (e.g. wetland restoration). However, in some other cases, their cost may be disproportionate (e.g. making room for river in highly populated areas). The EU Water Framework Directive (Directive 2000/60/EC) must be clearly considered in these evaluations. Regulations are also used to prevent risk, although they are often difficult to enforce, resulting in low compliance (e.g. restrictions for the development of new irrigated land in floodplains have often failed; EEA, 2009; OECD, 2008, 2013a; UN, 2014a). In this context, the EU contributes direct payments to stabilise and enhance farm income, and the farmers' commitment to protect natural resources and maintain the land's productive capacity, including on marginal land, prevents the risk of abandonment. In this way, the CAP aims to address a multitude of specific objectives related to the environment, food safety, animal health and welfare, although without focusing on the diverse nature of farming and natural conditions throughout the EU (Renwick et al., 2013). In this context, it is also worth pointing readers to the EU Floods Directive (Directive 2007/60/EC) and the associated ongoing activities.

Information and awareness campaigns generate intangible outcomes that are difficult to identify and quantify (OECD, 2013b; UN, 2014a) but represent an essential tool for soft adaptation (EEA, 2013). Finally, economic instruments (such as charges) can be designed and implemented with the purpose of adapting individual decisions to collectively agreed goals, including the prevention of risky attitudes or the generation of externalities that result in a higher risk for other agents (e.g. damage to valuable natural capital).

Some damages are technically difficult to predict and thus to prevent, or, even if predictable, they may not be economically efficient to prevent (Randall, 1981). This motivates the development of damage compensation policies. Damage compensation is structured around regulatory and economic instruments, notably tort law, insurance and state aid. Tort law is used where a liability is identified, e.g. where a binding regulation is not respected by an agent and this results in damage to a third party; insurance manages acts of nature – events that are no one's fault – through risk-sharing instruments; and state aid involves direct payments to compensate for non-insurable damage, and to enhance insurance uptake through greater affordability, equity and solvency in the provision of insurance policies (e.g. premium subsidisation, public reinsurance). The limits for the implementation of each instrument are often not completely set. For example, states may decide to step in to prevent disproportionate losses arising from insurable agricultural damages. Ad hoc emergency aid that compensates for damage from, for example, droughts is common in the EU Member States (Bielza et al., 2009), and may end up crowding out private insurance. This may be undesirable, as insurance schemes could offer a number of advantages compared with tort law and state aid, e.g. relieving budgetary pressures and not distorting trade, encouraging farm-level strategies to reduce risk and prevent damage, and complementing prevention policies by risk-based pricing. Finally, 'sufficiently insured events are inconsequential in terms of foregone output' (Von Peter et al., 2012). However, barriers and issues to be solved for a widespread crop insurance scheme in the EU have been identified (e.g. Cafiero et al., 2007; De Castro et al., 2011; Santeramo and Ramsey, 2017; Santeramo, 2019).

This has motivated calls for insurance policies that short-circuit the link between damage and losses (OECD, 2014; UN, 2014b). Several types of risks are insurable: yield damages; specific climatic risks (flood insurance, drought insurance, etc.); price (inputs and outputs) volatility; and climate and market risks (e.g. income insurance). The design is also varied, e.g. index-based insurance versus conventional commercial insurance based on observed damage. The conditions under which a specific insurance product is supplied are context-specific, and some insurance products may be more prevalent than others. For example, flood impacts on agriculture have received less attention so far than those on other sectors. Reasons may include the (perceived) minor importance of agricultural losses compared with other sectors, and the paucity of data for understanding damage mechanisms and deriving prediction models (Molinari et al., 2019). Although insurance schemes allow the transfer of damages from the public to the private market, damage mitigation is still the responsibility of private farmers and public authorities. The knowledge of damage mechanisms and of the main factors influencing damage/losses, as well as the possibility of simulating the effects of different risk mitigation strategies, are the key to identifying and prioritising risk mitigation solutions.

Notably, the EU and a few Member States are exploring the implementation of income insurance, a single policy that covers yield and price risks (European Commission, 2011; Meuwissen et al., 2011). The CAP 2014–2020 comprises a community income stabilisation tool 'in the form of financial contributions to mutual funds' (EU, 2013, Article 36(1)(c)), offering compensation of up to 65 % of the indemnities paid, provided that the indemnities compensate for less than 70 % of the forgone income and the income drop is above 30 % of a 3-year average based on the preceding 3 years or the preceding 5 years excluding the highest and lowest annual incomes. However, its development and implementation have been very limited (Cordier and Santeramo, 2019).

Realising the potential of subsidies to enhance insurance uptake and limit farm losses without bringing an excessive burden to the public budget necessitates efficient allocation of resources. Such welfare redistribution demands information on both producers' (insurers') and consumers' (insured's) surpluses (Dupuit, 1844; Marshall, 1879), which makes knowledge of insurance supply and demand necessary in turn (Skees et al., 1997; Martin et al., 2001; Collier et al., 2009; Mahul and Stutley, 2010; Maestro et al., 2013; Pérez-Blanco and Gómez, 2014; Santeramo et al., 2016).

Besides the aforementioned tools and policies, the EU adaptation strategy (European Commission, 2013; European Commission, 2018a; European Commission, 2018b) plays and will play a fundamental role in agricultural risk management. This policy has promoted the development of plans to increase agricultural resilience and better-informed decision support systems. An example of such a sectoral climate-oriented tool is the Italian water for irrigation information system([1]) addressing the needs of more than 12 000 farmers([2]).

At the farm scale, specific management practices can contribute to reducing the risk. As outlined and reviewed by Webber et al. (2014), these measures include, for instance, adapted sowing dates; cultivar and crop selection; reduced tillage; diversification; and integrated weed, pest and disease management. Shifting sowing dates may help to reduce the risks associated with heat stress and drought, especially under warmer climate conditions. Cultivar selection is and will be one of the key adaptation actions to deal with the interplay of climate change and climate variability, while crop selection also depends on other socioeconomic factors, such as consumer demand, market opportunities and support. Diversification of crops and of farms' investments represent an effective measure to stabilise both productivity and income. However, it is important to underline how most of these measures become effective in an integrated and optimised adaptation strategy. Efforts must be made to test combined integrated actions to respond to long-term climate change as well as to near-future changes, in which climate variability also plays a key role.

4 The 2018 drought

Heavy losses were caused by the 2018 drought in central and northern Europe. The shock did not spread, thanks to the favourable conditions in southern Europe. Derogation, advance payment and state aid were used to support the sector. This event highlights the importance of having early warning and local decision support systems and the need to develop better strategies balancing economic, financial, and adaptation multiannual tools.

Spring and summer 2018 saw unprecedented climate conditions in Europe. A combination of concurrent climate anomalies hit large regions of central and northern Europe and made this event exceptional. Extreme spring and summer temperatures associated with dry and very dry conditions were observed. As shown by Toreti et al. (2019a), the 2018 event can be considered unique in the past 500 years. Severe impacts were observed on several key socioeconomic sectors, including agriculture. Production losses were recorded in many EU Member States (Figure 2), with wheat production being the most affected (European Commission, 2018c).

Cereal production dropped remarkably, with several Member States having negative anomalies (estimated with respect to the long-term trend based on Eurostat data) exceeding – 10 % and even reaching – 48 % (Sweden). Heavy losses were also reported in potatoes, rapeseed, turnips and sugar beet. However, thanks to the favourable conditions in southern Europe (Figure 2), the negative effects did not spread throughout Europe and beyond. The effects on market prices are shown in Figure 3. The overall losses caused by this exceptional event are estimated to be around EUR 3.3 billion, of which only around 7 % was insured (Munich Re, 2019). To support Member States and farmers dealing with the extreme drought, three strategies were put in place by the European Commission:

- higher advance payments, with farmers in the affected countries receiving up to 70 % of their direct payments and 85 % of payments under rural development by mid-October 2018;
- derogation from specific greening requirements (crop diversification and ecological focus area on land lying fallow) to allow further production of animal feed;

([1]) See https://www.irriframe.it
([2]) See https://climate-adapt.eea.europa.eu

- further derogations to use winter crops as catch crops, use sown pure crops as catch crops and shorten the defined minimum growing period of catch crops.

Many EU Member States recognised the emergency situation to enable farmers to request state aid as provided for by the CAP. For instance, the German federal and state governments decided on support measures amounting to EUR 340 million to support farmers hit by the extreme weather if they experienced yield losses of more than 30 %. In Poland, the government supported farmers by allowing different ad hoc payment strategies depending on the level of losses (above 70 % or between 30 % and 70 %) and on whether or not the farms were insured (50 % less without insurance).

The 2018 event points to the importance of early warning systems (monitoring and forecasting adverse conditions), associated with local targeted decision support systems to help adopt strategies to reduce negative impacts. It also highlights the need to foster the integration and use of climate services acting on time scales ranging from months to seasons and serving the farm scale. The 2018 drought reveals how developing adaptation strategies should be put in place by looking at both the near future (next 5–10 years) and longer time scales (next few decades) as well as at both the local and regional spatial scales. Adaptation measures (e.g. breeding new varieties, diversifying crops and investments within a farm) can alleviate the impacts of weather and climate extremes; however, they must be complemented with a set of policy and economic tools that balance compensation, insurance and multiannual stabilisation tools better than now, and promote climate-oriented sustainable investments.

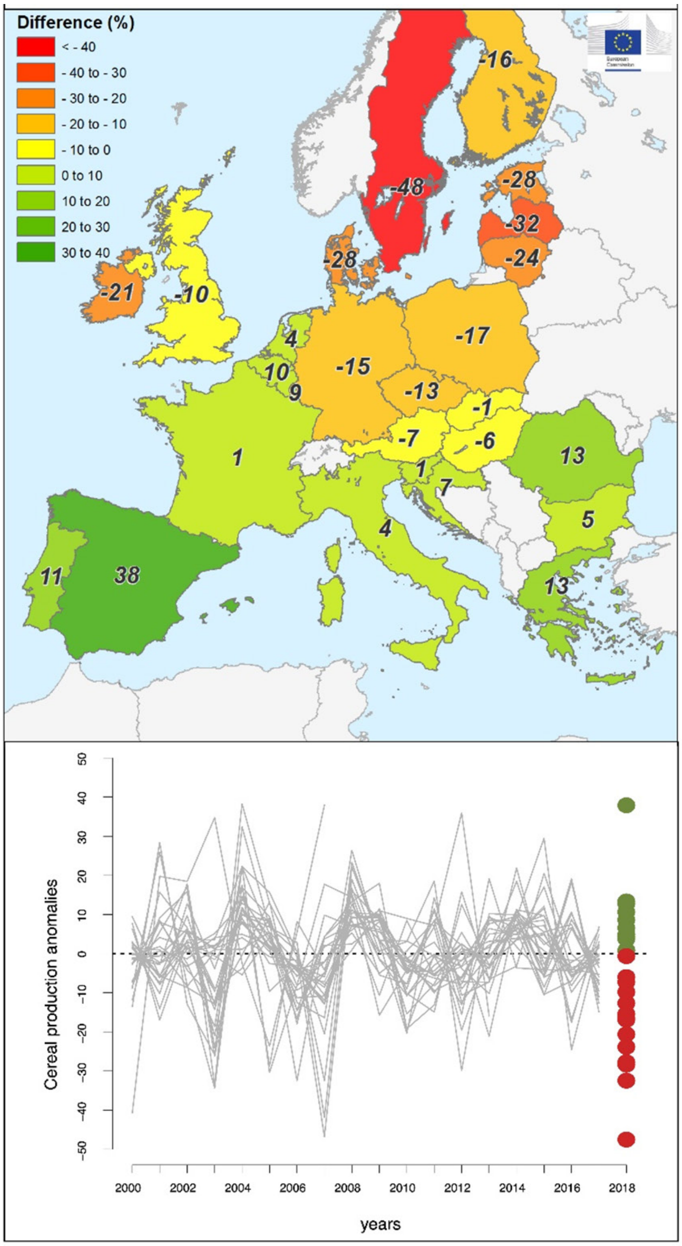
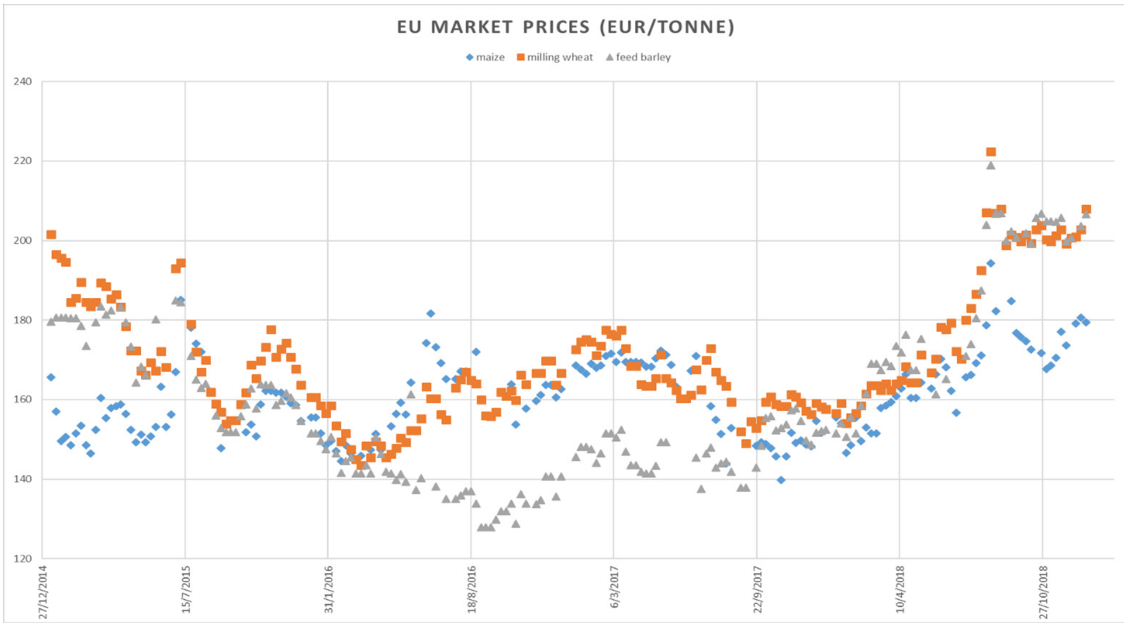


Figure 2. *Cereal production in the EU. Upper panel: estimated cereal production anomalies in 2018 with respect to the long-term trend, estimated by using a locally estimated scatterplot smoothing (LOESS) approach on the reported values from 2000. Lower panel: time series of estimated cereal production anomalies (with respect to the LOESS-based long-term trend) in the Member States from 2000 (grey lines, one per country) and estimated anomalies in 2018 (red and green circles)*
Source*: data from Eurostat, 2019.*

Figure 3. *EU market prices (EUR/tonne) for maize (blue), milling wheat (orange) and feed barley (grey).*
Source: *data from the Cereal Statistics of the Crops market observatory (European Commission, n.d.-b).*
Note: *The prices refer to Rouen (France) for milling wheat and feed barley, and to Bordeaux (France) for maize. The price stage is 'delivered to port'.*



5 Projections for the coming decades

Climate extremes, such as drought, heatwaves and floods, are expected to intensify and occur more often in the future. Concurrent extremes and adverse conditions will bring new challenges for the sector. Adaptation will play a fundamental role.

Climate change projected for the coming decades poses a challenge for European agriculture (e.g. Van Passel et al., 2017; Bozzola et al., 2018; Ciscar et al., 2018; Webber et al., 2018). Despite the beneficial effects of elevated atmospheric CO2 concentrations on some crops (e.g. wheat) and the favourable mean conditions that could be induced in some regions by higher mean temperatures and/or changes in precipitation regimes, the agriculture sector will need to deal with more frequent and more intense extreme events. Extreme drought events, such as the one that occurred in 2018, could become common as soon as 2043 (Toreti et al., 2019a). On the other hand, heavy precipitation events are projected to intensify (Toreti et al., 2013), and in some regions flood events could occur more often, causing higher losses (Hirabayashi et al., 2013, Alfieri et al., 2015, 2017). Heatwaves are also expected to intensity and occur more often, and events like the 2003 one could become common (Russo et al., 2014). Therefore, there is a need to identify optimal risk reduction strategies.

Adaptation will play a fundamental role in this context, as measures such as changes in agromanagement practices (e.g. different crops and/or cultivar) or the use of tailored high-level sectoral climate services can reduce the impact of climate and weather extremes. Better farming systems, efficiently using nutrient resources, improve resilience to climate change and extremes. Depending on the projected changes and the level of global warming, stronger intervention measures (hard/soft engineering) might be needed locally and should be evaluated in terms of costs and benefit. The high degree of connectivity of the global agricultural market and the shocks that concurrent events could induce in different producing regions of the world must also be taken into account in the design of future strategies (e.g. Toreti et al., 2019b; Chatzopoulos et al., 2020). The adoption of new technologies and farmers' behaviour are key factors in assessing the impacts of climate changes and the associated risks. For instance, Koundouri et al. (2006) show that risk preferences affect the probability of adopting new irrigation technologies, and they provide evidence that farmers invest in these new technologies as a way to hedge against input-related production risk. Foudi and Erdlenbruch (2012) showed that French farmers rely on irrigation technology as a self-insurance tool against production risk, particularly the risk of droughts. Di Falco et al. (2014) investigated how financial insurance for extreme events can play an important role in hedging against the implications of climate change.

6 Conclusions and key messages

Climate and weather extremes have severely affected the agriculture sector in recent decades by causing heavy losses and damages. Specific sectoral and policy measures (e.g. within the CAP) have been taken to deal with them, often in terms of damage compensation, while the European adaptation strategy (European Commission, 2013; see also its evaluation, European Commission, 2018) has promoted, boosted and supported the development of national adaptation plans, to increase the resilience of key socioeconomic sectors such as agriculture and fill the knowledge gaps. As weather and climate extremes are projected to intensify and occur more often in the coming decades, more should be done to reduce the risks and the impact of these events. Optimised adaptation strategies acting at different spatial levels are thus needed (EEA, 2019).

At farm scale, for instance, several options can be developed and implemented, e.g. new crops and crop varieties (adapted to the changing local climate), better crop rotation schemes and diversity programmes, improved infrastructures for livestock and disease prevention. Across the spatial scales (applied locally, but enforced and developed at regional, national or EU level), the use of dedicated climate services will play a key role in limiting losses and damages. Hard and soft engineering solutions may also be needed if nothing is done to limit/stop the current rate of global warming. Crop insurance, by spreading risk, could buffer the financial implications of unexpected crop failure following local extreme events; however, broader participation can only be achieved by using targeted tools such as information campaigns (e.g. Santeramo, 2019). More should be done to promote and develop effective mutual funds and income stabilisation tools (Cordier and Santeramo, 2019). Considering the future risks and the rapid changes in the climate system, evolving adaptation strategies that combine several different options and approaches are advisable. The need for dynamic strategies, to be implemented for instance through a periodic revision mechanism, can be understood by considering the uncertainties of climate change projections as well as the role of internal climate variability on a time scale of decades. As also previously pointed out (EEA, 2019), adaptation will not take place effectively without strong engagement of all those involved in the food system (e.g. farmers, farmers' organisations, food producers). Co-design and continuous feedback in the development and implementation phases are key elements of successful adaptation to climate change.

Despite all these efforts, large-scale concurrent and recurrent events may still pose a serious threat. European farmers are and will be influenced by external events occurring in other producing regions, implying higher exposure to price volatility, spikes and market shocks. Preparedness could be achieved by including concurrent extremes in sectoral risk and impact assessments, and then testing the reaction of current trade patterns and market structure to shocks induced by these events. This may allow the development of emergency plans and measures (e.g. involving stocks, temporary changes in trade patterns, etc.) to absorb shocks, at least partially, before they propagate.

Profound changes in dietary patterns, food habits and, thus, consumer demand are usually not fully considered in risk and impact assessments. However, they may play an important role in shaping the future of agriculture and its associated risks and adaptation under changing climate conditions. Interest in novel food (as defined by EU, 2015), including for instance algae- and insect-based products as well as food engineered with nanomaterials, is growing (Caparros Megido et al., 2016; Peters et al., 2016; Menozzi et al., 2017), and public acceptance may change in the coming decades.

Disruptions in agricultural activity may have significant impacts in terms of reduced food and water security and quality, habitat and landscape protection, soil conservation, CO2 sequestration, biodiversity conservation and the economy of rural areas where agriculture is the basis (directly or indirectly) of the livelihood of most families (Pérez-Blanco and Gómez, 2013; Gómez-Limón and Riesgo, 2004; Meuwissen et al., 2003; Quiroga and Iglesias, 2009). These local/regional impacts will have consequences on critical welfare variables (e.g. negatively affecting environmental quality and amplifying income disparities between urban and rural areas). Furthermore, as observed climate trends scale up the magnitude of these disruptions, impacts will start to be felt economy-wide as well, effectively constraining the ability of the economy to create employment and income.

Policymakers

Policymakers should promote and support the implementation and use of optimal adaptation strategies (e.g. sectoral climate services) together with a periodic revision scheme. Tools such as insurance, mutual funds and income stabilisation should be better developed, as an integrated approach balancing all the available measures is needed to deal with current and future challenges. New measures to deal with global market shocks and crises, and system disruption should be discussed and developed. Emergency plans should be designed.

Practitioners

Practitioners should be heavily involved in the design, implementation and test of adaptation strategies. Innovative local risk management tools and decision support systems should be co-developed with scientists.

Scientists

Scientists should develop and test new integrated adaptation strategies and actions. Emerging risks, global shocks and system disruption should be better investigated. Behavioural patterns and changes influencing food consumption and demand should be included in impact and assessment modelling.

Citizens

Citizens should be more engaged through information and awareness campaigns, as well as periodic surveys to follow closely food consumption changes and reaction to novel food. Simplified tools that exemplify the actions taken should be made available.

3.3.3 Industry and energy

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1 Introduction and background

This section focuses on the secondary sector, namely manufacturing and energy industries. These industries produce goods and services that are consumed as final or intermediate goods and services, and that are necessary for activities in a society, while they also employ labour and provide wages to households. Physical damage to these industries not only leads to a shortage of goods and services that they produce, but also causes declines in income to their labour forces. In addition, because of the globalised production networks as well as the lean production system employed in various manufacturing industries, the damage and business interruptions brought about in one region could spread to other regions in the same countries and potentially across the world. Some recent empirical observations, for example the declines in production of car-manufacturing companies at various countries in the aftermath of the 2011 east Japan earthquake and tsunami, proved that the modern manufacturing network appears vulnerable to such catastrophic disasters (Reuters, 2016). In this context, the production networks, such as intra- and interindustry linkages, should be encompassed to understand a comprehensive picture of disaster effects.

In this section, damage to physical facilities, resulting from internal causes or external forces, is called 'damage', while the decline in production level caused by the damage is called '(first-order) losses' of production (Okuyama, 2007). While the terminology used in the United Nations (2016) refers to damage and losses as 'direct economic losses' and 'indirect economic losses' respectively, the use of the words 'direct' and 'indirect' creates some confusion, such as adding these two different measures together, which is theoretically incorrect and potentially leads to the double counting of impacts. In addition, the methodologies to measure higher-order effects use the term 'indirect' with a different definition (Rose, 2004). The most up-to-date Handbook for Disaster Assessment by the Economic Commission for Latin American and the Caribbean (ECLAC, 2014), known as the ECLAC methodology, also employs definitions of damage and loss similar to Rose's. Therefore, in this section, 'damage', 'losses' and 'higher-order effects' are utilised, instead. These two numbers of damage and losses should be clearly distinguished, because adding them together would double-count the impacts, and Rose (2004) suggested listing both of them separately to paint an inclusive picture. A few methodologies are available for the quantification of damage and losses, and their details are discussed below.

2 Risks in industry and energy industries

Manufacturing and energy industries inherently involve risks that can be classified into internal and external, and/or can lead to broader effects on the macroeconomy and the natural environment.

Manufacturing and energy industries inherently involve risks that could lead to accidents that might result in a disaster, or could experience a catastrophic natural hazard, such as earthquake, flooding, severe weather, or drought, that would bring about damage or losses to the production facilities. These risks can be classified into internal (within the industry) and external (from other industries), and/or can lead to broader effects on the macroeconomy and natural environment. For example, internal risks include the malfunctioning of production equipment, software bugs, faulty operation of production systems by humans, financial risks, reputational risks if the company does not address climate change and so on. External risks can be threats of catastrophic natural (and man-made) hazards, which can cause physical damage to production facilities and/or networks, and increased climate variability leading to hazards. Internal risks can be dealt with by technological and behavioural means, while external risks may be responded to by prevention and preparedness, such as a business continuity plan (BCP).

In particular, modern manufacturing and energy industries rely heavily on supply chains (value chains) because of the increasing globalisation of production processes, through which a company purchases parts (intermediate inputs) provided by other companies (upstream industries) for its products and sells its products to other companies (downstream industries) or to consumers as final products. Specifically, upstream industries are mainly mining, material production (chemical, steel, etc.) and energy industries, and downstream industries include product-assembling industries (automobile, electrical and electronic products, etc.) and service industries. In this way, manufacturing and energy industries form complex and interwoven interindustry networks. Given this, one company's stoppage of production due to damage to its production facility resulting from internal or external causes would create a negative ripple effect on a wide range of industries and on the economy, as well as positive opportunities to other companies that can provide substitutable products. The impacts of such an event can be classified into the following five types: (1) production (supply) disruptions due to damage to production facilities; (2) forward effects of the supply disruptions to the downstream industries; (3) technical and/or spatial substitution effects for replaceable goods and services; (4) decline in both intermediate and final demands due to the decreased production and earnings; and (5) backward and positive effects from intensive demand injection of reconstruction activities (Oosterhaven, 2017). It is expected that the interindustry

2.1 Risks within industries

Manufacturing and energy industries inherently involve risks within their operations, and the realisation of such risks may cause damage to their facilities. These risks include faulty design of production processes, malfunction of the production facility and/or equipment, software problems, mismanagement of the company, or other human errors. Each company in these industries tries to minimise these risks using redundancy, backup facilities, periodical maintenance and so on. Because all the production systems, facilities, and equipment are designed and installed by humans, it is inevitable by our nature that they will contain some major or minor errors or drawbacks. While these risks originate internally in the production system in question, the systems are also exposed to external risks. Some natural hazards, for example earthquakes, flooding, severe storms, and drought, can damage or even destroy part or all of the production facilities, creating the similar impacts to the internal risks above. This risk will create production disruptions, as in type 1, and would trigger a ripple effect on the economy and society as described above.

2.2 Risks among industries

Modern manufacturing and energy industries require a set of intermediate inputs for producing their products, creating interwoven interindustry linkages. For example, car manufacturers require thousands of intermediate inputs, such as tyres, glass, seats, plastic materials, paints, electrical parts, electronic circuits and, water, from their suppliers. Even though a car-manufacturing company did not have any physical damage to its production facility, it would eventually halt or delay its operations if one of the suppliers that produces critical intermediate input were damaged and could not supply its products. This type of cascading impact on an undamaged company is called 'higher-order effects' (Rose, 2004), which can potentially produce the ripple effect of impacts through interindustry linkages (supply chains) to many other industries, described as types 2, 3, and 4 above.

This ripple effect would propagate not only to the downstream industries through the supply chain but also to the upstream industries. If one company (A) needs to pause its production because of severe damage to one of its critical suppliers (B), this is called the impact on downstream industry. Meanwhile, another company (C), which provides its product as an intermediate input to B, will need to decrease its production because B cannot produce its product therefore does not need intermediate inputs from C. This is an upstream propagation of the impact. Moreover, company A uses other intermediate inputs from another company (D) as well as from B. When company A halts production as a result of damage to B, it influences the production of company D, since A also stops purchasing D's product. This is also an upstream propagation of impact. Company A's production stoppage can also potentially lead to a downstream propagation of the impacts, if other companies purchase company A's product as their intermediate inputs. The ripple effect of impacts spreads through the web of supply chains that modern manufacturing industries have formulated and utilised. Some industries, such as car manufacturing and construction, require a wide range of intermediate inputs; if even a small supplier that provides a critical input to major companies is damaged by a disaster, it can create extensive ripple effects on many other industries.

Higher-order effects are quite entangled and complex to measure empirically by using usual macroeconomic indices, such as changes in gross domestic product, due to other macroeconomic disturbances and so on. Therefore, the quantification of higher-order effects requires economic models, such as input–output (IO), computable general equilibrium (CGE) or econometric models. Some of these models are briefly discussed below.

2.3 Effects on macroeconomy and environment

Since the higher-order effects can propagate across a broad range of industries, there is a concern that a catastrophic disaster, such as the 2005 Hurricane Katrina in the United States and the 2011 east Japan earthquake and tsunami, could affect negatively the regional or national economy. While a disaster caused by internal or external risk to manufacturing or energy industry would lead to localised damage and losses and could spread the higher-order effects further to other industries elsewhere, the economic impact of such a disaster, even a catastrophic one, may not affect the national economy of developed countries negatively in both the short and longer terms (Albala-Bertrand, 2007). This is because developed countries should have sufficient financial, technological, and other resources to better manage disaster risk through the implementation of countermeasures against the adverse impacts of disasters. In other words, if they did not prepare thoroughly against such events, there would be substantial and long-lasting negative effects in and around the country, such as after the 1986 Chernobyl nuclear accident and the 2011 Fukushima nuclear accident.

The timing of a disaster occurrence could influence the overall impact of a disaster in a macroeconomic context. When economies exhibit higher growth during a boom period, they may be more vulnerable to disasters than those with slower or declining growth in a bust period. This is because during a bust period idle and unused production capacity can serve to absorb the production shortage induced by the disaster, whereas during a boom period production capacity in economies is fully utilised and hence cannot deal with the production shortage (Hallegatte and Ghil, 2008). Having an inventory of intermediate inputs and final products can also serve as a buffer against the forward (downstream) effect of supply shortage, whereas modern manufacturing industry has been exercising the lean production system, under which it minimises or eliminates such inventories, embedding increased vulnerability to the forward effects. However, many manufacturing companies consider that such risk would last for a short period so they maintain the lean production system, even after experiencing prolonged production stoppage due to forward effects created by a catastrophic disaster (Reuters, 2016).

It is a somewhat common misconception that disasters might cause renewal or update of assets and facilities, leading to upward macroeconomic trends in the long term, which is sometimes referred to as the Schumpeterian creative destruction or fertilisation effect. Empirical investigations of the relationship between disasters and economic growth/trends indicate otherwise (Okuyama, 2019). The studies using socioeconomic disaster indicators, such as those by Noy (2009), Cavallo et al. (2013), and Fomby et al. (2013), provide somewhat mixed results for such a relationship, whereas the studies employing physical intensity indicators of disasters, for example those of Hsiang and Jina (2014), Felbermayr and Gröshcl (2014), and Berlemann and Wenzel (2016), found clear negative effects between them. Hallegatte and Dumas (2009) analysed this relationship that damage caused by hazards and subsequent reconstruction with renewed assets only increase production levels but cannot lead to overall technological progress, therefore they may not boost long-term economic growth.

Some industries, especially upstream industries (mining and energy industries), characteristically contain risks with the potential to trigger environmental damage due to their use of hazardous resources and materials. Some accident in such a company, with a natural or human cause, may result in a leakage of hazardous materials into the surrounding area, which contaminates the natural environment of the area. This may lead to an environmental disaster, such as the Exxon Valdez oil spill in 1989 in Alaska, the United States. While downstream industries (assembling products) also hold the similar risks to a lesser degree, they are not immune to causing environmental damage by fire in factories and/or inventory facilities, leading to temporary air pollution from the burning of their intermediate and final products.

3 Risks from climate change

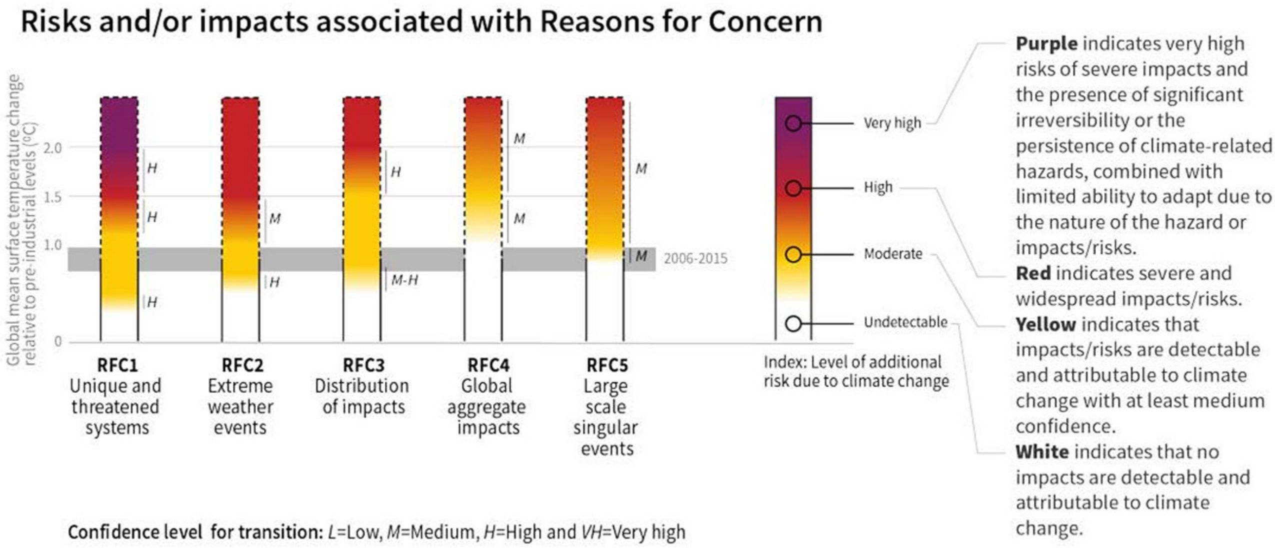
Uncertainties related to climate change risks (e.g. time of occurrence and level of increase in risk) prevent industry from organising optimal (timely and measured) and proactive preparedness.

Climate change is expected to increase both the frequency of occurrence and the magnitude of natural hazards, and this will increase the risks (exposure and consequences) to manufacturing and energy industries. The similarity of these hazards to already existing threats (i.e. extreme weather events) makes it easier for the industry to assess, prepare for and mitigate the risks. However, the uncertainties related to the issues, such as the time of occurrence and level of increase in the risk, prevent industry from organising optimal (timely and measured) proactive preparedness.

Premature and/or excessive adaptation presents risk itself. Additional uncertainty is related to regional impacts. A special report from the Intergovernmental Panel on Climate Change (IPCC) analyses the risks from various climate change scenarios between 2 °C and 1.5 °C warming above pre-industrial levels and related global greenhouse gas emission pathways (Hoegh-Guldberg et al., 2018). That report estimates the impacts and risks as high from extreme weather events, and moderate from large-scale singular events at 1.5 °C warming, with a moderate level of confidence, as shown in Figure 1.

However, the estimates of coastal flooding risk are very high, with a high level of confidence. The following two subsections discuss industry and government actions related to climate change risk assessment, adaptation and mitigation measures.

Figure 1. *Estimated impacts and risks from different levels of global warming associated with reasons for concern (RFCs)*
Source*: Figure 3.21 in Hoegh-Guldberg et al., 2018.*



3.1 Climate change risk management for the manufacturing and energy industries

The manufacturing and energy industries have been facing climate change risks to their market ratings and regulation requirements. Dealing with these risks is essential because the government regulations, financial market, and insurance companies force and/or expect them to implement timely reactions to such risks.

Goldstein et al. (2018) reviewed more than 16 000 corporate adaptation strategies and significant blind spots found in the assessments of climate change impacts and their management. CDP (2019) summarises the following findings from the companies reporting about climate change risks and opportunities: significant risks are identified as needing expanded analysis; the largest companies report major financial implications; the risks are smaller than the opportunities; some striking regional differences exist; many industries expect to experience fewer implications than the financial industry; management costs outweigh the benefits; the energy industry is a source of lessons to be learned because of early and wide-ranging impacts.

Industry could prepare better for climate change risks by incorporating its assessment into an overall risk management (RM) strategy. Continuous updating with the best available data and methodology is necessary for tackling all the related uncertainties.

3.2 Governance for reduction of climate change risk

Regulators and investors had already motivated the industry to transition towards a sustainable and low-carbon economy, even before climate-change-related risks were considered transitional risks and became highly publicised. All these various governance measures are imperative because they are designed to prepare for increased climate change risks in a socially optimal way. However, there are ongoing debates about what regulations should be imposed and which best practices should be encouraged. Considering the extensive uncertainties related to climate change risks, finding the best approaches is a daunting task. In this context, research and development to reduce uncertainties, and to improve risk assessment for efficient industry applications and effective regulations, are indispensable to tackle the climate change risks. Without the knowledge and insights from the best available sciences, all those involved would be more likely to underestimate or overestimate the future climate change risks. Either way, this would result in significant waste of resources.

4 Estimation methods

It is imperative to understand what assessment models/methods can or cannot cover based on their assumptions.

As argued in the 2017 report (Poljanšek et al., 2017), more consistent and systematically gathered data for the damage and losses to manufacturing and energy industries, and other industries, are needed for assessing the impacts of events. While the OECD governance of critical risks initiative has compiled the data([1]) for the policies, processes and practices through which OECD Member countries govern critical risks, the data for damage and losses, as well as higher-order effects, have not been collected consistently or systematically. Because the definitions of damage and loss in a disaster situation, such as the spatial and temporal extent and the valuation methodology, have not been set, nor is there any consensus among stakeholders (Okuyama, 2007), it is a good idea to start with the definitions proposed in the widely used ECLAC assessment methodology (UN ECLAC, 2014), which has been employed to assess damage and losses in recent major disaster cases in developing countries. Terminology used in this subsection – damage, losses and higher-order effects – follows the definitions in the introduction above.

4.1 Assessment of damage

In the ECLAC methodology, damage is defined as the effects that a disaster has on the assets of each industry, expressed in monetary terms. The assets here include physical assets such as buildings, machinery, equipment, furnishing, roads and ports, land, and inventory of final goods and intermediate inputs. Two pieces of information are required to evaluate damage: the level of destruction of each asset and their monetary value (UN ECLAC, 2014). While the ECLAC methodology uses the replacement cost of damaged assets for the conversion from physical quantity to monetary value, it becomes occasionally problematic, especially in a disaster situation (Rose, 2004). When a machine is partly damaged in a disaster, it does not have to be replaced but can be repaired; in this case, the cost should be the repair cost. In addition, even in a case of replacing the damaged equipment, it would not be replaced with the same machine; rather, newer equipment can be installed to replace the damaged old one. In this case, the replacement cost (the cost of new equipment) is not equal to the value of the

([1]) See https://qdd.oecd.org/subject.aspx?Subject=GOV_RISK

old one before the disaster. In an extreme case, if a company's factory were damaged by a disaster and it went bankrupt, there would be no replacement cost. Information on estimated damage is indispensable for industries to evaluate their preparedness and mitigation measures and to respond to the damage. Recent increased data collection capabilities and advanced information and communication technologies in many developed countries make it possible to estimate property damage immediately after a natural hazard hit. One such method has been proposed by Heatwole and Rose (2013); it can estimate property damage, including the damage to land, livestock, buildings, equipment, etc., from major US earthquakes based on a regression model. This model consists of 'exposure-related predictors', such as population, income, and land area of hazard-affected region, and 'hazard-related predictors', such as earthquake magnitude, distance from epicentre and so forth, to derive a set of property damage estimates (lower bound, average, and upper bound) in monetary value. While this model is only for earthquakes in the United States, this framework can be applied to other types of hazard and to other countries. This type of method can be useful to assess the damage that a natural hazard has caused and to assist timely disaster response and recovery activities.

4.2 Assessment of losses

Production or business interruptions caused by damage to production facilities lead to declines in production flows of goods and services. Losses are defined as goods and services that go unproduced during a period running from the time the hazard occurs until full recovery of the damaged assets is achieved.

By and large, different methods have been employed for the estimation of business interruption costs. The popular approaches are (1) applying an industry-specific reference value per unit affected or per day of interruption to estimate the production losses; (2) comparing production output between years with and without hazard; and (3) calculating production losses as a proportion of damaged production capital (Meyer et al., 2013). Furthermore, loss estimates can be obtained by fitting statistical models to available historical data (e.g. originating from the insurance industry) (Hogg and Klugman, 1984) by using methods such as parametric curve fitting based on extreme value theory, and generalised Pareto distribution due to the heavy-tailed and skewed nature of the data (McNeil, 1997; Jindrová and Pacáková, 2016). It is cautioned, however, that the hypothetical baseline (without disaster) case must be projected from the best information available, in order to avoid losses being over- or underestimated (UN ECLAC, 2014). Losses here are sometimes called first-order losses, to distinguish them clearly from higher-order effects, discussed below.

Like the frameworks to estimate damage discussed above, a few models have been proposed to estimate losses from hazard intensity index and socioeconomic data that are readily available. One such model is the estimation model for 'production capacity loss rate' by Kajitani and Tatano (2014).

Conventional approaches to production loss estimate require damage data on production facilities and equipment, whereas this model evaluates the production capacity loss rate through functional fragility curves and lifeline resilience factors. While their methodology is tailored to earthquakes and Japanese cases, the framework can be applied to other types of hazards and to other countries where similar data are available. One of the advantages in this methodology is that, once the ground motions of a particular earthquake are given, the estimated changes in the production capacity rate can be derived in the damaged area. This type of rapid assessment method for evaluating production loss is advantageous to timely decision-making in industry for managing response and recovery strategies as well as analysing the higher-order effects.

4.3 Assessment of higher-order effects [2]

As discussed in the introduction, the first-order losses stemming from the business disruptions caused by the damage to production facilities set off a chain reaction, or ripple effect, through interindustry linkages (supply chains). For instance, if a power station were damaged by an accident, electric power would not be available to some or all of the power grids that the power station covered, and manufacturing industries in the affected power grids would have to halt their production until power was restored, even if they were not damaged at all. Moreover, due to the lost production of those industries without power, the suppliers to and the customers of those industries would need to either decrease or pause their production, too. How the ripples of such effect spread across other industries in economies is rather complex, because of intertwined supply chains across industries and over space and even across countries.

In order to assess such higher-order effects of a disaster, one needs to use economic models, such as input-output (IO), computable general equilibrium (CGE), econometric, non-linear optimisation or some other macroeconomic models. These models are highly sophisticated and need some lengthy descriptions. In short, IO models highlight interindustry transactions to derive ripple effects from changes in demand to one or more industries, while CGE models simulate changes in demand and/or supply in various markets to replicate how an economy responds (or economies respond) to a shock. Econometric models are regression models based on historical data about an economy. Readers interested in this topic are encouraged to consult the relevant literature, such as Rose (2004), Okuyama (2007), Okuyama and Santos (2014) and Okuyama and Rose (2019). While these models have been popular and employed for numerous recent cases, they are not without criticisms (e.g. Albala-Bertrand, 2013). Because economic models are representations of specific aspects of the real world, they intrinsically neglect some other aspects, such as psychological impacts on the labour force. It is imperative to understand what assessment models/methods can or cannot cover. At the same time, there are also considerable ambiguities in the estimates, especially for higher-order effects from the cascading impacts, due to uncertainties in a disaster situation that might be amplified by these methods. Further studies on this topic are essential, given the importance of unbiased estimates of the economic impacts (Girgin et al., 2019).

5 Countermeasures against risks

Prevention, preparedness, mitigation, response and recovery measures are the most common countermeasure strategies.

In order to avoid an incident becoming a disaster, strategies for dealing with existing and emerging risks are necessary. These strategies, also known as countermeasures against risks, include prevention, preparedness, mitigation, and recovery measures. Particularly in manufacturing and energy industries, their production activities establish a complex system, which covers production, logistics networks, and budget constraints, and this complexity and the internal and external risks that they face burden their management decisions about how to formulate and implement countermeasures. For example, a company's production process relies heavily on the use of electric power, which is produced by a power company. If the power company could not produce and/or transmit power, causing a blackout, this company's production would be suspended as a higher-order effect of the power shutdown. If the accident were caused internally within the power company, the loss of revenue of

[2] The 2017 report (Disaster Risk Management Knowledge Centre, 2017) discussed the methodologies assessing higher-order effects ('indirect economic damage') to some extent, such as simultaneous equation econometric models, input–output models, and computable general equilibrium models. The issues with these models raised in the 2017 report, for example dynamic adjustment features such as recovery, resilience, interregional substitution, inventory adjustments, and changes in labour supply, have been dealt with by the recent models. In particular, Okuyama and Rose (2019) provide state-of-the-art modelling practices and examples of the recent advances.

this company could be contractually divided between the two companies and potentially compensated for by the power company. On the other hand, if the accident were caused by an external source, such as a natural hazard, it would often be out of the scope of contractual matters. As one of the preparedness measures, this company would want to install backup generators for such a case; however, the cost of generators and fuels is added to the production cost (the larger the backup generators become, the more they cost the company), whereas the occurrence of such blackouts is quite infrequent.

The countermeasure strategies against risks try not only to avoid an incident becoming a disaster but also to limit the impacts of such an event once it occurs. Usually, prevention, preparedness, and mitigation measures are identified during the pre-disaster phase, and the response and recovery measures are set up in the post-disaster phase. Measures to reduce or limit the impact of a risk are not arranged in isolation but are put in place along with strategic medium- and long-term plans, and always within the enterprise-wide RM, i.e. the overall management of the risks that organisations take, to make decisions about how to formulate and implement countermeasures and how to achieve their strategic objectives.

5.1 Risk management

Risk management is a 'combination of organisational systems, processes and procedures that identify, assess, evaluate and mitigate risks in order to protect the organisation, its strategies and objectives (Martínez Torre-Enciso, 2007). An effective RM system plays a significant role in reducing exposure to potentially unfavourable events. Many organisations follow RM frameworks([3]) and models for enterprise risk management (ERM), business continuity (BC), disaster management (DM) or crisis and emergency management (CEM), among others. Each of these models establishes its own processes and procedures; however, in certain respects they overlap regarding the identification and evaluation of risks and the control and financing of both the risks and the measures established to limit their effects. Moreover, these overlaps among different strategies (ERM, BC, DM, CEM) are allowed in many cases – and especially in regard to operational risks, which are the most important in manufacturing and energy industries – in order to obtain important synergies (Laye and Martinez Torre-Enciso, 2001). For example, a company that aims to develop ERM and BC plans should carry out the identification, assessment and evaluation of risks for both. If the same team deals with ERM and BC plans, significant savings in personnel costs and time are achieved, as processes will only be carried out once.

The Committee of Sponsoring Organisations of the Treadway Commission (COSO) ERM model and other risk management frameworks, such as International Organization for Standardization (ISO) 31.000, develop comprehensive identification, assessment and evaluation of risks through risk mapping, matrix, etc.(ISO, 2018). Once risks are determined by the company's risk tolerance levels, the ERM model and frameworks allow it to decide how the risks are treated: control, finance and transfer them. If the risk has been identified, there are several ways to deal with it, including acceptance, transference, and mitigation. To transfer the risk, the company may purchase insurance or outsource the activity to a third party. Mitigating the risk might mean that it is reduced in some way. By applying these processes, it is possible to reduce the inherent risk until only residual risk remains. ERM not only calls for corporations to identify all risks they face, so that they can decide which risks to manage actively, which helps companies in the complex decision-making process on establishing countermeasures against risks; it also involves making that plan of action available to all stakeholders, shareholders and potential investors, as part of their annual reports (e.g. figure 2).

([3]) Around the world, a number of risk management standards have been published in order to guide the application of risk management. These standards include (but are not limited to) Enterprise risk management – Integrated framework (Committee of Sponsoring Organisations of the Treadway Commission [COSO]–USA, 2017); ISO 31000:2009 Risk management – Principles and guidelines (International Organization for Standardization, 2009); BS 6079-3:2000 Project management – Guide to the management of business related project risk (British Standards Institute, 2000); King IV report on governance (Institute of Directors in Southern Africa, 2016).

Figure 2. *Enterprise risk management process* ***Source****: © COSO, 2017.*

For manufacturing and energy industries, these risks may entail consideration of supply chain delays/ disruption, third-party vendors, information technology (IT), staffing and succession planning, emerging markets, and productivity and quality issues, among others. Controls can be directed to all exposures to risk (hazard, operational, strategic and financial) and can be achieved by implementing policies, standards, procedures and physical changes to a workplace. For example, when there is an identified risk of fire, organisations may employ physical control measures such as good housekeeping, fireproof materials, sprinkler systems or a no-smoking policy. For security risks, control measures may include physical barriers and locks. For IT breaches, there are measures such as firewalls, increasing password complexity or moving to two-factor authentication. For fraud risks, control measures could include background checks on staff members, segregation of incompatible duties or implementing system security to limit access.

5.2 Business continuity management

Each company has a number of critical business functions that must not be interrupted and, if they are, must be recovered as quickly and at the lowest possible cost. For such situations, companies develop BC plans whose countermeasures against risks are planned in the pre-disaster phase, but have their full development in the post-disaster phases. Business continuity management (BCM) is a 'holistic management process that is used to ensure that operations continue and that products and services are delivered at predefined levels, that brands and value-creating activities are protected, and that the reputations and interests of key stakeholders are safeguarded whenever disruptive incidents occur' (ISO, 2012).

Implementing the business continuity plan (BCP) of a company can help sort out this complex decision-making and can direct it to establish sufficient countermeasures against risks as a result. A BCP is a 'document that describes how a firm intends to continue carrying out critical business processes in the event of disasters (American Bar Association, 2011: page 1). BC planning is also the process of creating systems of prevention and recovery to deal with a disaster situation (Elliott et al., 1999). It consists of three stages: (1) risk assessment, including 'risk evaluation' and 'business impact analysis'; (2) developing and documenting BCP, including 'develop recovery strategy' and 'document plan'; and (3) testing, approving, and implementing BCP, including 'test plan', 'approve and implement plan', and 'maintain plan' (AIG, 2013: Page 3). BC planning appears closer to preparation for how to recover from and/or respond during a disaster (including impact from higher-order effects); however, business impact analysis at the first stage can highlight weakness in production processes that are vulnerable to disaster scenarios. Therefore, constructing and implementing a BCP is not only critical for minimising the impacts during recovery from a disaster but also imperative for determining prevention, preparedness and mitigation strategies before such a disaster occur'

Two notes on BCP components (Martínez Torre-Enciso and Casares, 2011) are worth discussing here. Crisis and disaster situations usually result in the loss or temporary disruption of one or more of the following necessary key business resources: facilities, infrastructure, IT applications/systems, people and supply chain. Developing a correct and deep business impact analysis is a key element for a BCP's success, as it identifies the impact of a sudden loss of business functions, and evaluates which are the core and critical business activities that must not be disrupted. On other hand, some people think a disaster recovery plan is the same as a BCP, but a disaster recovery plan focuses mainly on restoring IT infrastructure and operations after a crisis. It is actually just one part of a complete BCP, as a BCP looks at the continuity of the entire organisation. In this way, BCP documentation may include (1) a disaster recovery plan, including the loss prevention and control measures and the emergency plan; (2) a crisis management plan; and (3) contingency plans.

Manufacturing and energy industries need to have strategic plans in place to ensure that disruptions are avoided in the areas of staffing, supplies and machinery; the aim is to recover plant operations. They focus their BCPs on recovery strategies and mitigation measures, given the difficulty in finding continuity solutions. On the one hand, setting aside alternative sites for them is usually avoided because of the costs involved. In the absence of alternative production sites, there are few recovery strategies available to manufacturers. When custom construction equipment and assembly lines used cannot be easily replaced, recovery options available are (1) slowing down when they feel the impact, by using inventory/buffer storage; (2) selective recovery of production lines; and (3) ensuring that the recovery/repair operations are performed quickly. Alternatively, if some equipment in their production lines is similar to that of their suppliers, manufacturers that assemble semi-finished products may try to resume limited production capacities at their suppliers' premises.

On the other hand, the ability of having redundancies of production process as a backup for efficiency is a key objective for manufacturers, and mitigation strategies are often prioritised. Those measures should focus on either preventing or limiting the impact of a disruption, taking into account the production of goods or energy. For instance, if there is a fire, the sprinkler system might be activated as a whole, and could damage production equipment that were otherwise unaffected by the fire. This can be avoided through the use of localised sprinkler discharges so that each sprinkler needs to be independently activated, or the use of a dry delivery sprinkler system so that, upon activation, fluids are directed to only the discharge point.

Healy and Malhotra (2009) studied public spending on disaster relief measures and countermeasures, and found that every USD 1 spent on preparedness saves the equivalent of USD 15 on relief measures for all future disasters. While their study concerns only government spending and its consequences, this tendency for pre-disaster preparedness to be less costly than post-disaster recovery applies to the private sector, especially the manufacturing and energy industries, considering the amount and extent of the higher-order effects on a society. At the same time, as discussed above, because the lean production system inherently comprises the risk of supply chain disruptions, careful preparation in the BCP for alternative suppliers or supply chain, instead of having and/or increasing inventory, should be seriously considered.

6 Case studies

The impacts related to industries and energy production systems are not limited to direct physical damage, but also include business interruptions and cascading events hazardous to human life and the environment. This is especially the case for the aftermath of natural disasters that affect multiple industries at once.

6.1 The 2013 floods of the Danube and Elbe rivers in Germany

The June 2013 flood was the severest large-scale flood in Germany for the last six decades for which a hydrological flood severity had been estimated (Merz et al., 2014). In May 2013, rainfall above the long-term average in many parts of central Europe caused severe flooding. In that month, 178 % of the long-term monthly precipitation fell across the whole of Germany. The flood began after some areas of Germany experienced a total of over 400 mm of rain within a few days. While there was only moderate flooding in the south-west of Germany, the authorities in parts of southern Bavaria and Austria declared a full-scale emergency.

In Upper Bavaria, some areas had to be evacuated after embankments were breached. Eastern Germany, such as the states of Saxony, Saxony-Anhalt and Thuringia, was also severely affected, and some rivers flooded towns and villages, causing damage to houses and vehicles and forcing the evacuation of almost 100 000 people (Munich Re, 2014) (Figure 3).

The floods caused damage to a railway bridge, and the important high-speed rail connection between Berlin and the western part of Germany was cut off for several months (Schulte in den Bäumen et al., 2015). Manufacturing companies were severely affected: Krones, a global market leader in manufacturing bottling machines, shut down production in two plants in Upper Bavaria, because its workers were unable to commute to work on inundated roads. Volkswagen in Zwickau had to stop its vehicle production, since its suppliers were unable to deliver the parts in time owing to the damage to the transport infrastructure (Wenkel, 2013). Thieken et al. (2013) interviewed 557 flood-affected companies in order to investigate impacts on economic activities.

Of those companies, 88 % answered that they were affected by 'interruption of operations' by flooding, followed by 'building and/or equipment damage' and 'turnover losses'. Manufacturing companies reported more frequently than other industries that 'their own delivery problems' and 'delivery problems by suppliers' affected their operations. Because manufacturing companies rely heavily on supply chains for intermediate inputs (parts and products), also known as vertical specialisation, once any transportation links and/or nodes are disrupted, suppliers cannot reach their customers to deliver their products. This leads to business interruptions to the downstream companies/industries, propagating higher-order impacts.

The economic cost of the flooding was estimated at EUR 10 billion in Germany alone (EUR 11.7 billion in the entire affected area), while the insured amount was EUR 1.8 billion in Germany (Munich Re, 2014). These numbers are estimates of damage, not losses, nor do they include higher-order effects over the surrounding regions. For a more comprehensive and broader assessment of the socioeconomic impacts of river floods, Alferi et al. (2016) proposed an integrated framework to estimate the economic damage and population affected by river floods at a continental scale, in which pan-European river flow simulations are linked with a high-resolution impact assessment framework.

Figure 3. *Wust-Fischbeck (Saxony-Anhalt) submerged by the river flood in June 2013.*
Photographer: *Jens Wolf. © European Union, 2020*

They applied this framework to the 2013 central Europe floods and derived aggregated estimates of (direct) damage in Czechia, Germany, and Austria amounting to EUR 10.9 billion and 360 000 people affected by this event. Their framework focuses mainly on simulating physical events (floods) and assessing physical damage, but not losses or higher-order effects. Nevertheless, this framework is quite useful to simulate events and monitor floods in severe weather conditions. For a more comprehensive evaluation of the event, especially covering a larger area, the losses and higher-order effects of the event need to be evaluated.

Employing a multi-regional IO model of Germany (including the 16 Länder of Germany and the rest of the world, with 41 types of industry) to simulate the supply chain disruptions, Schulte in den Bäumen et al. (2015) estimated that the higher-order effects of this event in Germany, which affected not only the motor vehicle and food industries in Germany but also foreign production, amounted to EUR 6.2 billion. The higher-order effects on regions and industries outside the flooded areas were around EUR 400 million. Their estimates suggest that losses of production in the damaged Länder were EUR 3.1 billion in Bavaria, EUR 750 million in Saxony, EUR 423 million in Saxony-Anhalt, EUR 398 million in Brandenburg and EUR 394 million in Thüringen. Outside the damaged Länder, it is estimated that other economies suffered production losses (higher-order effects) through supply-chain interruptions: for example, EUR 171 million in North Rhine-Westphalia, EUR 151 million in Lower Saxony, EUR 80.2 million in Baden-Württemberg and EUR 42.2 million in Hessen. In addition, economies outside Germany lost EUR 33.8 million in forgone production as the higher-order effects through supply-chain interruptions. The industries in Bavaria most severely affected by production losses were estimated to be real estate services (EUR 218 million), transport equipment production (EUR 181 million), 'other business services' (EUR 154 million) and motor vehicle production (EUR 80.2 million). On the other hand, the industries suffering the largest higher-order effects were motor vehicle production in Baden-Württemberg (EUR 85.7 million), and food industries in North Rhine-Westphalia (EUR 84.3 million) and Lower Saxony (EUR 34 million). As their results suggest, the impacts (higher-order effects) of the event spread geographically and across industries, especially among manufacturing industries, through interindustry supply chain networks.

As the globalised production system and the integrated economy, such as in EU Member States and regions, expand, it is essential to consider and evaluate the economic values not only of damage and losses but also of higher-order effects, which are becoming more extensive and crucial than before. As discussed in the previous subsections, standardising the definition and establishing the extent of higher-order effects are essential for implementing effective strategies and countermeasures to minimise such broad impacts. At the same time, because of the interconnected production systems of these industries, cooperative measures among related firms and with the public sector need to be promoted on a wider geographical scale.

6.2 Industrial accidents triggered by natural hazards

The impacts of natural catastrophes on the industries and energy production systems are not limited to direct physical damage and business interruption, but may also involve cascading events hazardous to human life and the environment, such as fires, explosions, and toxic or radioactive spills. Such cascading events may amplify the overall economic loss with further physical damage, injuries, fatalities, medium- or long-term health problems, environmental damage, loss of ecosystem services, business interruption, public unrest and social costs. These consequences can be quite substantial, and cost even more than the damage directly caused by the natural hazard. For example, the earthquakes of 5 March 1987 in Ecuador (Ms 6.9) caused the destruction of more than 40 km of the Trans-Ecuadorian Oil Pipeline in massive landslides triggered by the seismic activity. Approximately 100 000 barrels of oil spilled into the environment and the loss of revenue during the 5 months required for repair was USD 800 million, equal to 80 % of the total earthquake losses (NRC, 1991). Furthermore, if persistent or radioactive hazardous materials are also involved, environmental clean-up and restoration activities may require an exceptionally long time and enormous resources, as seen at the Fukushima nuclear power plant accident caused by the 2011 east Japan earthquake and tsunami.

Known as natural-hazard-triggered technological (natech) accidents, such cascading events are a recurring feature in many natural disasters, which affect industries and energy systems that store, handle, or transport hazardous substances. One noteworthy example in Europe is the 17 August 1999 Kocaeli earthquake (Mw 7.4), which resulted in many natech accidents with significant economic and environmental consequences. The earthquake, which was one of the most devastating natural disasters in the modern history of Turkey, caused about 17 500 fatalities, injured about 44 000 people, affected 15 million people and resulted in property damage totalling over USD 15 billion.

The affected area is one of the industrial heartlands of the country and is densely populated and heavily industrialised, accounting for 35 % of the gross national product (Özmen, 2000; Durukal and Erdik, 2008). The earthquake caused significant damage at numerous industrial facilities (Johnson et al., 2000; Rahnama and Morrow, 2000; Suzuki, 2002; Sezen and Whittaker, 2006; Durukal and Erdik, 2008), which led to many natech accidents ranging from small hazardous substance releases to enormous fires (Steinberg et al., 2001; Steinberg and Cruz, 2004). Among these events, two were especially noteworthy owing to their consequences: the huge fire at the Tüpraş İzmit Refinery in Korfez, Kocaeli, and the acrylonitrile spill at the Aksa acrylic fibre production plant in Ciftlikkoy, Yalova (Girgin, 2011).

Founded in 1961, the Tüpraş İzmit Refinery had 40 % of the refining capacity in Turkey and was one of the most advanced refineries in the Mediterranean region (Tüpraş, 2010). The fire at the refinery lasted for 5 days and could only be extinguished with international support (Danış and Görgün, 2005).

The Aksa plant, which was constructed in 1971 with a capacity of 5 000 tons per year, had a production capacity of 230 000 tons per year in 1999. Currently, it is the only acrylic fibre producer in Turkey and it is also the largest in the world, with a global market share of 18 % and an annual production capacity of 315 000 tons (Aksa, 2019). The spill of 6 500 tons of acrylonitrile, a highly flammable, toxic and carcinogenic substance, harmed domestic animals, affected agricultural activities, endangered public health and resulted in environmental pollution that required 5 years of continuous treatment for reclamation (Bayer, 1999; Zanbak, 2008).

Both events required the evacuation of the nearby settlements and hampered earthquake search and rescue operations. There were also considerable economic losses. In the case of the Tüpraş İzmit Refinery, the majority of the units were put back into operation within 3 months after the earthquake, but it required 1 year for all units to be functional. The total cost of restoration, including the oil spill cleanup, was about USD 58 million. However, the refinery also lost roughly 6 months of its crude oil processing capacity (4.6 million tons) during this period as operational losses (Girgin, 2011).

The Tüpraş and Aksa incidents showed that preparedness for large external events, considering the extraordinary and highly resource-limited conditions they cause, is critical to prevent and reduce the impacts on industries and energy production systems. Existing risk should be assessed taking into account temporal change due to factors such as climate change and ageing of the equipment; structural (e.g. strengthening of buildings) and organisational (e.g. training of personnel) measures should be implemented properly; and response and recovery plans should be prepared, periodically reviewed and practised. Sharing of information and involvement of public and other stakeholders in decision-making process are also crucial to limit consequences and increase resilience.

As for the lessons learned from the past natech incidents, analysis of historical incident data for selected industries shows that, although natech accidents occur less frequently than accidents from other causes, their economic consequences are more severe (Girgin and Krausmann, 2016). In fact, owing to synergistic and cascading effects among natural and technological hazards, natech accidents may result in complex consequences involving numerous hazardous events over large areas, damaging safety systems and barriers, and destroying lifelines needed for emergency management purposes. Therefore, it is essential to quantify the losses not only considering the direct damage, but also considering the cascading impacts. This can be challenging even for a single facility; hence, dealing with multiple facilities and mutual dependencies is a difficult task.

The main economic damage potential is attributable to fires and explosions, as they cause direct physical property damage. However, depending on the market dynamics, serious losses may also occur through business interruption even if the property damage is relatively minor. Occasionally, even the proximity of a hazard without any direct impact may lead to losses. For example, wildfires in British Columbia, Canada, in 2017 led the operators to temporarily shut down natural gas wells, pipelines and other facilities as a precautionary measure where wildfires came dangerously close to operations, leading to costly business interruptions (Marsh, 2018). The industry can transfer these risks to third parties using financial tools, such as insurance that covers the losses related to natural hazard impacts or business interruptions. But the coverage is usually limited and varies with estimated risk and existing RM practices (Olson and Wu, 2010). Safety expenditures are often not self-financing for low-probability high-impact risks such as natech risk. Therefore, in order to fill the existing gaps, some legislative or financial support might be necessary from the public authorities for the required prevention and mitigation measures (Girgin et al., 2019).

7 Conclusions and key messages

Disaster risks that manufacturing and energy industries face are rather wide-ranging. They can potentially trigger a disaster from internal causes, such as an industrial accident leading to air or water pollution, while they are also threatened by external risks, such as natural hazards and/or other companies' and/or industries' accidents. Furthermore, in some cases these industries can exacerbate disaster processes, resulting in natech events as discussed in the case studies above. Internal risks can be mostly treated through management strategies and technological means, whereas external risks are often difficult to predict. Integrating RM and BCM with their business operations can potentially reduce and/or mitigate risks, but it is still difficult and costly to prepare practically for infrequent but catastrophic events and their consequences. This type of event should be dealt with and prepared for by the public sector, i.e. various levels of government, through several means, such as regulations, subsidies, taxation, and so forth.

Some risk transfer mechanisms, for instance disaster insurance, should be considered together with RM and BCM. In the EU, disaster finance has been increasingly linked with insurance regulations (Botzen, 2013), climate change adaptation strategies (van Renssen, 2013) and a joint compensation scheme between Member States (Hochrainer et al., 2010). For developing such insurance mechanisms and joint compensation schemes for future disaster situations, detailed information on the probabilities of natural hazard occurrence and estimates of potential damage are essential (Jongman et al., 2014).

Because manufacturing and energy industries are a vital part of economies and because of the intersections of broad production factors (resources, intermediate inputs, labour, land, and money) across industries and over space, the implementation of RM and BCM requires a multidisciplinary perspective, involving engineers, management, finance, economists, and environmentalists. Since the higher-order effects could spread over an entire economic system in different ways, and in case environmental damage also results, it is vital to define, and potentially legislate about, to what extent these companies should be responsible in a disaster situation.

Policymakers

Policymakers should legislate and implement the countermeasures against disaster risks that these industries face both in the pre-event phase (regulations for handling hazardous material, pre-arrangement of compensation schemes, mandatory insurance, mandatory RM and BCM, etc.) and in the post-event phase (disaster relief, macroeconomic stabilisation, evacuation strategy, etc.), based on the findings and insights from scientific findings of disaster research.

Practitioners

Practitioners of risk management should support the efforts of these industries to install and maintain RM and BCM in each firm, encourage and help drills in the pre-event phase, and assist the operation of RM and BCM in .the post-event phase

Scientists

Scientists should work together in a multidisciplinary way to understand and anticipate the risks in these industries and provide perspectives and/or devise countermeasures that mitigate the risks and the consequences. More importantly, these four groups of stakeholders should work together to achieve the creation of a sustainable society and economy.

Citizens

Citizens need to be aware of the risks that these industries face and their impacts on society, and to understand how they can be affected both as workers (supply side) and as consumers (demand side).

In conclusion, each stakeholder has the following roles for dealing with the disaster risks that manufacturing and energy industries face.

More importantly, these four groups of stakeholders should work together to achieve the creation of a sustainable society and economy.

Conclusions

Every year, natural and human-made hazards cause sizeable damage and losses, the exact magnitude of which we do not know. Improving our understanding of the economic impacts of various hazard risks is fundamental for sound and evidence-based disaster risk management. This subchapter has reviewed the state-of-the-art knowledge, methodologies and practice of assessing damage and losses caused to residential building stock, agriculture, and industrial and energy assets.

Hazard risks are stochastic processes, which often are not stationary but respond to environmental changes, including climate change. Hazard manifestations of similar intensity and magnitude may result in different damage and losses, depending on circumstantial factors. The vulnerability and susceptibility to harm are also time-dependent, changing and evolving as our societies transform in demography, wealth, cohesion and use of technology.

Over the past few decades, disaster risk assessment has improved thanks to the advancements in high-performance computing, high-resolution topographic and other spatial data, a new generation of large-scale hazard and disaster loss/impact models, and high-resolution exposure datasets. An accurate spatial representation of exposure features such as residential and industrial facilities and assets, infrastructure, population density and gross domestic product make it possible to improve the estimates and spatial distribution of disaster impacts. Advanced quality and accessibility of Earth observation products, including from the EU's Copernicus programme, have led the way to coherent exposure and vulnerability data at continental and global scales.

Models and methods for assessing the economic damage to physical assets caused by various hazards are similar and rely on some relationship between the intensity of hazards – measured for example as floodwater depth, macro-seismic intensity, wave height or near-surface wind speed – and the vulnerability or fragility of the physical assets that is determined by their material and structural conditions (Huizinga et al., 2017; De Moel and Aerts, 2011). While the parameters of physical fragility are similar across the various hazards, their responses to various hazard intensities are different and need further study. The damage models typically rely on a monotonic function linking hazard intensity to damage in material and financial terms.

Recent analysis of a large empirical dataset of flood losses has revealed that this monotonic form may not always apply, and a beta function with bimodal distributions for different water depths may better explain the observed losses (Wing et al., 2020). Moreover, most damage models and studies fail to account for the functional interdependencies between various buildings, lifelines and transport infrastructure.

Models and methods used to assess the hazards' impacts on crop and livestock production have to deal with more complex and articulated relationships between hazard intensity and impact. The fragility of crops to extreme weather and climate-related events may not be constant over the various phenological phases. The damage revealed at the time of harvest reflects the cumulative impacts of various climate extremes and biological plagues suffered over the whole season, mediated by crop resilience and agronomic risk mitigation. Better computation and storage capacity have made it possible to advance coupled climate models and simulate climate extremes with higher temporal and spatial resolution. Still, some damaging local-scale extreme atmospheric phenomena such as frost and hail cannot be measured or simulated at a resolution that would be necessary for detailed damage assessment.

Assessment of damage and losses to industrial and energy production build upon and combine the approaches to address damage to physical assets, losses due to business interruption and systematic losses caused by the propagation of the initial impacts through a web of interconnected supply and transportation chains. The financial impacts consist of value of capital lost, recovery costs and opportunity costs. These impacts may set off supply and demand shocks that affect regional economies in and beyond the disaster-affected areas. The direct damage to tangible productive assets is equivalent to indirect economic losses caused by disruption of production webs, measured by flows.

The COVID-19 pandemic has taught a lesson about how closely environmental and human health are connected. What we have lived through during the lockdown, and still will, is a mild foretaste of the systemic shocks that climate and global environmental changes may and will cause in the future. Future improvements of risk assessment need to be focused on a better understanding of indirect and spillover economic losses generated by slow-onset hazards, compound risks and cascading risks, as well as losses caused by disruption of social networks, economic flows and ecosystem services. The EU Green Deal and the unprecedented post-COVID-19 recovery package will stimulate immense investments in green technologies and innovation, and lead the way to sustainable development and climate neutrality. Only with sound, evidence-based and multi-hazard risk assessments can we reconcile short-term 'building back better' recovery and medium- to long-term climate-resilient development.

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Conclusions

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