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Late lessons from early warnings: science, precaution, innovation

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Since 2001: many changes, crises and lessons relearnt

The first volume of *Late lessons from early warnings* was published in 2001. Since then, the world has changed significantly. It is larger in population but smaller in interconnectivity; faster in terms of technology adoption but slower in terms of policy action in the face of complex interlinked problems; more volatile in terms of economic and environmental changes, yet more static in terms of political reflexivity and adaptations in governance. Beyond the current financial and economic crises, there are several long-term, systemic and interconnected challenges, such as depletion of natural resources, climate change, a 2-billion person increase in the world population by 2050, and diminishing ecosystem resilience (EEA, 2011a; OECD, 2012; WEF, 2012).

These developments point to two important realities. First, the systems of governance misrepresent the socio-ecological system, making societies and the environment subordinate to the economy — essentially serving as sources of human and natural capital. This misrepresentation ignores the reality that any civilisation is ultimately dependent on its ecological and social foundations and that economies function to sustain and enhance human well-being (Passet, 2001). Second, the scale, interconnectedness and sheer complexity of feedbacks between nature and human interventions have outstripped society's capacity to understand, recognise and respond to these effects.

The first volume ended with a call to action for policymakers. How much progress has been made since then? One important area is that of innovation and the effect that precaution can have on it. In Volume 1, the difficulties of balancing precaution with technological innovation were recognised. However, there is now increasing evidence that precautionary measures do not stifle innovation, but can encourage it, in particular when supported by smart regulation or well-designed tax changes (EEA, 2011b, 2011c; Ambec et al., 2011; Ashford and Hall, 2011).

Volume 1 also invited policymakers to take more account of a 'richer body of information from more diverse sources'. It identified public health and the environment as two fields of science that were separate and polarised. And it suggested involving a wider range of stakeholders to expand the information base and to 'improve public trust in society's capacity to control hazards, without stifling innovation or compromising science'. These are all areas where improvements have been made since 2001.

There has been less progress with other lessons, particularly the call to 'identify and reduce institutional obstacles to learning and action'. Both political and scientific 'bureaucratic silos' do not seem to have disappeared, despite the frequent calls for policy integration and inter-departmental coordination (Hamdouch and Depret, 2010; Phoenix et al., 2012).

Worryingly, warnings of impending hazards are, in many areas, still not being heeded and the resulting damage is far more widespread, geographically, across species and extending to future generations, who will particularly suffer many of the harmful effects of our current energy systems, chemicals and technologies. Damage is now shown to be occurring at increasingly lower levels of exposure to pollution, and the polluters, for the most part, are still not paying the full costs of their pollution, partly because of a lack of incentives to do so. At the same time we see the destruction of the stocks of natural capital that underpin human well-being. It is easy to lose sight of the crucial dependence of economies on a diverse, healthy and resilient natural environment, especially in times of economic crises.

A key message in the 2001 report was the notion that 'the growing innovative powers of science seem to be outstripping its ability to predict the consequences of its applications, while the scale of human interventions in nature increases the chances that any hazardous impacts may be serious and global.' This is happening at an ever-greater pace, with globalised industries racing to introduce new technologies but with limited understanding of what their impacts might be. National governments now have less control over globalised technologies.

More positively, however, new transformative approaches are emerging for managing the systemic and interconnected challenges that we face (e.g. Gladwell, 2012; Stirling, 2008). They are building in particular on the increasing use by consumers, citizens and shareholders of the power of the internet and social media to demand and foster increased participation, responsibility, accountability and transparency.

Such approaches also need longer-term perspectives. Greater complexity, uncertainties, scientific ignorance, broader risks and the irreversibility of many harmful impacts together necessitate the increased use of long-term scenarios and strategy analysis by citizens, governments and corporations alike (EEA, 2011a). The long-term interests of society as a whole, distinct from the partial interest of particular stakeholders and individuals, also require new political and financial institutions that can help overcome the short termism of most politics and much finance (Ward, 2012; Roderick, 2010; Mainelli and Giffords, 2009; RMNO, 2009).

The case studies in this second volume of *Late lessons from early warnings* provide some new insights from the lessons of the past that can help stimulate actions to reinforce, complement and put into practice the emerging transformative approaches, mindful of the observation that 'those who cannot remember the past are condemned to repeat it' (Santayana, 1905).

2001–2013: what new insights emerge?

Many of the cases in this report reveal similar lessons to those in the 2001 report. Some insights have been strengthened, however, as the body of evidence has increased and our understanding of ecological and biological systems has improved. The case studies in the two volumes of *Late lessons from early warnings* cover a very diverse range of both recent and historical chemical and technological innovations and their impacts on humans and nature. All cases have unique characteristics stemming from the type of the innovation, the origins and nature of the hazards, the prevailing approaches to policymaking, and the cultural influences of time and place. The studies also share common features, such as key decisions on innovation pathways made by a few people on behalf of many; a lack of institutional and other mechanisms to respond to early warning signals; misleading market prices that do not properly reflect all costs and risks to society and nature; and inadequate accounting for assets and liabilities across different types of capital.

Such features from the past raise questions for the future. How, for example, can the innovations that are driving knowledge economies, such as nanotechnologies, be developed without repeating the mistakes of the past? How can the wider and wiser application of the precautionary principle support decision-making in the face of uncertainties from within complex systems that defy prediction and where 'surprises' are inevitable? How can we ensure that the lack of 'perfect' knowledge is not a justification for inaction in the face of 'plausible' evidence of serious harm? How can conflicting interests (including public and private ones) be balanced in the development, use and impact phases? How can the distribution of costs and benefits over time be made more equitable?

The *Late lessons from early warnings* case studies demonstrate the complexities of handling the interactions between the many actors and institutions involved — governments, policymakers, businesses, entrepreneurs, scientists, civil society representatives, citizens and the media. Each comes to the debate with different and often conflicting knowledge, perceptions, interests and priorities; balancing these numerous and often antagonistic positions should be seen as a prelude to making decisions on those innovations that have broad societal implications.

The opportunities are manifold but can be boiled down to three main ones:

- to correct the prioritisation of economic and financial capital over social, human and natural capitals through the broader application of the policy principles of precaution, prevention and polluter-pays, and improved accounting systems across government and business;
- to broaden the nature of evidence and public engagement in choices about crucial innovation pathways by balancing scientific efforts more towards dealing with complex, systemic challenges and unknowns and complementing this knowledge with lay, local and traditional knowledge;
- to build greater adaptability and resilience in governance systems to deal with multiple systemic threats and surprises, through

strengthening institutional structures and deploying information technologies in support of the concept of responsible information and dialogues.

Taken together the case studies provide some lessons to support action, supplementing the conclusions of Volume 1. These findings are presented in the remainder of this section.

Reduce delays between early warnings and actions

Most of the case studies in both volumes of *Late lessons from early warnings* illustrate that if the precautionary principle had been applied on the basis of early warnings, many lives would have been saved and much morbidity and damage to ecosystems would have been avoided.

Today, several factors related to the speed, scale and breadth of technological innovation exacerbate the tendency to delay action. First, by the time evidence of harm is confirmed, the technology has often changed, leading to assumptions that, unlike yesterday's technology, today's technology is now safe. Second, for some technologies (e.g. broad-scale energy production systems or chemical plants), the huge initial investments mean that yesterday's investments will be redeemed before any serious risk reduction is implemented, creating *de facto* technological lock-ins. Third, the scale of technological development puts very difficult demands on those attempting to monitor and respond to the risks before they have become serious, widespread and irreversible.

These features of contemporary life further strengthen the case for taking early warning signals more seriously and acting on lower strengths of evidence than those normally used to adduce 'scientific causality'.

The case studies have shown that the main barriers to timely action include the short-term nature of many political and financial horizons; the novel and challenging nature of the technologies and the scientific problems that arise from their interactions with complex biological, ecological and social systems; the conservative nature of much environment and health science; the ways in which scientific and other evidence is evaluated; the different perspectives and interests of many stakeholders and the vested interests of some powerful ones; and the broader cultural and institutional circumstances of public policymaking that often favour the status quo.

Addressing these causes of delay can help to reduce the negative impacts that arise from many innovations. But tackling them is not easy. For example, the problem of the unequal distribution of political power between citizens, business and financial actors, and governments is a persistent problem of politics, which has increased through globalisation and the rise of multinational corporations, yet it is an issue that is well beyond the scope of this report. Some of the other causes of delay are more amenable to change and these are addressed in the rest of this section.

In evaluating the pros and cons of using the precautionary principle, it is important to remember that the harm from most hazards analysed in the case studies turned out to be more diverse and widespread than anticipated and such damage is often found to occur at exposures lower than initially considered dangerous.

For example, it has been known since 1960 that asbestos causes the mesothelioma cancer, in addition to lung cancer (identified in 1955) and asbestosis (identified in 1906–1929). Similarly, it is now known that smoking causes a wide range of cancers, heart disease and foetal damage, beyond the harm of lung cancer identified in 1951. PCBs are now known to cause neurological problems in children, and cancer, in addition to harming the reproduction of eagles (identified in the 1960s). Lead has also been demonstrated to be more broadly chronically harmful — it was initially recognised as damaging children's IQ but it is now known to cause heart disease in adults. Radiation has gone through a similar expansion of known hazards.

This phenomenon of 'harm expansion' is rendered more problematic by the discoveries that harm from all of the above agents has been found to occur at lower and lower levels, such that, more often than not, no 'safe' threshold of exposure can be identified. This knowledge needs to be taken into account when evaluating the potential pros and cons of future precautionary action on emerging issues. Continuous, anticipatory reductions in exposures to emerging hazards could help to avoid repeating these histories of harm expansion.

More and better prospective and retrospective analyses of the costs of action and inaction, across the full lifecycle of a technology, would highlight the value of precautionary and preventive actions, particularly the value of 'secondary benefits and costs' which can be substantial, such as the health benefits from reduced fossil fuel use, where the main objective is to mitigate climate change. They should also consider the psychological and societal costs of both false alarms concerning a health hazard, e.g. the over-reaction to swine flu in the US in the 1970s, and misplaced reassurances concerning the safety of a technology, such as the downplaying of risks associated to nuclear power plants by Japanese authorities and utilities. Such pro and con analyses should be independent of interested parties, both commercial and political, as they often have a 'natural' tendency to exaggerate costs of hazard reduction and to underestimate the benefits of action.

As case studies from both volumes have also shown, the timely use of the precautionary principle can often stimulate rather than hamper innovation, in part by promoting a diversity of technologies and activities, which can also help to increase the resilience of societies and ecosystems to future surprises. Keeping options open and following multiple paths means that a particular option can be terminated if it turns out to pose high risks, and avoids situations of technological monopolies such as those experienced, for example, in the cases of asbestos, CFCs and PCBs.

In contrast, technological monopolies hamper innovation. For example, it was the monopolies of lead in petrol, asbestos, CFCs and PCBs that both prolonged the harms they caused and made those harms widespread. These monopolies contributed to technological 'lock-in' but also to institutional and ideological lock-ins, which further hampered innovation and the development of alternatives. These technologies and their products were also 'cheap' in the market place, bearing little relation to their real costs in terms of harm to the environment, human health and financial compensation to victims. These artificially low market prices in turn helped to stifle the development of smart substitutes.

This past experience should be taken into account with the emerging technologies such as GMOs and nanotechnologies, where there are already signs of technological monopolies, driven by the high costs of research, development and production involved and the patent protections for developers on many of their products and processes (Stirling, 2007; van den Hove et al., 2012).

When applying the precautionary principle, there are, therefore, not only scientific issues to be considered but also ethical choices, concerning the appropriate strength of evidence for action; the equity implications arising from the costs and benefits of action and inaction; the appropriate balance between generating false negatives and false positives; and the social necessity of large-scale innovations.

Clearly, acting to avoid or reduce harm on lower strengths of evidence than that used to establish scientific causality will sometimes increase the number of false alarms — although the review of 88 cases of alleged false positives in Volume 2 of *Late lessons from early warnings* confirmed just four actual cases, suggesting that the risks are considerably less than sometimes claimed. Moreover, it is important to recognise that, in cases where there are damages over a long time span that may irreversibly alter the system, there is a fundamental asymmetry between the competing policy and scientific options of avoiding false negatives and avoiding false positives. Examples of such situations of irreversibility include climate change, modification to the genetic make-up of humans or other species, persistent chemical or radioactive contamination, and species loss.

If an early warning signal triggers a double reaction of precautionary policy measures and more intensive research on risks and alternatives, then at some point the research may show that this was a false alarm and the precautionary measure can be cancelled. The loss in this case will be a delay in economic and social benefits from the technology (or the cost of mitigating actions in cases such as climate change) during the time it took to show that there was no cause for concern. But the system will not be irreversibly altered. In contrast, if the early warning triggers no precautionary action but more research shows, only much later, that there was indeed real cause for concern then irreversible systemic damages will already have taken place. Acknowledging this asymmetry is central to understanding when precautionary and preventive approaches are best deployed.

Tipping the overall balance of public policy towards avoiding harm, even at the cost of more false alarms, would seem to be a price that is well worth paying, given the costs of being wrong in acting or not acting. This is one of the strategic and ethical societal choices, similar to the choice of strengths of evidence to be used in civil or criminal court cases, that needs to be openly debated.

Acknowledge complexity when dealing with multiple effects and thresholds

The world is drawing down its natural capital through an over-reliance on fossil-fuel-based, synthetic chemicals that are compromising the health and resilience of ecosystems and key organisms such as fish and bees, in combination with other stressors such as climate change and invasive alien species. There is also evidence that some types of genetically modified crops (and the agrochemical substances used alongside them), which are released into the environment and the food chain, present a threat to human health, some species and ecosystems, and food security. Human health is being further compromised by chemicals that threaten health from before birth, through childhood and into adulthood. (Barouki et al., 2012; EEA, 2012; Kortenkamp et al., 2011).

Such exposures appear to contribute to increases of many types of cancers, birth defects, male infertility, and cardiovascular, neurological and immunological dysfunctions and diseases. The impacts of these hazards are being supplemented by the harmful effects of unhealthy eating habits and lifestyles in many parts of the world, and resulting in epidemics such as diabetes and obesity. Taken together, these multiple stressors have profound public health significance.

Growing scientific knowledge clearly shows that the causal links between stressors and harm are more complex than was previously thought and this has practical consequences for minimising harm. Much of the harm described in Volumes 1 and 2, such as cancers or species decline, is caused by several co-causal factors acting either independently or together. For example, the reduction of intelligence in children can be linked to lead in petrol, mercury and PCBs as well as to socio-economic factors; bee colony collapse can be linked to viruses, climate change and nicotinoid pesticides; and climate change itself is caused by many complex and inter-linked chemical and physical processes.

In some cases, such as foetal or fish exposures, it is the timing of the exposure to a stressor that causes the harm, not necessarily the amount; the harm may also be caused or exacerbated by other stressors acting in a particular timed sequence. In other cases, such as chemicals like BPA, low exposures can be more harmful than high exposures; and in others, such as asbestos with tobacco, and some endocrine disrupting substances, the harmful effects of mixtures can be greater than from each separate stressor. There are also varying susceptibilities to the same stressors in different people, species and ecosystems, depending on pre-existing stress levels, genetics and epigenetics. This variation can lead to differences in thresholds or tipping point exposures, above which harm becomes apparent in some exposed groups or ecosystems but not others. Indeed there are some harmful effects that occur only at the level of the system, such as a bee colony, which cannot be predicted from analysing a single part of the system, such as an individual bee.

The increased knowledge of complex biological and ecological systems has also revealed that certain harmful substances, such as PCBs and DDT can move around the world via a range of biogeochemical and physical processes and then accumulate in organisms and ecosystems many thousands of kilometres away. The practical implications of these observations are threefold. First, it is very difficult to establish very strong evidence that a single substance or stressor 'causes' harm to justify timely actions to avoid harm; in many cases only reasonable evidence of co-causality will be available. Second, a lack of consistency between research results is not a strong reason for dismissing possible causal links: inconsistency is to be expected from complexity. Third, while reducing harmful exposure to one co-causal factor may not necessarily lead to a large reduction in the overall harm caused by many other factors, in some cases the removal of just one link in the chain of multi-causality could reduce much harm.

A more holistic and multi-disciplinary systems science is needed to analyse and manage the causal complexity of the systems in which we live and to address long-term implications. For example, there would be substantial benefits from exploring, much earlier and more systematically, the multiple effects on people and ecosystems of chemical and other stressors, their cumulative effects, chemical metabolites, and their mixture effects. Exposures to low doses of contaminants and their effects, particularly in susceptible sub groups in populations, should also be more fully investigated, accompanied by more biological monitoring that would improve the detection of the precursors of disease.

Several case studies provide examples of where assertions that 'no evidence of harm' have been interpreted as 'evidence of no harm', which may not be the case if appropriate research over relevant time periods is missing. Examples include leaded petrol in the 1920s-60s, and risks to children from mobile phones before 2011, when the first study on children was published. Such authoritative but unsubstantiated assertions of safety have led to much harm, for example, in cases such as asbestos, tobacco, lead and mercury.

Acknowledging both uncertainties and scientific ignorance is particularly important where the science is relatively immature, as with such emerging technologies as GM crops, mobile phones, nanotechnology and invasive alien species and where exposures are widespread. Recognising uncertainty also helps to avoid putting too much reliance on simple models of complex systems as in the cases of floods, nuclear accidents, climate change, ecosystems resilience and multi-pollutant human exposures

Uncertainty, though, can be a two-edged sword, being used as the basis for challenging both assurances of safety and evidence of a hazard. In particular, uncertainty has been misused, exaggerated, or even 'manufactured' in order to delay and undermine regulatory measures to protect health and environments. Examples include climate change, tobacco, lead, honeybees and beryllium (Michaels, 2008; Oreskes and Conway, 2010).

There is also an asymmetry between the high levels of proof of harm demanded by proponents of a technology as sufficient to justify remedial or preventive actions compared to the level of evidence they deem sufficient to claim that their products are 'safe'. Waiting for high levels of proof of harm before acting not only leads to much harm but also to a stifling of innovation, as the case studies on asbestos, lead, mercury, PCBs and CFCs illustrate.

Rethink and enrich environment and health research

The need for research to focus more on the potential hazards of emerging technologies in addition to research on product applications has already been noted. It would also be helpful if there were a greater focus on emerging hazards rather than on well-known risks. Recent research (Grandjean et al., 2011) indicates that much environmental health research still focuses on well known hazards, such as lead and mercury, and tends to ignore newly emerging threats to health. The top ten substances studied are all metals such as copper, lead, zinc and cadmium. These established hazards account for approximately half of all the journal articles on impacts of chemical substances of the last ten years (Grandjean et al., 2011). This disproportion has crowded out research into other dangerous hazards and risks, such as on endocrine-disrupting substances and other hazards where less is known about their pathways and impacts (despite over EUR 100 million of EU research funding on endocrine disrupting compounds in the last decade) but where the evidence is growing of widespread impacts on humans and nature (EEA, 2012; Kortenkamp et al., 2011).

A major reason for this imbalance may relate to the prevailing regulatory science paradigm, where solid conclusions depend on replication and verification. Other likely contributing factors to scientific inertia are the effective use of costly infrastructure to ensure value for money; the desire of policymakers for more certainty from science regarding politically difficult choices; and the tendency of funding agencies to be conservative in their research strategies.

In order to identify hazards that may only appear over decades, there needs to be more long term monitoring of biological and ecological systems, focusing on 'surprise sensitive' parameters such as bees, amphibians, invertebrates, foetuses etc. Such monitoring will also be essential to evaluate the effectiveness of the precautionary and later measures to avoid harm. Monitoring can be supported in part by citizen scientists, using the latest geographical information systems (GIS) and monitoring technologies.

Several cases highlight the benefit of having lay and local knowledge alongside scientific evaluation of harm so that a broader knowledge base can support decision-making. For example, when a mother hypothesised that neurological signs observed in her son were due to exposure to mercury in her womb, this was dismissed by experts who did not question their assumption that the placenta provided protection (see Chapter 5 on Minamata disease). Patients, fishers, wives (e.g. in the sperm damaging, described in Chapter 9 on DBCP), mothers (see Chapter 5 as well as and the chapter on DES in Volume 1 (EEA, 2001, Ch. 8)), factory workers, and bee keepers, as well as clinicians and factory inspectors are amongst those non-scientists who have reliably provided early warnings in the case studies.

Precautionary actions are justified by lower strengths of evidence than those conventionally used for establishing scientific causation, yet in their search for 'certainty' scientists are cautious in attributing causation to an agent while some scientists may sometimes be less cautious when asserting 'safety'. The case studies show that in the past there have been premature assertions of safety based on inadequate scientific methods, such as an over-reliance on studies that were conducted over too short a period to reveal long-term effects for example.

Also evidence of harm has often had to reach the high standard of 'causality' as is the standard for less complex situations, rather than precautionary strengths of evidence based on plausible association between hazards and harms. The strength of evidence chosen can range from 'a scientific suspicion' of harm to 'beyond all reasonable doubt', depending on the complexity of the system, the level of protection required and the pros and cons of being wrong in acting or not acting.

To avoid waiting for strong evidence of harm in humans and ecosystems, data from animal or other species and methods (ECVAM), should be more widely used to justify precautionary action. This is particularly needed where the potential damage is irreversible — as with some cancers, species and ecosystems losses, and reproductive or developmental effects.

Research, precaution, and exposure control also need to be applied to the substitutes or alternatives to hazardous agents. The chapters on perchloroethylene (Chapter 4), leaded petrol (Chapter 3), DDT (Chapter 11) and booster biocides (Chapter 12) as well as the chapters on CFCs and MTBE in Volume 1 (EEA, 2001, Ch. 7 and Ch. 11) illustrate the hazards that some alternatives have brought in the wake of banned substances, especially when the alternatives are chemically very similar (e.g. HFCs for CFCs). Minimising the hazards of alternatives could be helped by the avoidance of such chemical characteristics as persistence, bioaccumulation, and large spatial range; by the hazard screening of alternatives; and by the greater use of the knowledge to be found in smarter and greener chemistry and technology.

Greater awareness of the complexity, interconnectedness, multi-causality and uncertainties inherent in global environmental issues underlines the need for greater humility about what science can and cannot tell us. Framing issues as purely scientific and technical inappropriately places scientific perspectives above equally valid social and ethical contributions that should be part of decision-making. A shift is needed to more explicitly integrative environmental science approaches in support of public policy, in which systemic considerations and early warnings feature strongly. This shift has started to take place in discourses but often not in practices.

The case studies in Volume 2 of *Late lessons from early warnings* also illustrate how regulatory health and environmental science is still defined in very narrow terms, which obstructs it from being able to identify the complex multifactorial stresses on environmental systems and humans. There is therefore a need for environmental science to become more attuned to the inherent complexities of socio-ecological systems by, for example, balancing a traditional disciplinary focus with more holistic cross-disciplinary scientific research, thereby complementing precision with relevance and comprehensiveness (Phoenix et al., 2012). Such science would often embrace longer timescales, more end-points, and multi-causality.

Since the first volume of *Late lessons from early warnings*, scientific approaches such as 'sustainability science', 'systems biology' or 'futures research' have continued to emerge to help deal with some of the challenges arising from the interconnections and dynamics of socio-ecological systems, focusing on analysis and interventions at the systems level. These emerging disciplines can also help build bridges between research, policy communities, other stakeholders and the public (Kates, 2011).

Last but not least, the case studies show that early warners — scientists and others — have often been harassed for their pioneering work which threatened economic interests and often challenged conventional scientific paradigms. This harassment can include bans on speaking out or publishing; loss of funding; legal or other threats; demotion; transfer to other work and character assassination in scientific and other media (McCulloch and Tweedale, 2007; Martin, 1999, 2008; UCS, 2012). Such early warners should receive better protection via the extension of 'whistle blowing' and discrimination laws; by more active support and protection from scientific societies in the case of scientists; and by awards that acknowledge the value of their work.

Improve the quality and value of risk assessments

Volume 1 stressed the differences between risk, uncertainty and scientific ignorance, and the need to acknowledge and identify all three when doing evaluations of evidence, as in formal risk assessments. Since 2001, some considerable progress has been made in characterising uncertainties in risk assessments, for example, in the food industry (EFSA, 2006, 2013), the field of emerging risks (SCENIHR, 2012), and in climate change (IPCC, 2010). This recognition of uncertainty and ignorance is particularly important where there is much reliance on modelling, as in climate change, invasive alien species, or exposure assessment.

The majority of case studies indicate that it is often inappropriate to use a narrow conception of 'risk' to manage the complex issues at hand with their inevitable features of ignorance, indeterminacy and contingency. The increasing awareness of the complexity of biological, ecological and technological systems, calls into question the relevance and prevalence of some of the simplistic methods, models and assumptions used in risk assessments. For example, linear dose response curves can be inappropriate when low doses are more harmful than high doses, as in the BPA story; the dictum that the dose alone 'makes the poison' is inaccurate when it is the timing of the dose that makes the dose harmful, as in the TBT and DES cases; assuming uni-causality is too simplistic when multi-causality is the reality, as in the lead case study and many ecosystems such as fisheries; testing for single substances is inadequate when mixtures are present as in all cases of chemical exposures; and there can be an over-reliance on statistical significance when use of confidence limits would be more appropriate.

Simplistic assumptions are also observed in technological risk assessments. As the Fukushima Investigation Committee (NAIIC, 2012) concluded, 'the accidents present us with crucial lessons on how we should be prepared for 'incidents beyond assumptions'. With its failure to plan for the cascade effects beyond design–base accidents 'the regulatory emphasis on risk based probabilistic risk assessment has proven very limited'.

In other words, narrow risk assessment approaches are now outstripped by the realities that they cannot address, recognise and communicate. Too often this contributes to effective denial of those risks that do not fit the risk assessment frame. It is therefore urgent to transform risk assessment practices to make them broader-based, more inclusive, transparent and accountable. That should also enable more transparent communication of diverse scientific views, especially on emerging issues where the uncertainties and ignorance are high and genuine differences of scientific interpretations are likely, desirable, and defensible (Stirling, 2010).

In practice, risk assessments could be improved by including a wider range of stakeholders when framing the scientific risk agenda, through ensuring all available evidence is readily accessible, by broadening the scope and membership of risk evaluation committees, by increasing the transparency and consistency of committee approaches and methods, and by ensuring their independence of vested interests. Improvements in transparency were recently announced by EFSA, who wish all data submitted as part of the product authorisation procedure to be made publicly available, (EFSA, 2013).

The case studies on mercury, nuclear accidents, leaded petrol, mobile phones, BPA and bees, have shown that there can be significant divergence in the evaluations of the same, or very similar, scientific evidence by different risk assessment committees. It is often not clear from their published reports why this is so. It would be helpful if each risk assessment report explained the committee's choice of paradigms, assumptions, criteria for accepting evidence, weights placed on different types of evidence, and how uncertainties were handled. This would also help reduce the confusion amongst users of such divergent risk assessments when they are faced with very different evaluations of essentially the same evidence. It would also help people to recognise the difference between 'settled fact, majority opinion, legitimate minority view, and unsubstantiated assertions' (Weiss, 2002). Moreover, it is helpful if the sources of finance for the research studies under consideration are made explicit because of the 'funding bias' that has been observed in research on issues such as tobacco, pharmaceuticals, food, BPA, GM products and mobile phones.

The case studies on bees, lead, BPA and nuclear accident risks have shown that the scope and membership of some risk assessment committees have been too narrow, and they have sometimes been dominated by one discipline or paradigm with shared assumptions which are not therefore questioned. Risk assessments can be made more reliable if they embrace all relevant scientific knowledge and approaches. For example endocrinology currently brings new insights into hormonally active biological systems that complement conventional toxicology. Toxicity test methods and risk assessments can benefit from more recent yet reliable scientific knowledge emerging from academic research fields.

The case studies also show that toxicity tests designed for acute effects are unlikely to be relevant to chronic effects, and that novel technologies, such as systemic pesticides that replace sprayed pesticides or new chemical compounds replacing earlier ones, usually need novel risk assessments.

The value of being transparent about what is known and not known and about uncertainties and disagreements is equally pertinent. Scientific conclusions should not be portrayed as if there is consensus when there is not. Science by its nature progresses by building on critical appraisal. Several cases show that disagreement can be helpful to decision-makers with a broader picture of the alternative directions and options available before making a decision.

The whole process of risk analysis which includes risk assessments, risk management and risk communication, would benefit from the involvement of stakeholders, particularly when framing the risk assessment and identifying options for risk management. This is illustrated in Ch. 27 on the precautionary principle.

Foster cooperation between business, government and citizens

An element that is often missing from innovation policies and practice is the recognition that innovation should be considered as a means, not an end in itself, and desirable to the extent that it improves human health and well-being while maintaining ecological resilience. Policy formulation should start from these premises and from a broader concept that includes not only technological innovation but also non-technological, social, institutional, organisational and behavioural innovation (van den Hove et al., 2012).

In this framework, governments have at least three roles: first, providing direction by putting in place smart regulations and consistent market signals; second, ensuring that the distributional consequences of innovations are balanced between risks and rewards across society; and third, fostering a diversity of innovations so that the wider interests of society take precedence over narrower interests.

Numerous case studies show that decisions to act without precaution often come from businesses. There are, however, several impediments to businesses acting in a precautionary manner, including a fundamental economic focus on creating and increasing short-term economic value for shareholders. There are also a number of psychological factors involved that lead to a so-called 'ethical blindness' or a 'self-serving bias' whereby people largely (and often unconsciously) tend to interpret ambiguous situations in their own interests.

This report reveals interesting parallels between older case studies and fast emerging issues such as nanotechnologies, genetically modified crops, new chemicals, and the possible link between brain tumours and non-ionising radiation from mobile phones. For example, only a very small number of actors were involved in making strategic decisions about lead in petrol in the USA in 1925 yet the technology spread all around the world before being phased out some 60 years later. With issues such as GMOs in food and energy options for a low carbon future, only a relatively few actors are involved in choosing innovation pathways that will shape the future of agriculture and energy supply and use for many decades.

Governments and businesses could collaborate more with citizens and civil society on publicly disclosing and analysing the potential value conflicts entailed in acting on early warning signals. Public disclosure and a culture of transparency and open discussion can in turn promote positive business attitudes and innovations. As stressed above, in many cases, accurate determination of risk is difficult and open to disagreement, making engagement, openness and transparency all the more important.

Involving the public can also help in choosing between those innovation pathways to the future (WBCSD, 2010; EC, 2011; WBGU, 2012); identifying and prioritising relevant public research (e.g. Diedrich et al., 2011); providing data and information from other knowledge holders — including NGOs, lay observers and citizens — in support of monitoring and early warnings; improving risk assessments; identifying and considering both alternatives to potentially hazardous agents and the unintended consequences of both actions and inactions on such agents; striking appropriate trade-offs between innovations and plausible health and environmental harms; and, making decisions about risk-risk trade-offs, such as the health benefits of consuming fish which contains mercury and PCBs. In particular, a feature of the studies is the top-down nature of innovations — the history of antibiotics in animal feed and lead in petrol, for example, show how a very small number of people can take decisions which have a major impact on millions. The public should help shape the future, including helping to choose strategic innovation pathways, for example, to sustainable agriculture and low impact renewable energy systems, by 2050.

The case studies also illustrate that there is often a lack of public accountability and access to the private research on which public protection authorities rely. Such access would help to increase independent verification of data submitted for licensing and would increase public trust in the regulatory authorities at a time when such trust in elites is very low.

Information and communications technologies (ICT) and their role in transforming social behaviour can help to engage the public on these issues. ICT has spawned a wide range of new collaborative tools and approaches, which, as we saw above, are already transforming the dynamics of governance and innovation, fostering two-way interactions, and which can be used to support a more diverse approach to engaging with citizens. Less positively, ICT developments and access to knowledge may be building barriers to collaboration by fostering more hectic interactions and competition in the pursuit of enhanced productivity, less face-to-face contact, and less space for thinking through possible solutions to complex realities. Creating the space for more deliberative thinking and innovation could contribute to more collaborative problem solving.

For public engagement to be effective there needs to be adequate procedures for identifying and including the relevant stakeholders and public interest groups and for the provision of adequate educational and financial resources to enable such groups to play an effective role. Public engagement can be encouraged and supported by substantially improved and simpler access to relevant data and information, building on the provisions of the Aarhus Convention and national freedom of information laws. Business concerns about confidentiality and competitiveness can be overcome through judicious use of information technologies to manage access rights while maintaining transparency on how such information has been used and the insights drawn.

Today there are large imbalances within publicly financed research between product development and the study of potential hazards, an imbalance that seems to repeat the histories of better-known hazards. In Europe for example, in the period 2002–2013, about 1 % of the total amount that the EU Framework Programmes of Research and Development allocated to developing products from nanotechnologies, biotechnologies and ICT was spent researching their potential hazards. Research carried out by private industry may well show a similar imbalance, but data is not easy to obtain.

Correcting this imbalance between researching innovations and their applications, and anticipatory researching of potential hazards posed throughout their life cycle (production, use, recycling and disposal) can help avoid unequal distribution of costs and benefits further down the line and support a better public acceptability of such technologies.

Correct market failures using the polluter pays and prevention principles

When evidence of initial harm emerges, the costs of such harm need to be internalised into the prices of polluting products, via taxes and charges, in line with the polluter pays principle. The revenues could be devoted partly to stimulating research into less hazardous alternatives, as was the case in the US with CFCs, and partly to reducing taxes and charges on labour.

The pollution taxes/charges would rise or fall in line with knowledge about increasing/decreasing harm and this would help to level the market playing field for innovative alternatives to the harmful products that are otherwise subsidised by the external costs of their pollution. Tax shifts from labour to pollution and inefficient use of resources bring other benefits such as increased employment, a stimulus to innovation and a more efficient tax system (EEA, 2011b and 2011c).

More realistic market prices, that reflect the true economic, environmental and social costs, can help encourage more sustainable behaviours by governments, businesses and citizens. More broadly, firms and governments need to extend their accounting systems beyond economic and financial capital considerations to incorporate the full human and natural capital impacts of their activities, building on developing practices worldwide (UN, 2012; EEA, 2011d; Puma, 2011).

Many case studies also demonstrate the long time lags between evidence of harm and the additional injustice and time of forcing victims to pursue their case through civil compensation claims. In the case of Minamata this took over 50 years. Prompt and anticipatory no-fault compensation schemes for victims of harm and damage to ecosystems could be set up and financed in advance of potential harm by the industries that are producing novel and large-scale technologies, thereby helping to correct this market failure. These schemes increase incentives for innovating companies to carry out more *a priori* research into the identification and elimination of hazards.

Precedents exist for such schemes in some countries, for example for nuclear accidents, oil spills, some radiation exposures, and some environmental liability laws, including contamination by GM crops of adjacent non-GM farms. Within the schemes there needs to be provision for penalising gross negligence, which under a tort system justifies punitive damages. Consideration also needs to be given to the use of anticipatory liability bonds by innovating companies so as to increase their incentive to minimise hazards and to provide adequate funds to compensate those who may suffer from any harm that may arise from their products. Re-insurance schemes are also playing a role in helping to anticipate long tail liabilities from emerging technologies.

Attributing responsibility and sometimes negligence to corporations and others active in the history of hazards has relied mainly upon evidence uncovered by the legal processes of document discovery in civil compensation cases. The further use and development of freedom of information laws and the Aarhus Convention could provide a speedier means of accessing documented history. This will be even more necessary if no-fault administrative schemes replace some civil compensation cases.

Governance of innovation and innovation in governance

This chapter opens with a picture of unprecedented global change and interdependence. Such change provides many benefits to societies but also exposes them to more shocks and surprises. Scientific and technological innovations proceed apace, more often than not on trajectories that exacerbate risks and threats. At the same time, those researching and developing technological innovations often fail to acquire relevant existing knowledge from other disciplines. Governments tend to use structures and methods from the past to monitor the potential hazards of future technologies, rather than implementing more advanced, flexible and relevant approaches.

Failures, such as those presented in the two volumes of *Late lessons from early warnings*, provide numerous valuable insights, yet it appears that memories fade quickly. Typically, a hazardous event generates a sense of urgency and enthusiasm for strengthening preparedness systems, initiating research and implementing long-term monitoring, and heavy expenditure often follows. In the aftermath of an event, relevant authorities elaborate ambitious plans and launch works, but lessons are soon forgotten. After some time without adverse events, willingness to invest in risk research, long-term monitoring etc. decreases sharply and projects are downscaled or suspended. Chernobyl and Fukushima are cases in point.

This cycle of events is termed the 'hydro-illogical cycle' in the case study on floods but could perhaps be called the 'homo-illogical cycle' as it seems to be a recurrent pattern for humankind, which is found across many cultural, political, social and economic systems. Despite its prevalence, this pattern need not be inescapable. Humans can learn, change and transform and there is enormous potential in human creativity and its capacity to inspire cultural, social, political, institutional, organisational and behavioural innovation, beyond 'mere' technological innovation. If, as Plato said, necessity is the mother of invention, then the crises we are facing create a level of necessity that will hopefully engender the needed innovations.

Crucially, governance systems also need to better recognise the value conflicts that are underpinning all societal and environmental issues. They are unavoidable and are even desirable as they are constitutive of the human condition. What is often missing is the institutional space to have a much more systematic, and non-judgmental, analysis of such conflicts so that they can be made explicit, enabling policymakers and other actors to start working together on the problems along the lines described in this chapter.

Of course such analysis already takes place (in part) in some quarters — examples include some parliamentary commissions and non-governmental organisations — but it is not sufficiently systematic and does not always focus on value conflicts. There could be merit in establishing a place in formal institutional frameworks where such value conflicts (and consequent conflicts of interests) could be analysed and proposals offered for their resolution.

The ideas for the governance of innovation and innovations in governance presented in this chapter will remain at the level of good intentions unless they are translated into institutional arrangements and practices. This is the task that lies ahead.

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