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Identifying emerging risks for environmental policies

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Contents

Figures and Tables

Images

Page 3: Cascade Butterfly Project 4. Mount Rainier National Park. Kevin Bacher, Flickr 2012, CC BY 2.0. https://creativecommons.org/licenses/by/2.0/
Page 4: Dry Riverbed: Evidence of the severity of a drought in Kenya. Flickr/Shever 2006. CC BY 2.0.
Page 6: Rainbow pollution: oil film on water. Flickr/gambier20 2007 CC BY 2.0
Page 11: Melting Glacier in a Global Warming Environment. IStock © Bernhard_Staehli, 2015.
Page 16: Slow Down Highway Warning Sign in Construction Zone. IStock © catnap72, 2011.

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Introduction

Identifying emerging risks for environmental policies

Butterflies can be sensitive indicators of climate changes because temperature influences the timing of an individual's life cycle and the geographic distribution of species.

We are living in a time of rapid and extensive global change. Driven by human development, the surface of the Earth is changing rapidly, along with its climate and ecosystems. In this rapidly changing world, risks are present in multiple systems and on multiple scales, from ongoing changes (such as those occurring in the climate), to more sudden-onset risks, such as mutating microbial pathogens or chemical pollutants.

While identifying, predicting and monitoring known risks is vitally important, perhaps the bigger challenge is anticipating the threats to the environment — and to human health via the environment — that are not yet observable.

This poses unique challenges to policymakers and their advisors: how can we better anticipate environmental changes? How can more, or more accurate, knowledge be obtained to prevent risks from becoming disasters? How can decisions best be made in the face of uncertainty? How can we make sure early warnings are not only received, but acted upon? And, what tools and governance systems are needed to make this happen?

This Future Brief will explore these questions, discussing some of the tools and approaches that can be used to identify emerging risk. These include strategic foresight tools, scanning of the internet for information, citizen science and state-of-the-art monitoring technologies.

Finally, the brief will discuss the policy implications of these new approaches, with reference to some of the strategies that are currently employed to search for emerging risks.

1. What is an early warning system?

Some of the first definitions of early warning systems come from the literature on natural disasters; however, the concept can be applied much more broadly. An **early warning system (EWS)** can be defined as

> "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss" (UNISDR, 2007).

In the environmental context, EWS have the potential to detect a wide range of risks. These can include rapid onset risks, such as floods, oil spills and chemical accidents, as well as slower, cumulative changes. The latter may give, in their early stages, little indication of danger, but over time cause crises — such as climate change, deforestation, loss of biodiversity and deteriorating water quality.

The basic idea of an EWS is simple: the earlier and more accurately a risk is predicted, the more likely it is that negative impacts can be mitigated. When properly integrated with communication and action plans, tools, technologies and methods for early warning can empower governments and organisations to take action to protect the environment.

EWS operate through a series of steps, beginning with the identification of the risk and ideally ending with an effective response. UNEP identifies four key elements: risk knowledge, monitoring and predicting, disseminating information, and response. While this provides a valuable blueprint for effective EWS in theory, often one or more of these elements is lacking in the real world (UNEP, 2012).

Indeed, there are several challenges to the design of an EWS. There is a trade-off between rapidity — as quick a response as possible — and accuracy, as more time allows the collection of a greater number of observations. Furthermore, all predictions will necessarily be characterised by some degree of uncertainty. This means flawed decisions can be taken: false negatives, when no warning is issued and necessary action is not taken; or false positives, when a warning is provided when it was unnecessary. Although the latter can result in unnecessary expense, historical evidence suggests they are scarce (and less impactful) compared with false negatives (European Environment Agency, 2013a).

So far EWS, such as river gauging networks, remote sensors (i.e. satellite platforms) and hydrological models, have principally been used to monitor and forecast hydro-meteorological hazards (Paron *et al.*, 2014) and have saved millions of lives in doing so (World Meteorological Organization, 2015). However, because of the fast rate of environmental change, looking forward they will need to respond to new challenges and detect presently unforeseen risks.

In Europe, work is underway to gather knowledge about some of these new environmental risks. The European Commission (EC) supports a series of environmental monitoring programmes, surveying a steadily increasing number of environmental pollutants in our ecosystems, the shortage of food and water supplies, changes in the climate, and natural disasters and hazards, to improve detection of emerging environmental issues (European Commission, 2015a).

2. What are emerging risks?

Before measuring or managing a risk, it first needs to be defined. Additionally, in order to evaluate risks consistently, it is important to be clear about the kind and importance of the risk being targeted.

Risk assessment can become biased by, among other things, the effect of the 'availability heuristic' (Kahneman, 2011). That is, if a risk can be easily remembered or imagined, it seems to be more important than alternative risks that are not as easily remembered or imagined. How to identify, measure and manage the risks that cannot be so easily understood is becoming increasingly important.

Emerging risks are, generally, those that have a high degree of uncertainty regarding the probability of occurrence and the amount of potential loss or harm.

Despite the increasing popularity of the term, there is no single accepted definition of emerging risk. Possible definitions include: a newly created risk; newly identified risk; increasing risk; or a risk becoming widely known or established (Flage and Aven, 2015).

The study of emerging risks has become increasingly important in both in the academic literature and in professional contexts, notably in insurance, where an emerging risk (such as a shock to the global economic system), is discussed in terms of organisational impact; and in medicine, where it can be used to describe new risk factors for disease (Flage and Aven, 2015). It has also begun to be used by European organisations, such as the European Food Safety Authority (EFSA, 2015).

BOX 1.

Some definitions of emerging risk

"A new manifestation of risk, of a type which has never before been experienced" (Locklear, 2011)

"The likelihood of a new material causing harm in a manner that is not apparent, assessable or manageable based on current approaches to risk assessment and management" (Maynard, 2011)

"The likelihood of loss, i.e. the probability of a certain consequence to occur in specific time and space under specified or insufficiently specified conditions" (Aven and Vinnem, 2007)

"A risk resulting from a newly identified hazard to which a significant exposure may occur, or from an unexpected new or increased significant exposure and/or susceptibility to a known hazard" (EFSA, 2007)

"A risk that is new, or a familiar risk that becomes apparent in new or unfamiliar conditions" (International Risk Governance Council, 2010)

Emerging risks can also be categorised by their 'knowability'. Credited to an approach used by NASA to plan space missions, risks can be split into four categories: known knowns, known unknowns, unknown knowns, and unknown unknowns (see Table 1).

TABLE 1: The NASA approach to risk categorisation

	KNOWNS	UNKNOWNS
KNOWN	*Things we are aware of and understand*	*Things we are aware of but do not understand*
UNKNOWN	*Things we understand but are not aware of*	*Things we are neither aware of nor understand*

Adapted from a speech by Donald Rumsfeld, Press Conference at NATO Headquarters, Brussels, Belgium, June 6, 2002 http://www.nato.int/docu/speech/2002/s020606g.htm

'Known unknowns' can result from phenomena which are recognised, but poorly understood (UK Government Office for Science (GOfS), 2012) – risks we know exist but do not fully understand and cannot accurately predict. Much scientific enquiry is based on investigating this type of risk. Regarding the environment, examples could include air pollution, land degradation and biodiversity loss.

But absence of evidence is not the same as the evidence of absence. Risks can also arise from entirely unknown hazards, which cannot be expected because there has been no prior experience or theoretical basis for expecting the phenomena. These can be thought of as 'unknown unknowns' — risks we do not even know exist yet. By their rare and speculative nature, and their potential to cause impacts beyond everyday experience, these types of risk are extremely difficult to identify (UK GOfS, 2012). If undetected, and high-impact, these risks can lead to catastrophic outcomes.

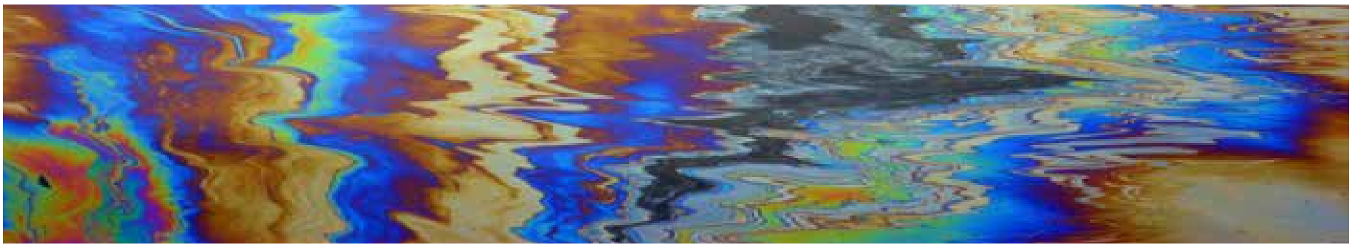
The concept of an unknown unknown has become widely adopted in risk assessment, both in science and policy (Logan, 2009; Pawson, Wong and Owen, 2011). There are several examples of its use in the environmental science literature, where the term 'unknown unknown' has been used to describe events, contaminants or processes that, if undetected, could lead to catastrophic outcomes for nature (Carpenter, Bennett and Peterson, 2006; Filella, Williams and Belzille, 2009; Sumpter and Johnson, 2008; Wintle *et al.*, 2010). Unknown unknowns have been discussed in the context of environmental monitoring, where non-targeted approaches are used to provide genuinely new ecological insights. These have sometimes greater benefits than learning more about known problems (Wintle *et al.*, 2010). The idea has also been used to represent possible futures for ecosystem services, as in the Millennium Ecosystem Assessment scenarios (Carpenter, Bennett and Peterson, 2006).

An 'unknown unknown' risk, which results in an extremely high-impact event, has been termed a 'black swan': an unpredictable incident that can destabilise an entire system. Such risks seldom occur; examples might be the Indian Ocean tsunami or the September 11 attacks in 2001 (Nafday, 2011). The term 'black swan' developed as a metaphor for an impossibility that is contradicted by new information, and has since been developed to describe unexpected events of large magnitude and consequence. Such events can only be rationalised retrospectively (Ploetz *et al.*, 2013). A number of these can be found in the recent past, where actions have been taken with unforeseen consequences for future generations, e.g. the development of the Internet. Environmentally, several twentieth-century innovations were successful in their original intended use, but later led to unintended and extremely harmful consequences (such as asbestos and lung disease, and CFCs and ozone depletion).

The Intergovernmental Panel on Climate Change (IPCC) refers to similar risks as 'low-probability, high-impact' events. In the context of the IPCC, they are rapid responses of the climate system to human pressure, and include changes to the carbon cycle and rapid glacier loss. For example, it has been suggested that the large-scale thermohaline circulation in the North Atlantic Sea could suddenly collapse. Although a weakening of the thermohaline circulation is more likely, a collapse cannot be ruled out, and could have major consequences across northwest Europe (IPCC, 2015; Rahmstorf, 2006).

As well as being defined by different sectors, emerging risks can be categorised by source, which may help when talking about unknown unknowns. The International Risk Governance Council (IRGC), a think tank in Switzerland, specifies three separate categories of emerging risk:

1. risks with uncertain impacts, with uncertainty resulting from new products or technologies, such as nanotechnology or synthetic biology;
2. risks with systemic impacts, stemming from complex interconnected systems which may interact with other types of risk, such as energy, transportation and information technology; and
3. risks with unexpected impacts, where new risks emerge from the use of established technologies in evolving environments or contexts.



3. Tools and approaches to identify emerging risks

Although there are some genuine black-swan-type events, which we cannot predict, most issues will be preceded by some form of signal. There are a range of tools and approaches, brought together in various EWS, which can be used to detect these signals, so that policymakers can act to minimise the damage from environmental change.

These EWS can be based on technology, such as ecotoxicological methods to detect contamination, or based on pattern identification, such as observations of the rate of ecosystem change. Other approaches include those based on community participation and citizen science, utilising citizens' knowledge and monitoring capabilities to detect change in the environment, and online media monitoring, which involves scanning the internet for warning signals.

3.1 Early warning signals from foresight approaches

Foresight approaches use analysis and creativity to provide advanced warning of environmental change. Using a foresight 'tool' involves gathering information about possibilities, and can help to anticipate future challenges and identify mitigation strategies (Leigh, 2003). Famously used by Shell Oil to anticipate the impact of rising oil prices in the 1970s, they are increasingly used by governments to identify emerging issues in many policy areas (Cook *et al.*, 2014). The UK Government uses multiple foresight approaches to address complex issues (UK GOfS, 2013). They are also used at an early stage in the EC's policy cycle (European Commission, 2015b) and the Joint Research Centre uses the approach to identify societal challenges that may emerge in the coming five to 30 years (Joint Research Centre, 2015).

The two most commonly used tools for this purpose are horizon scanning and scenario planning (Cook *et al.*, 2014). Horizon scanning involves collecting and organising a wide range of information to identify emerging issues. It can be split into six stages: scoping the issue; gathering information; spotting signals; watching trends; making sense of the future; and agreeing the response (Sutherland and Woodroof, 2009). Horizon scanning can be exploratory (generating hypotheses and seeking unknown unknowns) or issue-focused (focused on previously identified issues) and forms the basis of other foresight processes, which can analyse the signals it reveals. A notable example of its use in environmental policy is in the 2013–15 work plan of the review panel of the Ramsar Convention, an international treaty for the conservation and sustainable utilisation of wetlands (Sutherland *et al.*, 2015). Within the 'Strategic, emerging and ongoing issues' theme, the Ramsar Convention panel utilised horizon scanning to review relevant emerging issues that may require action in the near- or medium-term future (Ramsar Convention Secretariat, 2015).

Horizon scanning is also used to produce an annual list of global conservation issues (emerging risks that may have substantial effects on global biodiversity, but are not yet widely recognised or understood), in a project initiated in 2010 by the Cambridge Conservation Initiative in the UK. Every year, it brings together a global team of horizon scanners, subject specialists and academics to identify the most pressing threats (Cambridge Conservation Initiative, 2015). Topics identified by this scanning process have generated policy responses in a number of cases. The 2011 scan, for example, identified nitrogen trifluoride as a new and potent greenhouse gas. Two years later, it was added to the World Resources Institute Greenhouse Gas Protocol (World Resources Institute, 2013) as the seventh gas for which emissions should be reported. The most recent scan (in 2015) identified a novel class of insecticides, legalisation of recreational drugs and the emergence of a new ecosystem associated with ice retreat in the Antarctic as emerging issues (Sutherland *et al.*, 2015).

In complement to horizon scanning, which tends to be more focused, scenario planning is a broader method of envisaging possible alternative futures. Scenario planning may be particularly useful for anticipating black swan-type events, because it is not constrained by historical precedent. It instead relies on creative thinking to develop visions of possible future paths. Its tools help risk assessors develop their imagination to consider low-probability risks, and expand their mental boundaries and heuristics to overcome the brain's blind spot for 'unknown unknowns' (Brotherton, R. 2015; UK GOfS, 2012).

Scenario planning can be qualitative (e.g. narrative stories about how the future may look), quantitative (e.g. empirical models and simulations), or a combination of both. Furthermore, its participatory approach, often including diverse stakeholders, means it can capture the social, political and economic dimensions of a problem, which perhaps expert analysis alone might not. This, alongside its versatility, makes scenario planning a useful tool for complex environmental problems (Cook *et al.*, 2014).

The IPCC uses scenario planning to develop its climate change scenarios, which, in turn, inform models of climate impact. Scenario planning was also employed by the Millennium Ecosystem Assessment to identify actions that could improve the condition of the world's ecosystems. More recently, the Intergovernmental Science—Policy Platform on Biodiversity and Ecosystem Services (IPBES) has proposed to develop scenarios of how global drivers of change will influence natural systems (Cook *et al.*, 2014). Other environmental applications of scenario planning include sustainable land use, water and forest management (Cook *et al.*, 2014).

The effectiveness of these different foresight approaches can help to guide long-term planning for environmental decisions and — importantly — detect emerging risks. Emerging risks are inevitably not well documented, which makes them difficult to detect using techniques that rely on conventional approaches and publicly available information. However, by using a combination of analysis and trend identification and imaginative projections, their detection is sometimes possible (demonstrated by the global conservation issues lists).

3.2 Early warning signals from technology

Technology can strengthen the scientific basis for EWS, by collecting the data used in foresight approaches. Monitoring technologies, for example, play a vital role in identifying emerging risks by surveying the environment for indicators of change. According to the UNISDR (2006), systematic monitoring services are essential to detect (and issue) warnings for a range of risks.

Technologies, such as Doppler weather radars and telemetry systems to transmit meteorological data, are used to provide early warnings of tornadoes, flash floods and severe storms (UN, 1997). Monitoring and feedback technologies are also an essential component of the International Early Warning Programme, developed in the wake of the 2004 Indian Ocean tsunami (UNISDR, 2006). More broadly speaking, environmental sampling of air, soil and water is essential to assess the potential risk of harmful effects caused by human activities.

There are many forms of monitoring technology that can help to detect environmental change. A particularly well-established technology used for early warning is satellite, which monitor the earth for signals of known geological and hydro-meteorological hazards, such as floods and tsunamis. There are currently 10 satellites orbiting the Earth whose sole purpose is to monitor rainfall, which have significance in monitoring long-term trends and are crucial for global flood management (Reed *et al.*, 2015).

A more novel use of satellite data is to monitor marine parameters, such as phytoplankton concentrations, to provide early warning of algal blooms, which can be toxic to marine life and human health, and could indicate more unknown, high-impact changes, like ecosystem collapse. The US Environmental Protection Agency is developing a satellite-based EWS to detect algal blooms, and EU project ASIMUTH (http://www.asimuth.eu/) has developed a similar warning system to detect blooms off Europe's Atlantic coast.

A range of technologies are available to detect early warning signals of change in the quality of surface waters. The aquatic environment has been negatively affected by almost all human activities (European Environment Agency, 2015). Industry, transport, agriculture and urbanisation have polluted water with nutrients, metals, minerals, oil and a huge range of synthetic chemicals, many of which are harmful to the environment. Recent statistics show that, between 2004 and 2013, almost half (42%) of the total production of chemicals represented environmentally harmful compounds (Eurostat, 2015, see Table 2). However, production volume is only one measure of toxicity, and cannot fully represent the risk posed by some more recently produced chemicals which have a higher specific toxicity (i.e. hazard per unit weight).

Methods of monitoring water pollution include analytical chemistry techniques, such as chromatography and mass spectrometry; toxicological tests which study pollution via the growth, death, reproduction and/or other response of indicator species; and DNA-based methods, which aim to understand the effects of pollutants at the molecular level (Bae and Park, 2014; Gavrilescu *et al.*, 2015; Geissen *et al.*, 2015; Hellou, 2010; Pintado-Herrera *et al.*, 2014; Poynton and Vulpe, 2009).

TABLE 2: Production of environmentally harmful chemicals, by environmental impact class, in the EU (aggregated production volumes in million tonnes)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total production of chemicals	***354.7***	***356.7***	***360.4***	***370.3***	***339.3***	***296.0***	***339.9***	***326.8***	***329.6***	***321.8***
Environmentally harmful chemicals, tota	*152.5*	*153.3*	*152.8*	*155.2*	*142.5*	*130.9*	*145.6*	*139.0*	*136.9*	*133.9*
Chemicals with severe chronic environmental impacts	*56.0*	*56.9*	*57.4*	*56.5*	*50.8*	*46.7*	*51.2*	*48.3*	*48.4*	*48.0*
Chemicals with significant chronic environmental impacts	*26.9*	*27.5*	*26.2*	*27.0*	*26.1*	*25.1*	*27.3*	*26.9*	*25.7*	*25.1*
Chemicals with moderate chronic environmental impacts	*9.5*	*9.8*	*9.9*	*10.3*	*9.4*	*8.3*	*10.4*	*10.1*	*9.6*	*9.7*
Chemicals with chronic environmental impacts	*30.4*	*29.0*	*29.3*	*30.8*	*25.5*	*24.1*	*26.9*	*26.1*	*25.8*	*24.2*
Chemicals with significant acute environmental impacts	*29.7*	*30.1*	*30.1*	*30.6*	*30.7*	*26.8*	*29.7*	*27.5*	*27.4*	*26.9*

Adapted from Eurostat data (http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=ten00011)

Existing legislation on water quality in Europe covers a range of contaminants in surface waters, including some designated as priority substances[1,2]. Traditionally, these consisted of industrial or agricultural chemicals (Petrie *et al.*, 2015). However, that EU legislation only covers the 'known knowns'; many less-studied contaminants are not regulated (Gavrilescu *et al.*, 2015). These emerging pollutants pose a big challenge to water management. How can we assess water quality comprehensively if we are not able to account for the presence of unregulated compounds? And how can we identify chemicals that may be unknown, unexpectedly dangerous, or that may reach dangerous concentrations in the future?

The only way to identify completely unknown molecules is by similarity comparisons with known molecules. Where there are some clues but no reference materials, substances can be identified via databases and/or *in silico* predictions. The new EU watch list mechanism[3], for example, seeks to gather monitoring data to identify substances that pose a risk, taking into account what we already know about their intrinsic properties.

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1. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

2. Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on Environmental Quality Standards in the Field of Water Policy, as amended by Directive 2013/39/EU: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:348:0084:0097:en:PDF and http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:226:0001:0017:EN:PDF

3. Commission Implementing Decision (EU) 2015/495 of 20 March 2015 establishing a watch list of substances for Union-wide monitoring in the field of water policy pursuant to Directive 2008/105/EC of the European Parliament and of the Council: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015D0495&qid=1450274157517&from=EN

Another potential approach to identifying 'known unknowns' is non-target screening: an instrumental technology that could detect otherwise overlooked harmful substances. Non-target screening applies an open-ended approach to screening pollutants in water samples (Ibáñez *et al.*, 2008). It typically involves sampling, sample preparation, liquid-chromatographic sample separation, ionic transfer and mass spectrometric detection (Letzel, 2014). Diaz *et al.* (2011) posit that these so-called full-spectrum acquisition techniques, such as liquid chromatography coupled to mass spectrometry, can be used to screen rapidly for non-target pollutants. Bearing in mind that there are a range of decisions and variables at every stage that may affect the results, the data can then be further processed, and unexpected or perhaps even unknown contaminants can be identified from spectra (Müller *et al.*, 2011).

Biosensors and similar tools like bioassays and biomarkers can also provide information on the pollutants present in the aquatic environment, and thus to some extent an early warning of potential environmental change (Duque *et al.*, 2013; Hansen, 2008). These techniques determine the activity or concentration of a substance by measuring its effect on biological material. For example, biosensors detect the presence of a substance using reactive biological components, such as enzymes or nucleic acids. The reaction is detected by a physiochemical detector that transforms the reaction's signal into a more measurable form. Such tools can be used to determine the type and concentration of contaminants in aquatic environments and, in the context of environmental change, can track the concentration of contaminants over time. Importantly, biosensors are able to provide continuous measurements, enabling the comprehensive characterisation of a contaminated site.

Recently developed biosensor clusters can be used to monitor multiple chemical species in parallel. Such a cluster was applied to simultaneously detect a range of endocrine-disrupting compounds with high sensitivity (Scognamiglio *et al.*, 2012). More recently, German researchers developed a biosensor based on rat liver cells to detect small changes in water quality. The system provides a read-out indicating the possible physiological damage caused and the chemical or class of chemicals responsible (Guijarro *et al.*, 2015). Techniques of this sort are being investigated in the context of the five-year EU 7th Framework Programme project SOLUTIONS[4], which is also considering how to address the relevance of chemical mixtures.

The issue of exposure to multiple chemicals and their possibly additive or synergistic effects is a significant 'unknown'. Efforts are being made to collate spatial data on the presence in the environment of chemicals that might have interactive effects on the environment and/or human health, including the European Commission's Information Platform for Chemical Monitoring (IPCheM)[5]. Analyses of these data and their comparison with spatial data on effects could help to identify correlations that might be critical in warning of the significance of some types of exposure.

3.3 Early warning signals from citizen science

Foresight techniques essentially rely on human capacity for reviewing information and open-minded, often creative thinking (see Section 3.1). People are increasingly being engaged in early warnings, such as utilising the cooperation and local knowledge of citizens to disseminate early warning messages effectively. In other ways too, human populations are progressively being recognised as a powerful tool for environmental management.

Community-based monitoring can increase public engagement and interest in research, monitor ecosystems that may otherwise not be monitored and provide data at lower cost. Across the globe, governments and NGOs are already using knowledge from citizen volunteers to monitor and manage natural resources, track at-risk species and conserve protected areas (Conrad and Hilchey, 2010). But citizens can also identify early warning signals of environmental risks, raising initial warnings about changes of key indicators (e.g. rising water levels, increased prevalence of disease symptoms). They can then transmit these 'bottom-up' messages to centralised systems (Conrad and Hilchey, 2010; Cowan *et al.*, 2014).

Community- or people-centred EWS have well-reported uses for the detection of natural hazards, and EWS can capitalise on the knowledge, tools and systems already present within communities. In this context, communities can offer local knowledge, and use technology or traditional techniques to track river levels and rainfall over long periods. They can monitor threats and initiate warnings themselves and, in many cases, feed into much larger monitoring systems (Cowan *et al.*, 2014).

4. http://www.solutions-project.eu
5. https://ipchem.jrc.ec.europa.eu/RDSIdiscovery/ipchem/index.html

Citizen-based EWS can also detect invasive species: animals and plants that are introduced into a natural environment where they are not normally found, and where they might pose a threat to existing ecosystems. There are rapidly accumulating examples of citizen science being used to detect invasive alien species. Such early warnings that an invasive alien species of concern has entered the EU are important for responding rapidly. Early detection may permit an invasive alien species to be assessed, contained or eradicated before it becomes established. This can be more cost-effective than long-term management (Mandrioli, 2014).

Community monitoring of the natural environment can contribute knowledge of not only the presence of alien species but of changes in their population and distribution. This can lead to early warnings of encroachment on more sensitive habitats. In 2009, the Mediterranean Science Commission initiative *Jellywatch* produced important information on the spread of the comb jelly (Boero *et al.*, 2009). Citizen scientists in Greece recently identified 28 alien marine species, four of which previously had a restricted distribution and were therefore not considered invasive. By identifying these looming invaders, Greek citizens may help to prevent them from spreading (Zenetos *et al.*, 2013).

There are also an increasing number of smartphone applications for recording invasive species, such as the 'That's Invasive!' app[6] developed by RINSE (Reducing the Impact of Invasive Non-Native Species in Europe), a European project focused on the 'Two Seas Region' (Belgium, England, France and the Netherlands). This is an area where invasion levels are among the highest in Europe. Available in three languages, the app aims to gather accurate data records, which are then verified to create a detailed map of invasive species' distributions.

If properly developed and embedded, citizen science can provide effective early warning of hard-to-foresee changes to ecosystems. Developments to communication technology, such as recent smartphone apps, coupled with widespread access, enable almost anyone to become a citizen scientist. This expands data collection more than specialised approaches and increases the accuracy of data, as many smartphones have built-in GPS for precise positioning. Most importantly, they facilitate real-time records, cutting the time between observation and documentation, making app-derived data particularly valuable for EWS.

Access to technology is not the only consideration; usability and uptake are also factors. EWS that have multiple purposes might be more effective than single-use technology or tools. This is particularly true if the hazard does not occur frequently (e.g. radios and phones can be useful in everyday life). Cowan *et al.* (2014) also assert that, to operate an effective EWS, both approaches — top-down and bottom-up — are crucial. Communities cannot at present achieve the same knowledge as specialised scientific systems. Communities must receive clear and relevant early warning messages regarding specific risks, particularly those relating to weather, which should then lead to well-informed responses.

3.4 Early warning signals from online media monitoring

Another way advances in communication technology are being used for early warning is via media monitoring. This approach to early warning is widely used in the health sector, where it is also referred to as 'tele-epidemiology', a novel form of epidemiology. Applying, telecommunications to conventional epidemiological research allows the detection of incidences of pathogens or diseases in a population. Media monitoring has been applied to print and broadcast media, but newer approaches rely on data from web-based sources (internet news, online discussion sites and social media) (Keller *et al.*, 2009).

So-called 'scanning software' has been developed to gather information on emerging signals from these sources, using algorithms and structured search terms (Cook *et al.*, 2014). This can be a low-cost approach to providing early warnings of emerging threats (Hartley *et*

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[6] http://www.rinse-europe.eu/smartphone-apps

BOX 2.

Case study: MediSys web intelligence for medical emergencies

The Medical Information System MediSys has been developed by the European Commission`s Joint Research Centre.

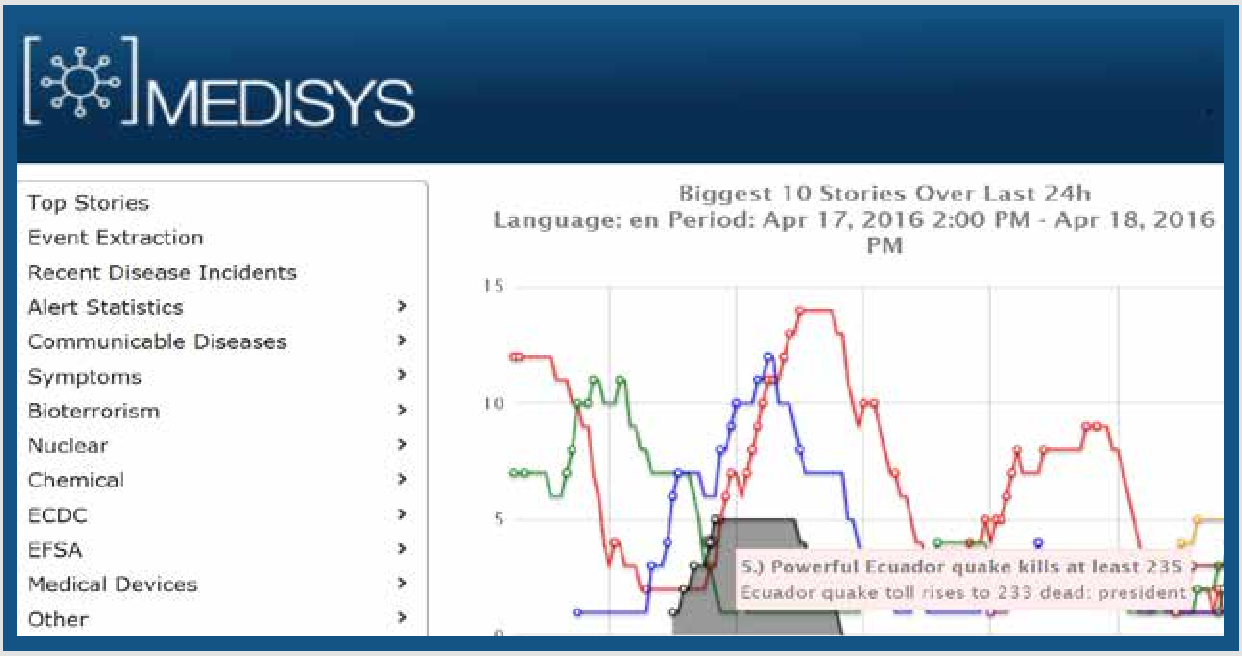
MediSys is an internet monitoring and analysis system that scans information from the European Media Monitor (EMM), software that gathers reports from worldwide news portals, in 60 different languages, to rapidly identify potential threats to public health.

MediSys continuously monitors around 400 specialist medical information sources to provide real-time analysis of medical and health-related topics and automatically generates early warning alerts.

MediSys is used systematically by the Health and Food Safety Directorate-General of the European Commission to provide early warnings of emerging threats to human health. The information is also available to the public via the website.

As well as human disease, MediSys monitors information on:

- Toxins
- Bioterrorism
- Bacteria and viruses
- Nuclear threats
- Chemical threats, like nerve agents and toxic metals
- Animal health
- Biological hazards including fungi, parasites and viruses
- Pesticides
- Plant health



(from European Commission, 2015c)

al., 2013). Non-automated systems can be more effective at identifying important warning signals but are generally more expensive, as they require expert review (Cook, 2014).

MediSys, and other platforms collecting internet data on emerging risks, are important tools in helping to predict events before they are officially reported by governments (Mantero *et al.*, 2010). Such systems could offer several advantages over other monitoring approaches: providing timely, cost-effective, comprehensive information available in many languages and directly accessible by citizens (Hartley *et al.*, 2013).

The potential to mine the Internet for early warning signals of sudden ecological change has been explored in the context of monitoring coral reef ecosystems (Galaz *et al.*, 2010) and forests (Daume *et al.*, 2014). The latter study involved use of a social-media-mining platform to collate twitter messages explicitly mentioning oak processionary moth, a spreading species whose caterpillars cause major damage to forests. The moths also pose a public health risk, as they produce a toxin that can cause skin irritation and respiratory distress. Initially developed for invasive alien species, the platform, (Ecoveillance, http://www.ecoveillance.org), is now under beta development to obtain early warnings for other ecological changes.

An already operational media monitoring tool for the environment has been developed by the International Biosecurity Intelligence System (IBIS). Combining media monitoring and citizen science, its scanning tools collect official (i.e. media published) and unofficial (i.e. Twitter) records. These provide realistic estimates of difficult-to-anticipate threats, such as illegal trade in wildlife or invasive species, providing species- and location-specific information to help target protection activities. It also engages an online community (including subject matter experts) to evaluate whether an article collected by the automated software robot is relevant (IBIS, 2015). For example, the IBIS Aquatic Animal Health network (http://aquatic.animalhealth.org/) collects information on aquaculture and fisheries to identify drivers of disease and detect outbreaks ahead of time.

This system was used to detect an emerging risk by the Australian Department of Agriculture, as part of its regular foresight planning to detect emerging threats to biosecurity (Cook *et al.*, 2014). Their interrogation of the network provided evidence for the unregulated movement of used aquaculture equipment and its link to the spread of oyster herpes virus (OHV). This virus has been associated with mass mortality in Pacific oysters (Morrissey *et al.*, 2015). The first report to highlight the problem described an oyster farmer from the UK who experienced an outbreak of OHV after using equipment previously used in France. Prior to this, imported aquaculture equipment was not known to play a prominent role in disease spread. Within weeks of the threat being recognised, the Government introduced preventive measures to ensure that all used equipment exported to Australia was decontaminated on arrival (Lyon *et al.*, 2013).

While such tools are unlikely to provide early warning when used in isolation, it is probable that internet monitoring of this kind will increasingly complement more traditional forms of ecological monitoring and risk assessment, and may help to avoid reaching 'late warnings'.

Intelligence tools and computer-aided analysis can help to make sense of signals from science, such that emerging risks can be detected before they damage the environment (IBIS, 2015). However, before Internet monitoring can contribute more fully to early warning of known unknown, or unknown known, environmental threats, there are several challenges to be addressed (for example, in in terms of data integration, expert analysis and knowledge management). Despite these difficulties, Internet monitoring tools could be a powerful tool for anticipating the ecological challenges of the future (Galaz *et al.*, 2010). Indeed, successes in the early detection of epidemics using similar tools demonstrate the potential of information posted on the web for detecting environmental risks.

3.5 Early warning signals from rate-change theories

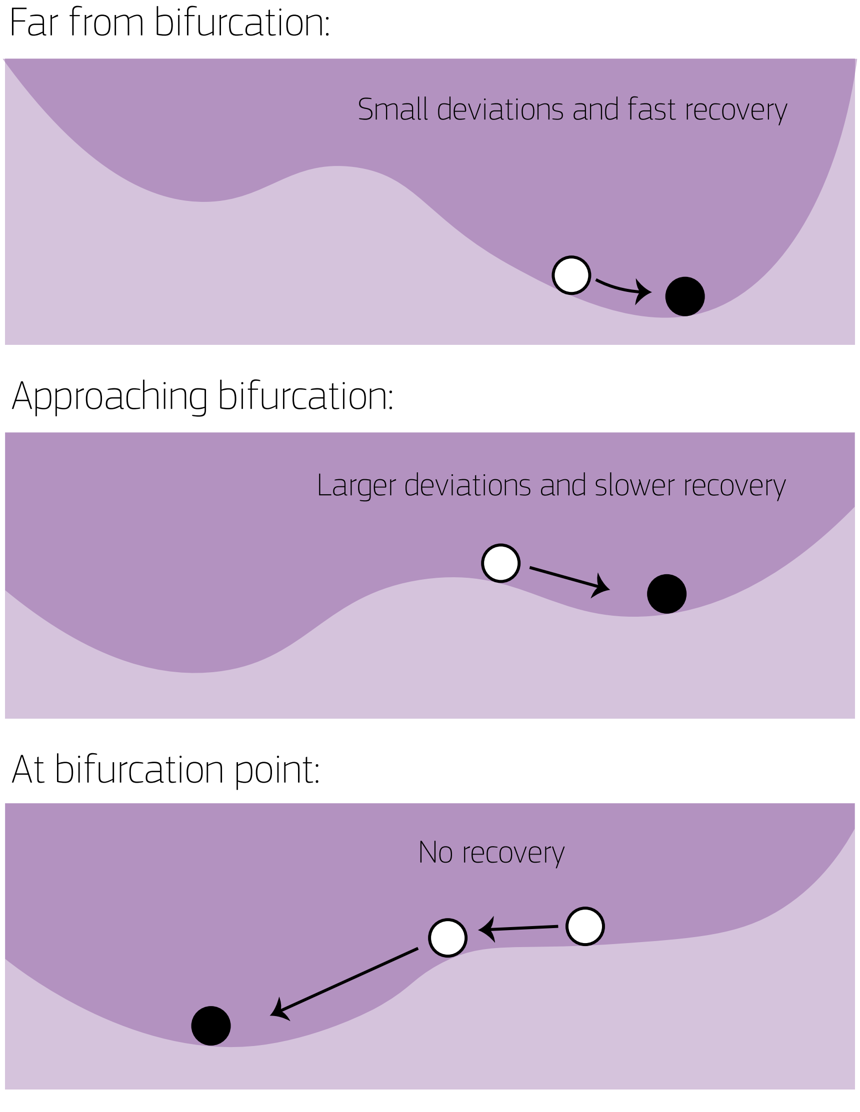
More abstract approaches have also shown the potential to point towards early warning signals. It is well documented that localised ecosystems can shift abruptly and irreversibly from one state to another (Scheffer *et al.*, 2009). In the environment, biological investigations in populations, disease outbreaks and various ecosystems (lakes, coral reefs, oceans, forests, islands and arid land) have all shown sudden switches to different states (Barnosky *et al.*, 2012; Scheffer *et al.*, 2001).

Planetary-scale transitions have also been postulated. In a Nature review summarising such transitions, the most recent example is the last glacial-interglacial transition period approximately 11 000 years ago. The review also summarises evidence that indicates humans are forcing another such critical transition, citing the quadrupling of human population in the last century, and the growth of the per-capita resource-consumption rate (Barnosky *et al.*, 2012).

Over the long term, there has also been a drastic shift in the behaviour of energy flows, which are now being overwhelmingly routed through one species (Homo sapiens commandeers 20–40% of net primary productivity). There is also an increase in the overall energy budget via releases of the energy stored in fossil fuels — which produce major modifications to the atmosphere and oceans. The authors suggest large 'dead zones' in coastal regions, the widespread introduction of novel communities (such as agricultural and invasive species), and the replacement of > 40% of Earth's formerly biodiverse land areas with landscapes containing only a few crops, plants, domestic animals and humans are observable responses. Such accumulated anthropogenic changes are expected to produce further pronounced changes in atmospheric and ocean chemistry, losses of biodiversity, changes in the assemblage of species, and modifications to food webs and geographical ranges. This could, according to the authors, result in a 'critical transition' (see Box 3).

Critical transitions can be visualised via the 'rivet popper' hypothesis of Paul Ehrlich, in which various species in an ecosystem act as 'rivets' holding the whole together. This hypothesis posits that, as species gradually become extinct, the ecosystem as a whole does not experience an equivalently gradual loss of function. Rather, there comes a point when crucial 'rivets' become lost, precipitating the collapse of the entire interlinked structure (Ehrlich and Ehrlich, 1981). In ecological terms, sudden 'tipping point' changes are often irreversible. Capturing signals that indicate their onset is therefore an important goal (Lade and Gross, 2012).

Although these tipping points are extremely difficult to predict, a growing body of evidence suggests it may be possible to detect generic early warning signals of an approaching critical threshold (Scheffer *et al.*, 2009). Critical slowing down (CSD) is a theory found across a range of apparently unrelated complex systems, from financial markets and neuronal activity to ecosystems and


Far from bifurcation:

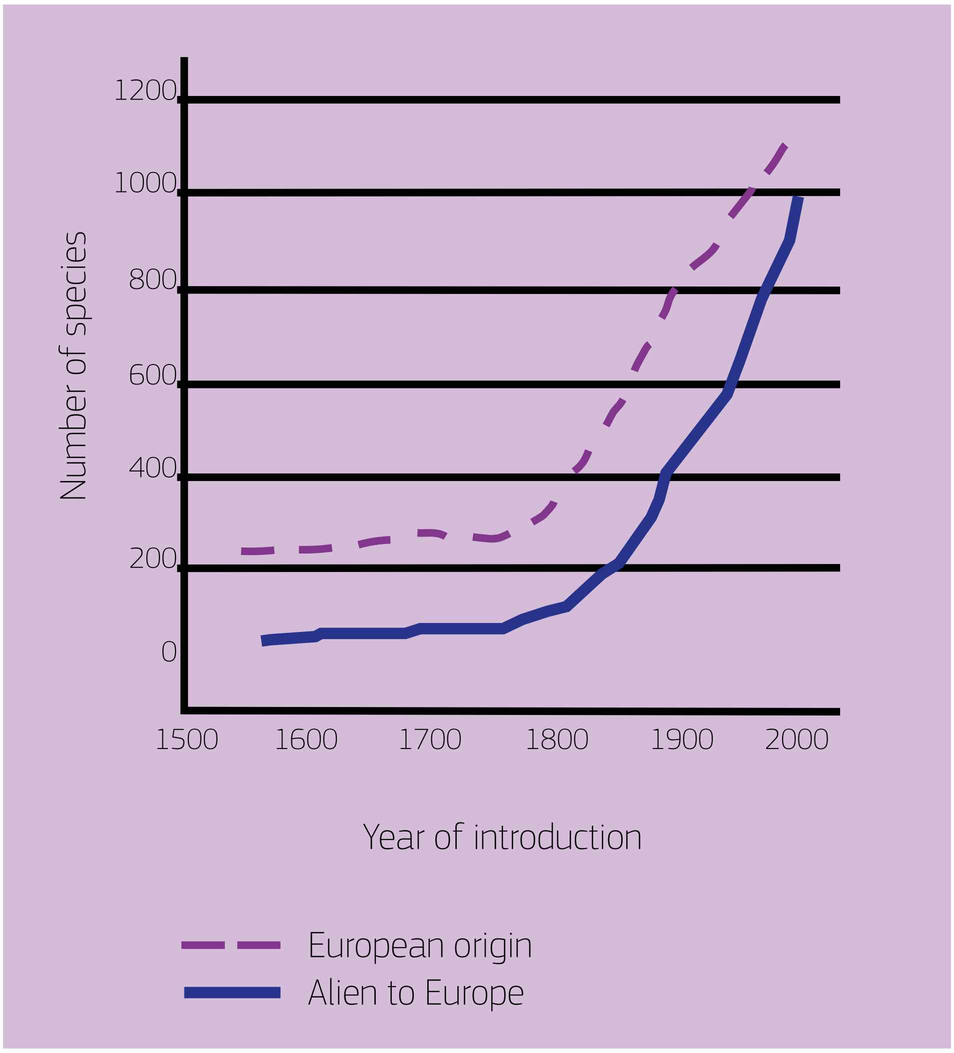
Approaching bifurcation:

At bifurcation point:

FIGURE 1: Heuristic basis for early warning of an approaching bifurcation point. Adapted from Lenton, 2011.

"The valleys or potential wells represent stable attractors, and the ball represents the state of the system. Under gradual forcing, the right potential well becomes shallower and finally vanishes (bifurcation) causing the ball to roll abruptly to the left. Picture the system being nudged around by a short-term stochastic process (noise). The radius of the potential well is directly related to the system's response time to such small perturbations, which tends towards infinity as bifurcation is approached, that is, the system becomes more sluggish in response to peturbations ('critical slowing down'). Larger fluctuations are also expected as bifurcation is approached."
(Lenton, 2011)

FIGURE 2: Cumulative number of introduced alien plant species to Europe over time.
Source: Lambdon *et al.*, 2008, referenced in European Commission, (2014). Invasive Alien Species: a European response. Luxembourg: Publications Office of the European Union.



climate systems. All of these systems have been shown to exhibit 'tipping points', at which sudden change or 'critical transitions' occur (Lade and Gross, 2012). One possible way to detect when a system is approaching a tipping point is to measure how quickly it recovers to the status quo ante following a small perturbation. If the system is close to a critical transition, the recovery time should increase or the recovery rate should decrease (Veraart *et al.*, 2012). This apparent sluggishness in responding to disruptions is called CSD (Early Warning Signals Toolbox, 2015) and is currently the most general indicator of an approaching tipping point (Lenton, 2013; Scheffer *et al.*, 2009). The 'bifurcation' in Figure 1 describes a 'branching' process, and can be broadly used to describe any situation in which the qualitative, topological picture of the object under study alters with a change of the parameters on which the object depend. Bifurcation is a term which originates in mathematics, but which is increasingly given a biological interpretation when talking about critical transitions.

Detecting CSD could represent a powerful approach. Existing EWS can generally only provide relatively short lead times. Earthquake warnings for example are often issued just seconds before the event. It is possible that the generic early warning signals provided by CSD could provide much longer lead times (Lenton, 2013).

CSD-based EWS have begun to be tested in laboratory, field and modelling experiments. In a whole-ecosystem experiment, Carpenter *et al.* tested the hypothesis that statistical indicators (including slow recovery from perturbation) could provide early warning signals of a major shift in an aquatic food web. The researchers gradually added top predators to a lake over three years to transform its food web (characterised by abundant prey fish, small zooplankton and high chlorophyll concentrations to a state dominated by predatory fish, small zooplankton and high chlorophyll concentrations). They monitored an adjacent lake as a reference ecosystem. They detected early warning signals of the regime shift in the manipulated lake over a year before the food web regime shift was complete, using indicators of critical slowing down in time-series data (Carpenter *et al.*, 2011). In a later study (Cline *et al.*, 2014), they showed that spatial early warning signals (e.g. changes to the spatial distribution of fish populations) can also be detected at the ecosystem scale.

A more recent study posits a preliminary theoretical framework for detecting tipping points. The researchers ran simulations of ecological scenarios en route to a tipping point, using the structure of 79 'mutualistic communities' of plant-pollinator and plant-seed-disperser networks, reconstructed from empirical data (Dakos and Bascompte, 2014). Their results suggested that specialist species could be some of the best indicators for detecting potential abrupt transitions before collapse. They suggest that their approach could be used to identify the vulnerable elements of networks under global environmental change, and even indicate imminent extinctions, hence providing early warnings of the collapse of entire ecological networks.

While it is possible to deliberately perturb a system experimentally and measure its responses, this is not often a viable approach for real-world systems. However, there is another way of identifying CSD, which involves analysing existing time-series data to identify relevant fluctuations. This approach has recently been illustrated in the context of climate change. Throughout Earth's history, periods of relatively stable climate have been interrupted by sharp transitions to a contrasting state (Dakos *et al.*, 2008). These may represent critical tipping points (Lenton, 2011). Corroborating this theory, when Dakos *et al.* (2008) analysed eight abrupt climate shifts from the past, they found that all were preceded by a characteristic slowing down of fluctuations, much before the change itself. This provides the first evidence that climate shifts are associated with the passing of critical thresholds. It is feasible therefore that slowing down, perhaps a mathematical hallmark of tipping points, could be used to predict future shifts in climate. However, coherent with the 'rivet popper' hypothesis, perhaps a more obvious indicator of approaching a catastrophic tipping point is an acceleration of change.

BOX 3.

Environmental change: slowing down or speeding up?

In contrast to the slowing down observed in certain time-series data, many environmental processes are directly speeding up, largely due to rapidly increasing anthropogenic pressure.

There are a multitude of examples of accelerating environmental phenomena, perhaps most widely reported being the increase in frequency of severe weather events seen in recent decades (Fischer and Knutti, 2015): high-impact, low-probability events like the European heat wave of 2003 and Pakistan flooding in 2010 (Coumou *et al.*, 2014). The IPCC Special Report on extreme events summarises evidence gathered since 1950 that extreme weather and climate events have increased in frequency and magnitude. Evidence, such as an overall increase in warm days and nights and statistically significant trends in heavy precipitation, could act as an EWS for extreme weather events (IPCC, 2012).

Climatic changes are also hastening the melt of glaciers and ice sheets. The past 50 years have seen unprecedented warming of the Antarctic, complete with accelerating loss of glacier mass and collapse of ice sheets (Abram *et al.*, 2013). Since the late 1400s, there has been a nearly tenfold increase in melt intensity in the Antarctic Peninsula (Abram *et al.*, 2013). A number of different data sources have confirmed this accelerating ice loss (Abram *et al.*, 2013; Chen *et al.*, 2009; Harig and Simons, 2015; Jevrejeva *et al.*, 2014; Velicogna, I., 2009;), which can be considered an early warning of sea-level rise (Rignot *et al.*, 2011).

Declines in fauna have occurred at a similarly rapid pace. Intensive fishing has led to a vast reduction in fish stocks, for example. In the past 50 years, food fish supply has increased at an average annual rate of 3.2%, outpacing world population growth of 1.6% (FAO, 2014). In 1974, the proportion of marine fish stocks being fished at sustainable levels was 90%. By 2011, this had dropped to 71%, with 28.8% of fish stocks being fished at an unsustainable level (overfished) and 61.3% of stocks being fully fished (FAO, 2006; 2014). A recent analysis of fish stocks in the Mediterranean (1990–2010) also showed that the rate of exploitation has been steadily increasing and stocks have been declining (Vasilakopoulos, Maravelias & Tserpes, 2014).

The decline of honey bees in Europe has also been accelerating in the past 20 years. A recent report showed 9% of bees in the EU-27 to be threatened with extinction and over a third of bee populations to be in decline (Nieto *et al.*, 2014). Other pollinators, butterflies, are also rapidly declining, by almost 50% in Europe between 1990 and 2011 (European Environment Agency, 2013b).

Some species, however, have thrived in recent years, but not where they used to. Plant diversity has increased as a result of human introductions, and numbers of invasive alien species have risen exponentially in the past half-century (See Figure 2). It is estimated that the number of invasive alien species in Europe has increased by 76% since the 1970s, and this increase is likely to continue (European Commission, 2014). As populations of invasive species spread, their impacts on other species (and by extension biodiversity) increase (Keller *et al.*, 2011). The increase in numbers of alien species is an important indicator of widespread change, as once a species has spread, there are few remaining options to control the population and the resources required are extensive (Keller *et al.*, 2011).

All of these rapid accelerations provide warning signs of extinctions and highlight the need for rapid conservation action to stem net biodiversity loss. They could furthermore suggest that another global-scale state shift is highly plausible within decades to centuries, if it has not already been initiated (Barnosky *et al.*, 2012). Such an increase in biological instability and unpredictability would have huge implications for the natural resources we take for granted within a few generations.

4. Conclusions

In times of unprecedented global change, human society is faced with an immense challenge: not only to mitigate the impact of changes to the environment already occurring, but also to anticipate the changes we cannot yet observe. Great progress has been made in developing methods, techniques and technologies to better assess the unknown risks present in the environment, and to generate warnings as a result. However, even the most sophisticated early warning systems cannot eliminate uncertainty when predicting emerging risks.

Standard approaches to decision making under uncertainty rely on data regarding the likelihood of different states, how actions will generate outcomes, and the net benefits of those different outcomes. However, when it comes to emerging risks, the set of possible states is often unknown, as therefore are their probabilities and the effects of different actions (Polasky *et al.*, 2011). Beyond better data generation and foresight approaches, one crucial adaptation will be to include expectations of instability, such as changes to the climate (Barnosky *et al.*, 2012).

Several approaches to help policymakers to make the best possible decisions under such conditions have been touched upon in this brief. Foresight approaches help to prepare policymakers for unexpected events by creating visions of the future, and by obtaining the evidence and comparative evaluation needed to avoid or plan for these possible futures. If technological access is increased and enabled, citizen science has the potential to monitor changes to the environment in a cost-effective manner also engaging the public in science and conservation.

There is potential to develop further strategies for detecting early warning signals from this springboard, subject to appropriate verification processes. Media monitoring — gathering and analysing data from the Internet to anticipate critical transitions or events — could generate large data sets to supplement more traditional forms of monitoring. This would provide early warning of sudden ecological change. Such techniques currently collate what has already been published on other platforms, potentially leading to the recognition of an unknown but widespread

BOX 3.

Case study: emerging risk identification in food safety

A good illustration of emerging risk identification can be found in the field of food safety. The European Food Safety Authority is required to “undertake action to identify and characterise emerging risks” in food and feed safety, and has therefore developed a robust procedure for emerging risk identification. The procedure has three key steps: preliminary identification of priority emerging issues, identification of appropriate data sources and data collection, evaluation of collected information and identification of emerging risks.

The EU SAFE FOODS project[7] has also developed a system for the early identification of emerging food-borne risks, which is science-based, open and participatory. The framework aims to enhance the transparency and accountability of the risk-analysis process. It relies on an interface committee, headed by a risk manager, including risk management experts, independent scientific advisors and stakeholders. The committee allows dialogue between those with different expertise and perspectives, while maintaining strict separation of responsibilities between managerial and scientific/stakeholder members. The results of each stage of the five-stage risk analysis process are made public, ensuring transparency and encouraging citizen engagement. The framework was built based on analysis of existing policies, laws and practices. It is also designed to fit in to the existing EU legal and institutional setting and may provide useful design elements for similar, future systems (from SAFE FOODS, 2007).

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7. SAFE FOODs was funded by the European Commission under their Seventh Framework Programme. See: http://www.safefoods.nl/

phenomenon. Integrating these technologies with increasingly advanced citizen-science techniques could, in future, result in a much-reduced time lag between the first signs of a risk and its early warning.

More theoretical approaches to anticipating critical environmental risks are analysing time-series data and long-term trends for signs of a change in the rate of change i.e. 'critical slowing down' or 'critical acceleration'. Critical slowing down has been successfully applied to predict major changes in aquatic systems and may help to anticipate future tipping points in the climate. However, the method requires improvement to apply the abstract idea in the real world (Lenton, 2011). The theories of critical acceleration, or rivet popping, leading to critical transition, may be supported by more tangible real-world signs, such as the creation of aquatic dead zones, the rate of land-use change, and the behaviour of energy flows. According to this theory, increasing state shifts of the overlapping, nested, small-scale complex systems may also signal a state shift of the entire system.

A range of existing technologies can facilitate analysis of the small-scale systems. In the field of water quality, for example, combined technological approaches have been developed to identify emerging pollutants, even when the substances are initially unknown. These increasingly sophisticated methods, including the use of biomarkers and other effect-based tools, can detect contaminants and provide early warning of possible impacts. They are, however, only as good as their parameters, and so probably unable to detect 'unknown unknowns'. Satellites have capacity to generate data for identifying both short- and long-term warning signals — but strategic and collaborative extension of data coverage is required.

Improving data coverage, modelling techniques and metrics will all increase foresight and create a more comprehensive understanding. However, for any EWS to be useful, it must be followed by appropriate and timely actions (Sutherland and Woodroof, 2009) — or, better, preceded by timely preparation. Transparent, clear-cut institutions that properly separate responsibilities will help to empower this (EEA, 2002; 2013a), as will increased cooperation, or 'coopetition' (Ramirez and Selsky, 2014), between sectors and organisations. An increased alignment of international goals is equally necessary. Moreover, full citizen cooperation and participation will be essential for the effective dissemination of early warning messages and for the implementation of appropriate responses or adaptation. Also the development of useful and accessible feedback loops and sources of information is crucial. In terms of climate variability, it has been suggested that the rehearsal of adaptive responses to prepare for inevitable climate-driven events such as migration, disease and food and water shortages is necessary for ensuring populations' wellbeing (Barnosky *et al.*, 2012).

The tools outlined in this brief are essential for appraising environmental risk, picking up early warning signals, and responding to a world of rapidly evolving change, but none offers a complete solution. Each system of thinking provides different insights, and different gaps, so a combination of approaches — along with a deepening collaboration between governments and citizens — will be necessary to develop the best and most comprehensive responses to our changing environment.

References

Abram, N., Mulvaney, R., Wolff, E., Triest, J., Kipfstuhl, S., Trusel, L., Vimeux, F., Fleet, L. and Arrowsmith, C. (2013) Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century. Nature Geoscience, 6(5), pp. 404-411.

Aven T & Vinnem JE (2007) Risk Management: With Applications from the Offshore Petroleum Industry. London: Springer.

Bae, M.-J. and Park, Y.-S. (2014) Biological early warning system based on the responses of aquatic organisms to disturbances: A review. Science of The Total Environment 466–467, 635–649.

Barnosky, A., Hadly, E., Bascompte, J., Berlow, E., Brown, J., Fortelius, M., Getz, W., Harte, J., Hastings, A., Marquet, P., Martinez, N., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D., Revilla, E. & Smith, A. (2012) Approaching a state shift in Earth's biosphere. Nature 486(7401): 52-58.

Boero, F., Putti, M., Trainito, E., Prontera, E., Piraino, S. and Shiganova, T. (2009). First records of Mnemiopsis leidyi (Ctenophora) from the Ligurian, Thyrrhenian and Ionian Seas (Western Mediterranean) and first record of Phyllorhiza punctata (Cnidaria) from the Western Mediterranean. Aquatic Invasions, 4(4): 675-680.

Brotherton, R. (2015) The Brain Has a Blind Spot for 'Unknown Unknowns'. Discover Magazine. Kalmbach Publishing Company. Available from: http://blogs.discovermagazine.com/crux/2015/11/17/brain-unknowns/#.VmFaYISKFFK [Accessed 4 December 2015].

Cambridge Conservation Initiative (2012) Horizon Scanning – A CCI Collaborative Activity. Available from: http://www.conservation.cam.ac.uk/horizon-scanning-cci-collaborative-activity [Accessed 3 December 2015].

Carpenter, S. R., Bennett, E. M., and Peterson, G. D. (2006) Scenarios for ecosystem services: an overview. Ecology and Society 11(1): 29. Available from: http://www.ecologyandsociety.org/vol11/iss1/art29/

Carpenter, S., Cole, J., Pace, M., Batt, R., Brock, W., Cline, T., Coloso, J., Hodgson, J., Kitchell, J., Seekell, D., Smith, L. and Weidel, B (2011) Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment. Science, 332(6033), pp.1079-1082.

Chen, J.L., Wilson, C.R., Blankenship, D., and Tapley, B.D. (2009) Accelerated Antarctic ice loss from satellite gravity measurements. Nature Geosci 2: 859–862.

Cline, T., Seekell, D., Carpenter, S., Pace, M., Hodgson, J., Kitchell, J. and Weidel, B. (2014) Early warnings of regime shifts: evaluation of spatial indicators from a whole-ecosystem experiment. Ecosphere 5(8): p.art102.

Cook, C.N., Inayatullah, S., Burgman, M.A., Sutherland, W.J. and Wintle, B.A. (2014) Strategic foresight: How planning for the unpredictable can improve environmental decision-making. Trends in Ecology & Evolution 29 (9): 531–541

Conrad, C.C. and Hilchey, K.G. (2010). A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ Monit Assess 176: 273–291.

Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S. and Schellnhuber, H. (2014) Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. Proceedings of the National Academy of Sciences, 111(34):12331-12336.

Cowan, Y., O'Brien, E. & Rakotomalala-Rakotondrandria, N. (2014) Community-based Early Warning Systems: Key Practices for DRR Implementers. OCHA & FAO. E-ISBN 978-92-5-108345-1.

Crall, A.W., Newman, G.J., Jarnevich, C.S., Stohlgren, T.J., Waller, D.M. and Graham, J. (2010) Improving and integrating data on invasive species collected by citizen scientists. Biol Invasions 12: 3419–3428.

Dakos, V. and Bascompte, J. (2014) Critical slowing down as early warning for the onset of collapse in mutualistic communities. PNAS 111, pp. 17546–17551.

Dakos, V., Scheffer, M., van Nes, E.H., Brovkin, V., Petoukhov, V. and Held, H. (2008) Slowing down as an early warning signal for abrupt climate change. PNAS 105: 14308–14312.

Daume, S., Albert, M. and von Gadow, K. (2014) Forest monitoring and social media – Complementary data sources for ecosystem surveillance? Forest Ecology and Management 316: 9-20.

Díaz, R., Ibáñez, M., Sancho, J.V. and Hernández, F. (2012) Target and non-target screening strategies for organic contaminants, residues and illicit substances in food, environmental and human biological samples by UHPLC-QTOF-MS. Anal. Methods 4 (1): 196–209.

Duque, T., Chaves Ribeiro, A.C., de Camargo, H.S., da Costa Filho, P.A., Mesquita Cavalcante, H.P. and Lopes, D. (2013) New Insights on Optical Biosensors: Techniques, Construction and Application, in: Rinken, T. (Ed.), State of the Art in Biosensors – General Aspects. InTech.

Early Warning Signals Toolbox (2015) Perturbation experiments. The Synergy Program for Analyzing Resilience and Critical Transitions. Available from: http://www.early-warning-signals.org/perturbation-experiments [Accessed 18 August 2015].

Ehrlich, P.R., Ehrlich, A.H. (1981) Extinction: The Causes and Consequences of the Disappearance of Species. New York: Random House.

European Commission (2014) Invasive Alien Species: a European response. Luxembourg: Publications Office of the European Union. Available from: http://ec.europa.eu/environment/nature/invasivealien/docs/ias-brochure-en-web.pdf

European Commission (2015a) Environmental monitoring. Available from: https://ec.europa.eu/jrc/en/research-topic/environmental-monitoring [Accessed 20 August 2015].

European Commission (2015b) Foresight. Available from: http://ec.europa.eu/research/index.cfm?pg=foresight [Accessed 19 November 2015].

European Commission (2015) Medical Information System – MEDISYS. Available from: https://ec.europa.eu/jrc/en/scientific-tool/medical-information-system [Accessed 8 November 2015].

European Environment Agency, (2002). The precautionary principle 1896-2000. Late lessons from early warnings. Luxembourg: Office for Official Publications of the European Communities. Available from; http://www.eea.europa.eu/publications/environmental_issue_report_2001_22

European Environment Agency, (2013a). Science, precaution, innovation. Late lessons from early warnings. Luxembourg: Publications Office of the European Union. Available from: http://www.eea.europa.eu/publications/late-lessons-2

European Environment Agency, (2013b). The European Grassland Butterfly Indicator: 1990–2011. Available from: http://www.eea.europa.eu/publications/the-european-grassland-butterfly-indicator-19902011

European Environment Agency (2015) Water pollution — overview. Available from: http://www.eea.europa.eu/themes/water/water-pollution [Accessed 19 August 2015].

European Food Safety Authority, (2015). Identification of emerging risks: an appraisal of the procedure trialled by EFSA and the way forward. Available from: http://www.efsa.europa.eu/sites/default/files/scientific_output/files/main_documents/824e.pdf

European Food Safety Authority (EFSA) (2007) Definition and description of "Emerging Risks" within the EFSA's mandate. Available from: http://www.efsa.europa.eu/sites/default/files/scientific_output/files/main_documents/escoemriskdefinition.pdf

European Media Monitor (2015) EMM Overview. Available from: http://emm.newsbrief.eu/overview.html [Accessed 19 August 2015].

EUROSTAT (2015) Eurostat — Tables, Graphs and Maps Interface (TGM) table: Production of environmentally harmful chemicals, by environmental impact class. Available from: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=ten00011 [Accessed 20 August 2015].

Filella, M., Williams, P. and Belzile, N. (2009). Antimony in the environment: knowns and unknowns. Environ. Chem. 6(2): 95.

Fischer, E.M. and Knutti, R. (2015) Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. Nature Clim. Change 5: 560–564.

Flage, R. and Aven, T. (2015) Emerging risk – Conceptual definition and a relation to black swan type of events. Reliability Engineering & System Safety, 144: 61-67.

Food and Agriculture Organization of the United Nations (2014) The State of World Fisheries and Aquaculture 2014. Available from: http://www.fao.org/3/a-i3720e.pdf

Food and Agriculture Organization of the United Nations (2006) The state of world highly migratory, straddling and other high seas fishery resources and associated species. ftp://ftp.fao.org/docrep/fao/009/a0653e/a0653e00.pdf

Galaz, V., Crona, B., Daw, T., Bodin, Ö., Nyström, M. And Olsson, P. (2009) Can web crawlers revolutionize ecological monitoring? Frontiers in Ecology and the Environment 8: 99–104.

Gavrilescu, M., Demnerová, K., Aamand, J., Agathos, S. and Fava, F. (2015) Emerging pollutants in the environment: present and future challenges in biomonitoring, ecological risks and bioremediation. New Biotechnology 32, pp. 147–156.

Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., van der Ploeg, M., van de Zee, S.E.A.T.M. and Ritsema, C.J. (2015) Emerging pollutants in the environment: A challenge for water resource management. International Soil and Water Conservation Research 3: 57–65.

Guijarro, C., Fuchs, K., Bohrn, U., Stütz, E. and Wölfl, S. (2015) Simultaneous detection of multiple bioactive pollutants using a multiparametric biochip for water quality monitoring. Biosensors and Bioelectronics 72: 71–79.

Hansen, P. (2008) Biosensors and Eco-toxicology. Eng. Life Sci., 8(1): 26-31.

Harig, C. and Simons, F. (2015). Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains. Earth and Planetary Science Letters, 415: 134-141.

Hartley, D.M., Nelson, N.P., Arthur, R.R., Barboza, P., Collier, N., Lightfoot, N., Linge, J.P., van der Goot, E., Mawudeku, A., Madoff, L.C., Vaillant, L., Walters, R., Yangarber, R., Mantero, J., Corley, C.D. and Brownstein, J.S. (2013) An overview of Internet biosurveillance. Clinical Microbiology and Infection 19: 1006–1013.

Hellou, J., 2010. Behavioural ecotoxicology, an "early warning" signal to assess environmental quality. Environ Sci Pollut Res 18: 1–11.

Ibáñez, M., Sancho, J.V., Hernández, F., McMillan, D. and Rao, R. (2008) Rapid non-target screening of organic pollutants in water by ultraperformance liquid chromatography coupled to time-of-light mass spectrometry. TrAC Trends in Analytical Chemistry 27, pp. 481–489.

Intergovernmental Panel on Climate Change (2015) Working Group II: Impacts, Adaptation and Vulnerability. Available from: http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=146 [Accessed 19 November 2015].

Intergovernmental Panel on Climate Change (2012) Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

International Biosecurity Intelligence System (2015) How IBIS works. Available from: http://biointel.org/manual/how-ibis-works [Accessed 15 December 2015].

International Risk Governance Council (2010) The Emergence of Risks: Contributing Factors. Available from: http://irgc.org/wp-content/uploads/2012/04/irgc_ER_final_07jan_web.pdf.

Jevrejeva, S., Moore, J.C., Grinsted, A., Matthews, A.P. and Spada, G. (2014) Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change 113: 11–22.

Joint Research Centre Science Hub (2015) Foresight and Horizon scanning. European Commission. Available from: https://ec.europa.eu/jrc/en/research/crosscutting-activities/foresight [Accessed 8 December 2015].

Kahneman, D. (2011) Thinking, Fast and Slow. Penguin: London.

Keller, R., Geist, J., Jeschke, J. and Kühn, I. (2011). Invasive species in Europe: ecology, status, and policy. Environ Sci Eur, 23(1): 23.

Keller, M., Blench, M., Tolentino, H., Freifeld, C.C., Mandl, K.D., Mawudeku, A., Eysenbach, G. And Brownstein, J.S. (2009) Use of Unstructured Event-Based Reports for Global Infectious Disease Surveillance. Emerging Infectious Diseases 15: 689–695.

Lade, S.J. and Gross, T. (2012) Early Warning Signals for Critical Transitions: A Generalized Modeling Approach. PLoS Comput Biol 8, e1002360.

Leigh, A. (2003) Thinking ahead: Strategic foresight and government. Australian Journal of Public Administration 62 (2): 3–10.

Lenton, T. (2013) What early warning systems are there for environmental shocks? Environmental Science & Policy, 27: S60-S75.

Lenton, T.M. (2011) Early warning of climate tipping points. Nature Clim. Change 1: 201–209.

Letzel (2014) Non-target screening, suspected-target screening and target screening – of technologies and philosophies, databases and crafts. Lab&More Int. 1/2014. Available from: http://www.int.laborundmore.com/archive/555305/Non-target-screening,-suspected-target-screening-and-target-screening-%E2%80%93-of-technologies-and-philosophies,-databases-and-crafts.html

Locklear K (2011) Emerging risk: An integrated framework for managing extreme events. 2011 ERM Symposium. http://www.ermsymposium.org/2011

Logan, D. (2009) Known knowns, known unknowns, unknown unknowns and the propagation of scientific enquiry. Journal of Experimental Botany, 60(3): 712-714.

Lyon, A., Grossel, G., Burgman, M. and Nunn, M. (2013) Using internet intelligence to manage biosecurity risks: a case study for aquatic animal health. Diversity and Distributions, 19(5-6): 640-650.

Mandrioli, M. (2014) Early warning for invasive pest crops and citizen science. The Aphid Room. Available from: https://theaphidroom.wordpress.com/2014/01/24/early-warning-for-invasive-pest-crops-and-citizen-science [Accessed 25 August 2015].

Mantero, J., Cox, A., Linge, J., van der Goot, E. and Coulombier, D. (2010) The European Centre for Disease Prevention and Control strengthening MedISys as a tool to accelerate detection of threats to human health from communicable diseases in the EU. International Journal of Infectious Diseases 14 (Supplement 1): e274–e275.

Maynard, A.D., Warheit, D.B. and Philbert, M.A. (2010) The new toxicology of sophisticated materials: Nanotoxicology and beyond. Toxicological Sciences 120 (Supplement 1): S109–S129.

Morrissey, T., McCleary, S., Collins, E., Henshilwood, K. and Cheslett, D. (2015) An investigation of ostreid herpes virus microvariants found in Crassostrea gigas oyster producing bays in Ireland. Aquaculture, 442: 86-92.

Müller, A., Schulz, W., Ruck, W.K.L and Weber, W.H. (2011) A new approach to data evaluation in the non-target screening of organic trace substances in water analysis. Chemosphere 85:1211–1219.

Nafday, A.M. (2011) Consequence-based structural design approach for black swan events. Structural Safety 33: 108–114.

NATO (2002) Press Conference by US Secretary of Defence Donald Rumsfeld. Available from: http://www.nato.int/docu/speech/2002/s020606g.htm [Accessed 18 January 2016].

Nieto, A., Roberts, S.P.M., Kemp, J., Rasmont, P., Kuhlmann, M., García Criado, M., Biesmeijer, J.C., Bogusch, P., Dathe, H.H., De la Rúa, P., De Meulemeester, T., Dehon, M., Dewulf, A., Ortiz-Sánchez, F.J., Lhomme, P., Pauly, A., Potts, S.G., Praz, C., Quaranta, M., Radchenko, V.G., Scheuchl, E., Smit, J., Straka, J., Terzo, M., Tomozii, B., Window, J. and Michez, D. 2014. European Red List of bees. Luxembourg: Publication Office of the European Union

Paron, P., Di Baldassarre, G. and Shroder Jr., J. F. (2014) Hydro-Meteorological Hazards, Risks, and Disasters. Elsevier.

Pawson, R., Wong, G. and Owen, L. (2011) Known Knowns, Known Unknowns, Unknown Unknowns: The Predicament of Evidence-Based Policy. American Journal of Evaluation, 32(4): 518-546.

Petrie, B., Barden, R. and Kasprzyk-Hordern, B (2015) A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring. Water Research, 72: 3-27.

Pintado-Herrera, M.G., González-Mazo, E. and Lara-Martín, P.A., (2014) Atmospheric pressure gas chromatography–time-of-flight-mass spectrometry (APGC–ToF-MS) for the determination of regulated and emerging contaminants in aqueous samples after stir bar sorptive extraction (SBSE). Analytica Chimica Acta 851: 1–13.

Ploetz, R., Hulcr, J., Wingfield, M. and de Beer, Z. (2013) Destructive Tree Diseases Associated with Ambrosia and Bark Beetles: Black Swan Events in Tree Pathology? Plant Disease 97(7): 856-872.

Polasky, S., Carpenter, S.R., Folke, C. And Keeler, B. (2011) Decision-making under great uncertainty: environmental management in an era of global change. Trends in Ecology & Evolution 26: 398–404.

Poynton, H.C. and Vulpe, C.D. (2009) Ecotoxicogenomics: Emerging Technologies for Emerging Contaminants. Journal of the American Water Resources Association 45: 83–96.

Rahmstorf, S. (2006) Thermohaline Ocean Circulation. In: Encyclopedia of Quaternary Sciences. Elsevier, Amsterdam.

Ramirez, R. and Selsky, J. W. (2014) Strategic Planning in Turbulent Environments: A Social Ecology Approach to Scenarios. Long Range Planning. Available online 23 October 2014. doi:10.1016/j.lrp.2014.09.002

Ramsar Convention Secretariat (2015) Theme 2: Strategic, emerging and ongoing issues [online]. Available from: http://strp.ramsar.org/about-us/thematic-areas/theme-2-strategic-emerging-ongoing-issues [Accessed 08 December 2015].

Reed, P. M., Chaney, N. W., Herman, J. D., Ferringer, M. P. & Wood, E. F. (2015). Internationally coordinated multi-mission planning is now critical to sustain the space-based rainfall observations needed for managing floods globally. Environmental Research Letters 10(2): 024010.

Rignot, E., Velicogna, I., van den Broeke, M., Monaghan, A. and Lenaerts, J. (2011) Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. Geophys. Res. Lett. 38(5).

SAFE FOODS (2007) SAFE FOODS: Progress and Results. Available from: http://www.safefoods.nl/upload_mm/8/d/9/4791be34-026f-4e48-8238-2857c924dc41_Folder_SafeFoods_Finalversion2007.pdf

SAFE FOODS (2007) Food safety governance revolutions in aftermath of BSE crisis. Available from: http://www.safefoods.nl/en/safefoods.htm [Accessed 16 September 2015].

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M. and Sugihara, G. (2009) Early-warning signals for critical transitions. Nature 461, pp. 53–59.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. And Walker, B. (2001) Catastrophic shifts in ecosystems. Nature 413: 591–596.

Scognamiglio, V., Pezzotti, I., Pezzotti, G., Cano, J., Manfredonia, I., Buonasera, K., Arduini, F., Moscone, D., Palleschi, G. And Giardi, M.T. (2012) Towards an integrated biosensor array for simultaneous and rapid multi-analysis of endocrine disrupting chemicals. Analytica Chimica Acta 751, pp. 161–170.

Stuart, M., Lapworth, D., Crane, E. and Hart, A. (2012) Review of risk from potential emerging contaminants in UK groundwater. Science of The Total Environment 416: 1–21.

Sumpter, J.P. and Johnson, A.C. (2008) 10th Anniversary Perspective: Reflections on endocrine disruption in the aquatic environment: from known knowns to unknown unknowns (and many things in between). J. Environ. Monit. 10: 1476–1485.

Sutherland, W., Clout, M., Depledge, M., Dicks, L., Dinsdale, J., Entwistle, A., Fleishman, E., Gibbons, D., Keim, B., Lickorish, F., Monk, K., Ockendon, N., Peck, L., Pretty, J., Rockström, J., Spalding, M., Tonneijck, F. and Wintle, B. (2015). A horizon scan of global conservation issues for 2015. Trends in Ecology & Evolution, 30(1): 17-24.

Sutherland, W. and Woodroof, H. (2009). The need for environmental horizon scanning. Trends in Ecology & Evolution, 24(10): 523-527.

KH-BB-15-002-EN-N

UK Government Office for Science, (2012). High impact low probability risks: Blackett review.

UK Government Office for Science (2013) Foresight projects. Available from: https://www.gov.uk/ government/collections/foresight-projects [Accessed 18 November 2015].

United Nations (1997) International Decade for Natural Disaster Reduction IDNDR Early Warning Programme Report on Early Warning for Hydrometeorological Hazards including Drought. http://www.unisdr.org/files/1867_VL102134.pdf

United Nations Environment Programme (2012). Early Warning Systems: A State of the Art Analysis and Future Directions. Division of Early Warning and Assessment (DEWA), United Nations Environment Programme (UNEP), Nairobi.

United Nations Environment Programme, (2010). UNEP Emerging Issues: Global Honey Bee Colony Disorder and Other Threats to Insect Pollinators.

United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UNISDR) (2007) Terminology. Available from: http://www.unisdr.org/we/inform/terminology#letter-e. [Accessed 18 August 2015].

UNISDR (2006) Global Survey of Early Warning Systems.

UNISDR (2006) 'International Early Warning Programme – IEWP.' International Strategy for Disaster Reduction Platform for the Promotion of Early Warning. Bonn, Germany. Available from: http://www.unisdr.org/2006/ppew/iewp/about-iewp.htm. [Accessed 10 December 2015].

UNISDR (2004) Terminology: Basic terms of disaster risk reduction. Available from: http://www.unisdr.org/2004/wcdr-dialogue/terminology.htm. [Accessed 18 August 2015].

Vasilakopoulos, P., Maravelias, C. and Tserpes, G. (2014). The Alarming Decline of Mediterranean Fish Stocks. Current Biology, 24(14): 1643-1648.

Velicogna, I. (2009) Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophys. Res. Lett. 36: L19503.

Veraart, A.J., Faassen, E.J., Dakos, V., van Nes, E.H., Lürling, M. and Scheffer, M. (2012) Recovery rates reflect distance to a tipping point in a living system. Nature 481: 357–359.

Wang, R., Dearing, J.A., Langdon, P.G., Zhang, E., Yang, X., Scheffer, M. (2012) Flickering gives early warning signals of a critical transition to a eutrophic lake state. Nature 492: 419–422.

Wilson, K., Brownstein, J.S., 2009. Early detection of disease outbreaks using the Internet. CMAJ 180: 829–831.

Wintle, B., Runge, M. and Bekessy, S. (2010) Allocating monitoring effort in the face of unknown unknowns. Ecology Letters, 13(11):1325-1337.

World Meteorological Organization (2015) 'Multi-Hazard Early Warning Systems (MHEWS)' Disaster Risk Reduction Programme: WMO. Geneva, Switzerland. Available from: https://www.wmo.int/pages/prog/drr/projects/Thematic/MHEWS/MHEWS_en.html [Accessed 8 December 2015].

World Resources Institute (2013) Greenhouse Gas Protocol: Required Greenhouse Gases in Inventories. World Resources Institute and World Business Council for Sustainable Development.

Zenetos, A., Koutsogiannopoulos, D., Ovalis, P., and Poursanidis, D. (2013) The role played by citizen scientists in monitoring marine alien species in Greece. Cah. Biol. Mar. 54: 419-426.