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12 Booster biocide antifoulants: is history repeating itself?

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Tributyltin (TBT) was widely used as an effective antifouling agent in paints for ships and boats until the European Community restricted its use in 1989 because of its proven harm to the environment and shellfisheries. Thereafter, booster biocides were introduced to enhance the performance of antifouling paints. They were believed to be less damaging to aquatic life than TBT. Subsequently, however, it has been established that booster biocides can also create significant environmental risks.

This chapter outlines the background to booster biocide use, the early warnings about their potential physiological and ecological impacts on non-target species, and the actions taken in response. The science that set some alarm bells ringing is described, along with lessons that could influence the future of an industry still searching for less environmentally invasive solutions.

Booster biocide antifouling agents threaten a variety of habitats — from coral reefs and seagrass beds to open moorings — within the EU and globally. Their primarily herbicidal properties mean that coral zooxanthellae, phytoplankton and periphyton are particularly vulnerable. Compared to TBT, an antifouling agent with a quite specific action, booster biocides have more broad-spectrum impacts. The wider ecological effect of shifting to booster biocides remain poorly understood but of considerable concern because they may affect the base of marine food chains.

From a toxicological viewpoint, booster biocides do not threaten to have endocrine disrupting properties similar to TBTs. At current environmental concentrations, however, some can damage primary producers and some are persistent. While legislation has been introduced to control their use, the rigour of regulations varies between countries. These geographical disparities need to be addressed, and future biocidal products and novel approaches to antifouling should be better appraised.

For policymakers, the challenge is to protect non-target biological communities from selective change resulting from booster biocide use. Persistence, bioaccumulative and toxic (PBT) criteria can be used to evaluate the relative potential impact from the available biocides, and consequently target appropriate legislation. Nevertheless, lateral thinking, aiming to identify novel materials and strategies to address antifouling, could pay dividends in the future.

12.1 Introduction

12.1.1 The need for antifoulants

Preventing plants and animals from growing on and fouling the hulls of boats is essential for the shipping industry and boating communities. The application of coatings to vessel hulls to prevent fouling organisms from settling dates back to Ancient Greece (Yebra et al., 2004) and possibly even earlier.

Protecting the hull was initially the principal concern and the earliest antifoulants often acted more as physical barriers than chemical toxicants. They prevented the isopod crustacean 'gribble' (*Limnoria*) and the infamous *Teredo* worm (actually a mollusc) from reducing hardwood planking to pulp within a matter of months. However, hull damage was not the only concern. Fouling organisms made sailing ships sluggish and severely limited their capacity to sail to windward. For naval and fighting ships, severely reduced speed and impaired manoeuvrability could mean losing sea battles ([1]).

Fouling organisms create 'hull roughness', increasing friction between the hull and the water (Evans et al., 2000). Combined with the weight of fouling organisms attached to the hull, this can lead to considerable increases in fuel consumption. A layer of algal slime only 1 mm thick will increase hull friction by 80 % and cause a 15 % loss in ship speed, while a 5 % increase in fouling for a tanker weighing 250 000 deadweight tonnes will increase fuel usage by 17 % (MER, 1996; Evans et al., 2000).

Antifouling agents, applied as paint, are the most economically efficient solution found so far. Yet they come at an environmental cost, as graphically illustrated by the organotin compound tributyltin (TBT).

12.1.2 The rise and fall of TBT

Shortly after World War II, TBT became a common additive in antifouling paints, especially in 'self-polishing' formulations which, by design, release toxic persistent substances into the environment. The use of powerful antifoulants enabled the periods between dry-docking for repainting to be extended and TBT was particularly valued because it does not cause galvanic corrosion to aluminium hulls. By the 1980s, however, TBT had been recognised as a global pollutant and its environmental effects on non-target organisms are now infamous (Santillo et al., 2002).

TBT's effects include shell malformations in oysters, which can render the produce worthless. In Arcachon Bay (France) alone TBT caused an estimated loss of USD 147 million through reduced production of the oyster *Crassostrea gigas* (Alzieu, 1991). A more serious and pervasive impact was 'imposex' — the development of male sexual organs in female marine gastropods. Worldwide, imposex has been documented for around 150 species (Vos et al., 2000). This endocrine disruption was first discovered in the early 1970s (reviewed in Santillo et al., 2001). Because of limited analytical capabilities, however, the physiological and ecological consequences were only attributed to TBT in the 1980s when many gastropod populations had declined. Importantly, mollusc species can be affected at very low concentrations — less than 10 billionths of a gram per litre (10 ng/L). By the late 1980s, the TBT problem was global.

Steps were taken to ban TBT because of its unacceptable toxic effects on commercial shellfish (especially oysters) and other non-target organisms. Regulatory controls included the EC Directive 89/677/EEC (1989) banning TBT use on small boats (< 25 m, primarily pleasure craft). Important legislation to phase out TBT use on larger vessels includes the International Maritime Organization (IMO) International Convention on the Control of Harmful Anti-fouling Systems (IMO, 2008). Santillo et al. (2001) provide further insights into the complexities surrounding TBT, its ban and the delay in controls

Barnacles on a boat. Application of coatings is used to prevent plants and animals from fouling on the hulls of boats.

Photo: © istockphoto/Carsten Madsen

([1]) Yebra et al. (2004) provide additional information on the historical development of antifouling systems.

coming into force. The extent of hazard was initially underestimated for both technical and socioeconomic reasons. Specifically:

- it was incorrectly assumed that an environmental quality target (EQT) of 20 ng/l would be sufficiently protective;
- persistence, accumulation and wider dissemination in the environment were underestimated;
- organotin bioaccumulation was underestimated (Labare et al., 1997);
- the geographical scale of the problem was not fully appreciated (inadequate data collection);
- imposex observed in 1970 in predatory gastropods in Arcachon Bay was considered acceptable — it had no immediately obvious economic cost — whereas the failure of the oyster stocks soon after was not acceptable;
- the transboundary nature of the problem was not fully appreciated until continuing TBT problems in Japan (despite a national ban in the late 1990s) highlighted the issue.

Many of these findings from TBT are useful reminders for managing booster biocides. They highlight the value of recognising potential environmental hazards early, and introducing protocols for monitoring and appropriate regulatory measures.

12.1.3 Effects of the TBT ban

EU and national legislative prohibitions on using TBT for small craft reduced pollution substantially. In Arcachon Bay, for example, concentrations fell from 900 ng/L in 1983 to below 10 ng/L in the late 1980s. The oyster beds recovered and commercial harvesting resumed during the same period. The (limited) controls imposed were hailed by some as a 'solution' to the TBT problem. Evans et al. (2000) reported a general recovery of dogwhelk populations in the United Kingdom, partially confirming this claim. However, in other European areas recovery appears to have been mixed, or slower than expected, despite the imposition of regulations for small craft (see Santillo et al., 2001).

Experience in New Zealand is one of several examples illustrating the complex interactions between TBT inputs, concentrations, accumulation and biological effects and, most importantly, the beneficial effects of legislation (Table 12.1).

On the other hand, the ban on TBT does not seem to have been very effective everywhere. Levels are still going up in Asia, implying either that it is still being used or that there are issues surrounding persistence and transportation that are not yet fully understood.

12.2 Early warnings, actions and inactions

Booster biocides were developed, at least initially, for the 'small boat' market, following the European Community ban on TBT for vessels of less than 25 m in 1989. A wide range of booster biocide compounds have been used or promoted (Box 12.1). Whilst the list is substantial, not all products have been marketed and some newly introduced compounds such as phenylborane pyridine, Econea, capsaicin and medetomidine (Thomas and Brooks, 2010) are not included.

For example, in the United Kingdom during the 1990s, antifouling agent use was massively dominated by copper(I) oxide, followed by (in order of use) diuron, Irgarol 1051, zinc pyrithione and dichlofluanid. Some of these are now banned (see Section 12.4.1). The organic biocides included agrochemicals (e.g. diuron), other compounds that were previously registered as biocides (e.g. Irgarol 1051) and personal care products such as the anti-dandruff agent zinc pyrithione.

Contamination of coastal waters by booster biocides was first reported in the early 1990s. Irgarol 1051 concentrations of up to 1700 ng/L were reported around the Cote d'Azur on the French Riviera (Readman et al., 1993). These high levels were actually discovered during a survey of agricultural triazine herbicides, which are measured using the same analytical protocol. That study triggered subsequent research, which confirmed broad contamination of boating areas in Europe, Bermuda, the United States of America, Japan, Singapore and Australia (Konstantinou and Albanis, 2004; Readman, 2006; Scarlett et al., 1999). Interestingly, Irgarol 1051 was detected in Australia, despite not being used in Australia's boating industry.

Readman et al. (1993) was followed by the pioneering studies of Dahl and Blanck (1996) on Irgarol 1051's toxicity to periphyton communities. These algae and microbes live in a surface film attached to submerged surfaces including plants,

Table 12.1 Complexities associated with TBT accumulation and legislative controls for leisure boats and ships in New Zealand from studies in 1988/1989 and 1994/1995

Issue	Environmental and governance implications
Imposex measured at different resolution (% imposex, or penis length in females relative to males)	Judging the effect of TBT on gastropods depends partly on the sensitivity of the measure used
Re-release of TBT residues in sediments and long half-life of TBT (2.5–3 years) in sediments	Can obscure actual TBT levels and the effectiveness of legislation
1989 legislation (TBT ban on < 25 m leisure craft)	No fall in % imposex at Evans Bay marina in Wellington harbour, despite TBT ban for small craft, due to close proximity of commercial Burnham Warf and leaching of TBT. Continual monitoring needed to determine the effectiveness of legislation for larger ships
1993 legislation (TBT banned completely for New Zealand vessels but not for foreign ships)	
Sampling strategy (e.g. presence of commercial ships near leisure craft)	

Source: Smith, 1996.

rocks and the hulls of boats. Periphyton is also an important indicator of water quality. The authors demonstrated the potential for ecological effects to occur at the concentrations of Irgarol 1051 present in coastal waters. Together, these studies raised concerns and inspired other scientists to conduct more in-depth research.

Besides antifouling paints, however, booster biocides in aquatic environments derive from a variety of other sources, including:

- agricultural and domestic uses of chlorothalonil, dichlofluanid and diuron as agents to deal with weeds, fungi and other unwanted plant growth;
- some anti-dandruff shampoos, in which zinc pyrithione (ZPT) is the active agent against the scalp fungus, *Malasseziaglobosa*.

A comprehensive picture of booster biocide distributions and concentrations in European waters emerged from the Assessment of Antifouling Agents in Coastal Environments (ACE) project, which ran from 1999 to 2002. In the course of the project, water samples (and sediments from some areas) were collected from marinas, harbours,

Box 12.1 Examples of booster biocides used or promoted as agents in antifouling paints

- 2-methylthio-4-tertiary-butylamino-6-cyclopropylamino-s-triazine (Irgarol 1051)
- 1-(3,4-dichlorophenyl)-3,3-dimethylurea (diuron)
- 4,5-dichloro-2-n-octyl-4-isothiazolin-3-one (Sea-Nine 211)
- N-dichlorofluoromethylthio-N', N'-dimethyl-N-phenylsulphamide (dichlofluanid)
- 2,4,5,6-tetrachloro isophthalonitrile (chlorothalonil)
- bis(1hydroxy-2(1H)-pyridethionato-O,S)-T-4zinc (zinc pyrithione)
- 2-(thiocyanomethylthio)benzthiazole (TCMBT)
- 2,3,5,6-tetrachloro-4-(methyl sulphonyl) pyridine (TCMS pyridine)
- cuprous thiocyanate
- 4-chloro-meta-cresol
- arsenic trioxide
- cis1-(3-chloroallyl)-3,5,7-triaza-1-azonia adamantanechloride
- zineb
- folpet
- thiram
- oxy tetracycline hydrochloride
- ziram
- maneb

estuaries and coastal waters, covering diverse European coastal systems (ACE, 2002; Readman, 2006). Of the major booster biocides, diuron was found in the greatest mean concentrations, with the highest levels in north-western Europe. Irgarol 1051 was present at lower mean concentrations than diuron, with Mediterranean coastal environments the most contaminated. Chlorothalonil, dichlofluanid and Sea-Nine 211 were sporadically encountered, primarily in the Mediterranean. In isolated cases, however, high concentrations were recorded. Measurable concentrations of the degradation products of Irgarol 1051 and diuron were also recorded, albeit at lower levels than the parent compounds.

Globally, data for the most common biocides (diuron, Irgarol 1051 and Sea-Nine 211) are available for Europe, North America and Japan, while negligible data are available for other regions. Konstantinou and Albanis (2004) summarise data on Irgarol 1051 levels in water and sediment samples reported in the literature. More recently, booster biocides have been detected in the remotest part of the Indian Ocean, although at negligible concentrations. Indeed, of the substances sought, only Irgarol 1051 was detected. Moreover, it was only encountered in two of the 31 samples analysed, at concentrations of 2 ng/L and 8 ng/L (Guitart et al., 2007).

12.3 Early warnings: the science on antifouling agents

12.3.1 Persistence and toxicity

Concerns about the potential environmental impacts of booster biocides arose because of the high concentrations reported at an increasing number of areas, coupled with findings regarding their toxicity to periphyton (at equivalent concentrations). The high concentrations in coastal environments are maintained by leaching from vessels, although dilution and degradation act to reduce concentrations (see below). While some antifouling biocides have other uses (e.g. as agrochemicals), in marinas and harbours antifouling use normally dominates the total input (Konstantinou and Albanis, 2004). Compounds can be removed from the water column through, for example, biotic degradation, photo-degradation, chemical hydrolysis, attachment to particulates followed by sedimentation, volatilisation or bioaccumulation (Readman, 2006).

The MAM-PEC model (van Hattum et al., 1999) was developed to predict environmental concentrations of antifouling agents in the marine environment. It has been validated using the data set collected during the ACE project and can now be applied to predict future concentrations.

The half-lives of booster biocide compounds vary and can be considerable. The abiotic and biotic half-lives for these booster biocide agents, examined in laboratory studies and under controlled field conditions, indicated that diuron and Irgarol 1051 were substantially resistant to degradation in comparison with other agents. Thomas et al. (2002) and Thomas and Brooks (2010) have reported the following highly variable half-lives for booster biocides:

- Irgarol 1051: 100 days;
- dichlofluanid: 18 hours;
- chlorothalonil: 1.8 days;
- Sea-Nine 211: < 24 hours;
- zincpyrithione: < 24 hours;
- TCMTB: 740 hours;
- zineb: 96 hours;
- diuron: no degradation over 42 days in seawater when associated with antifouling paint particles (without this particle association it has a 14-day half-life).

More worrying still were the toxic effects that scientists were beginning to identify, reviewed in studies such as Jones (2005), Yamada (2006) and more recently by Thomas and Brooks (2010). The herbicidal properties of most antifoulants mean that marine plants appear to be particularly vulnerable to many of these biocides. As noted above, the first published study on the herbicidal properties of booster biocides was by Dahl and Blanck (1996), addressing the toxicity of Irgarol 1051 to periphyton communities. Long-term effects were detected at 0.25–1 nM (63–250 ng/L), which is within the range of concentrations reported for coastal waters. Later studies (Okamura et al., 2003; Jacobson and Willingham, 2000; Fernandez-Alba et al., 2002) have confirmed the vulnerability of algae/phytoplankton to booster biocides.

Using natural populations of phytoplankton, Readman et al. (2004) reported toxic effects of Irgarol 1051 at low concentrations with a 72-hour half maximal effective concentration (EC50) of

70 ng/L ([2]). The endpoint used in this study was the selective reduction in 19'-hexanoyloxyfucoxanthin. Again, this concentration is well within the range of concentrations reported in coastal waters.

Devilla et al. (2005) provide some insights into relative susceptibilities to a range of booster biocides. Growth inhibition results following 72 hours of exposure indicated that *Synechococcus* sp. was more tolerant to zinc pyrithione (NOEC ([3]) of 1 000 ng/L) and Sea-Nine 211 (NOEC of 900 ng/L) than *E. huxleyi* (EC50 of 540 and EC50 of 350 ng/L, respectively). In contrast, *Synechococcus* sp. was more sensitive to diuron (EC50 of 550 ng/L) than *E. huxleyi* (EC50 of 2 260 ng/L), whereas exposure to Irgarol 1051 similarly impacted both species (EC50 of 160 and 250 ng/L, respectively).

Endocrine disruption was also assessed within the ACE Project. None of the antifoulants evaluated (Irgarol 1051, Sea-Nine, chlorothalonil, diuron, dichlofluanid, maneb and ziram) showed a strong estrogenic response. Thomas et al. (2001) identified persistence and toxicity as critical features in the risk evaluation of booster biocides.

Despite accumulating substantial information, Voulvoulis et al. (2002) considered that additional data would still be required to properly evaluate the risks associated with widespread use of the booster biocides Irgarol 1051, diuron, Sea-Nine 211 and chlorothalonil. They cautioned against the use of TCMS pyridine, TCMTB and dichlofluanid, although again identified a lack of appropriate data. And in their initial risk evaluation, zinc pyrithione and zineb appeared to be the least hazardous options for the aquatic environment. However, analytical constraints for these latter booster biocide compounds render environmental assessment difficult.

12.3.2 Adverse ecological effects on corals

The herbicidal (chlorophyll photosystem II-inhibiting) mode of action of Irgarol 1051 also raises concerns regarding the potential impact on zooxanthellae — the symbiotic microalgae that live within warm water corals to the mutual benefit of both the coral polyps and the algae. This has important implications for the growth, survival and health of corals, already rendered vulnerable by events such as the 1998 coral bleaching episode in the Indian Ocean. That event arose from exceptional seawater warming in 1997–1998 and led to massive coral mortality. Most island archipelagos were severely affected, with mortality of over 90 % to considerable depths in the Maldives, Seychelles and Chagos (Sheppard et al., 2002).

During bleaching events coral expel, to a greater or lesser extent, their symbiotic algae known as zooxanthellae. In extreme events, as occurred in 1998, zooxanthellae are totally evicted from their host. All that remains is dead white coral skeletons or, worse still, rubble and debris — something very different from a vibrant, living reef attached firmly to the seabed (see Price, 2009). Recent publications have shown that Irgarol 1051 inhibits the photosynthesis of both zooxanthellae isolated from the coral tissues and also zooxanthellae still within the host (coral) tissues (i.e. in symbio) at environmentally relevant concentrations (as low as 60 ng/L) (Owen et al., 2002; Owen et al., 2003; Jones, 2005). Studies at many harbours in the world report concentrations of Irgarol 1051 at or above this level (Konstantinou and Albanis, 2004). This creates the possibility that antifouling agents will disperse to offshore sites, including coral reefs.

'Coral bleaching' — the dissociation of symbiosis between corals and algae — is a common but significant sub-lethal stress response requiring many months to recover. It is generally considered to be caused by elevated water temperatures but diuron and Irgarol 1051 will also cause bleaching and, like warm water bleaching, they may operate by affecting algal/zooxanthellae photosynthesis (Jones, 2005). The notion that Irgarol and diuron contamination could exacerbate bleaching caused by elevated water temperatures has not yet been tested.

Jones (2005) points out that at low levels and over short exposure periods, the coral-bleaching effects of herbicides can be reversible (i.e. when corals are returned to clean seawater) and vary according to type of herbicide. However, on exposure to higher concentrations in the light or over longer exposure periods, sustained long-term reduction of the photochemical efficiency of the algae (symptomatic of chronic photo-inhibition) follows.

Corals and reefs in European waters lack symbiotic microalgae, meaning that booster biocide toxicity

([2]) The EC50 is the concentration of a toxicant that induces a response halfway between the baseline and maximum after a specified exposure time.

([3]) NOEC denotes 'no observable effect concentration'.

to coral microalgae is not directly relevant within the EU. However, several European countries have dependent territories with significant coral reefs. In some cases (e.g. France, the Netherlands and some UK dependent territories), the environmental legislation of the dependent territories is closely allied to that of the European country. In others, such as Chagos, British Indian Ocean Territory, environmental legislation is more independent.

Chagos happens to lie in the remotest part of the Indian Ocean and studies more than 10 years ago revealed that these atolls and islands were virtually pristine and contaminant free (Everaarts et al., 1999; Readman et al., 1999), despite the fact that the biggest atoll and island, Diego Garcia, is an important military base. Booster biocide concentrations from the atolls of Chagos were determined during early 2006 as part of an international environmental research effort (Guitart et al., 2007). This has provided a useful international baseline or standard, against which biocide concentrations in European waters and elsewhere could be compared. More generally, studies have recently highlighted the scientific importance of Chagos as a 'clean' control site for monitoring environmental change (SOFI, 2009; Sheppard et al., 2009). Environmental monitoring is also an important requirement of national, European and international agreements to which the British Indian Ocean Territory is party.

12.4 The lessons drawn

12.4.1 Permitted agents

Controls and legislation have been developed to address the accumulation of booster biocides in the marine environment and the marked toxicity of certain agents. The booster biocides permitted in European waters and the legislative situation, as of 2002, are listed in Tables 12.2 and 12.3. This shows that several agents previously permitted for small craft in the United Kingdom, including diuron and Irgarol 1051, are now prohibited. In the United Kingdom, only three organic booster biocides are permitted. In Sweden there is even greater restriction. In the Netherlands, France, Greece and Spain, a greater number of agents are permissible. In the Netherlands, files for antifouling agents are being reviewed. In Denmark, diuron and Irgarol 1051 were banned for use on pleasure craft in 2000. Results from an environmental risk analysis of Sea-Nine 211 and zinc pyrithione in Danish waters demonstrated that, in most cases examined, the PEC/PNEC (predicted environmental concentration/predicted no effect concentration) ratio was less than 1, indicating an acceptable risk.

The Biocidal Products Directive (98/8/EC) provides for the authorisation of biocidal products within the European Union. The Directive harmonises the data requirements for existing and new biocides within the EU, including antifouling agents (product type 21). Any company seeking to register an antifouling agent was required to submit a notification in 2002 and provide a base set of data. Time scales for submitting additional necessary data have not been established.

National legislative positions on antifoulings are presented in IYP (2008) and Thomas and Brooks (2010) provide a review of the current legislative position.

Experiences in Bermuda provide insights that may have useful applications elsewhere. Within a period of 10 years, harmful booster biocides were identified in some harbour areas and, because of their potential harm to corals, were banned in the entire territory (Box 12.2).

Box 12.2 Case study — Bermuda

In June 1995, Readman visited Bermuda and analysed seawater samples for antifouling agents including booster biocides. Levels of Irgarol were high in some harbour areas and sparked fears of damage to coral endosymbiotic algae (Readman, 1996). Extended data were later published (Connelly et al., 2001).

The Bermuda Government (Ministry of the Environment) funded toxicological studies at the Bermuda Biological Station for Research that demonstrated the vulnerability of the corals (Owen et al., 2002 and 2003). On 1 July 2005, Irgarol- and diuron-based antifouling paints were banned in Bermuda by amendment to the Bermuda Statutory Instrument BR 20/1989 Fisheries (Anti-Fouling Paints Prohibition) Regulations 1989.

Table 12.2 Use of metallic antifoulants and organic booster biocides on yachts < 25 m in European waters

	United Kingdom	France ([a])	Greece ([a])	Spain ([a])	Sweden	Denmark ([b])	Netherlands ([b])
Copper(I) oxide	+	+	+	+	+ ([c])	+	+
Copper thiocyanate	+	+	–	–	+ ([c])	+	+
Cu powder	–	–	–	–	+ ([c])	+	–
Chromium trioxide	–	–	–	–	–	–	+
Diuron	–	+	+	+	–	–	+
Irgarol 1051	–	+	+	+	+	–	+
Zinc pyrithione	+	+	+	+	–	+	
Dichlofluanid	+	+	+	+	–	–	+
TCMTB	–	–	–	–	–	–	–
Chlorothalonil	–	+	+	–	–	–	–
TCMS pyridine	–	–	–	–	–	–	–
SeaNine 211	–	–	–	+	–	+ ([d])	–
Ziram	–	–	+	–	–	–	+
Zineb	+	–	–	–	–	–	+
Folpet	–	–	+	–	–	–	–
Total (booster biocides)	3	5 ([a])	7 ([a])	5 ([a])	1	2	5

Note: (+) Agent permitted.
(–) Agent not permitted.
([a]) Very limited/no approval scheme (in principle, all can be used).
([b]) Regulations currently under debate.
([c]) Leach rate regulated on west coast; banned on east coast.
([d]) Although approved, product not used on pleasure craft.

Source: ACE, 2002, cited in Readman, 2006.

Table 12.3 Legislative position of EU Member States, October 2008 update

European Union Member States	Antifoulings applied in EU Member States must be notified or authorised for use. Products sold in Austria, Belgium, Finland, Ireland, Malta, the Netherlands, Sweden and the United Kingdom must be registered under national pesticide laws. The Biocidal Products Directive (98/8/EC) is now in force and a review of all antifouling biocides submitted for approval is well under way. Decisions on the acceptability of these biocides are expected shortly. If a biocide is deemed 'acceptable' under the directive, EU Member States will then re-review the antifouling products containing biocides that are on the market. If acceptable, a product registration will be issued allowing sale and application of the product. Products deemed 'unacceptable' will be removed from the EU market. In the interim period before all products on the market are reviewed, the directive has required manufacturers of antifouling paints to notify details of antifouling products on the market in each EU Member State.
Restrictions	Application of TBT antifoulings to all vessels is forbidden in all EU Member States under the Marketing and Use Directive (76/769/EEC). Under Regulation (EC) No 782/2003, application of TBT antifoulings on all ships and boats flying flags of EU countries are also banned and those with active TBT antifoulings are forbidden from entering European ports and harbours. Ships over 400 gross tonnage flying flags of EU Member States must be surveyed and carry certificates of compliance with the Regulation. Ships over 24 m in length and less than 400 gross tonnage must self-certify as compliant.
Sweden	Use of antifouling products is evaluated on a case-by-case basis using risk assessment to determine if the paint's use is acceptable.
Denmark	Import, marketing and use of biocidal antifouling paint with release of copper exceeding 200 µg Cu/cm^2 after the first 14 days and 350 µg copper/cm^2 after the first 30 days are banned for pleasure crafts of 200 kg and above that are mainly used in saltwater. Import, marketing and use of biocidal antifouling paint for use on pleasure crafts less than 200 kg and mainly used in salt water is banned. This does not apply for wooden boats and it does not apply for pleasure craft belonging to harbours classified as A or B for insurance purposes. Use of Irgarol 1051 and diuron in antifoulings applied to pleasure craft is banned.
United Kingdom	Use of the organic biocides Irgarol 1051 and diuron in antifoulings is banned.
Netherlands	Use of diuron in antifoulings is banned.

Source: IYP, 2008.

12.4.2 Effects of banning selected booster biocide agents

While the positive impact of banning TBT has been well demonstrated in European waters and elsewhere, the effectiveness of legislation outlawing specific booster biocides has been determined only recently. The following summarises key findings of a study by Cresswell et al. (2006).

In 2001, the United Kingdom introduced legislative measures restricting the antifouling agents that could be used in paints for small (< 25 m) vessels to three substances: dichlofluanid, zinc pyrithione and zineb. This removed the previously popular booster biocides diuron and Irgarol 1051 from the market (for small vessels) on the grounds of environmental concerns. To investigate the impact of this legislation, water samples were taken from locations where previous biocide levels were well documented. Results from analyses demonstrate a clear reduction in water concentrations of Irgarol 1051 (by 10–55 % of levels in pre-restriction studies), indicating that the legislation appears to have been effective (Cresswell et al., 2006). No comparable data were reported for diuron. Although other booster biocides were screened for (chlorothalonil, dichlofluanid and Sea-Nine 211), they were below the limits of detection (< 1 ng/L) in all samples. It is unclear whether the Irgarol 1051 remaining resulted from some ongoing use, continued presence on pre-painted hulls, continued use on non-UK vessels entering UK ports or simply persistence of the chemical in the environment, even after use stopped completely. It is likely to be a combination of all these factors.

The reduced concentrations are attributed to changes regulating the distribution, advertising, sale and use of the booster biocide. A survey of antifouling paint retailers revealed that small amounts of Irgarol 1051-based paints were still being sold and that there was no routine monitoring of retailers. However, by regulating the production and distribution of Irgarol 1051 at the manufacturer level, the UK Health and Safety Executive has been successful in reducing environmental concentrations of the compound to below the proposed Environmental Quality Standard, EQS, of 24 ng/L. The survey of chandlers and discussions with legislative authorities supports these results and concurs with removing Irgarol 1051-based paints from the market using simple regulations targeted at manufacturers (Cresswell et al., 2006).

12.4.3 History repeats itself?

The development and use of booster biocides has followed a very similar pattern to the evolution and demise of organotin and earlier antifoulants:

- identification of new antifouling agents to replace older supposedly more toxic or less effective products (although the relative efficacy and toxicity of antifouling paints can only be determined by subsequent monitoring to establish whether initial suppositions/hypotheses were correct);
- monitoring of distribution, accumulation and toxicity of the new agent(s) to determine whether the initial supposition or hypotheses about the net benefits of new products were correct;
- concern, debate and review of the new antifouling agent(s);
- banning of the most harmful agents;
- search for less toxic solutions to the problem of biofouling communities on hulls of small craft and ships.

Detailed toxicity tests have not been undertaken for all booster biocides. There is evidence, however, for example for diuron and Irgarol 1051, that non-target organisms are exposed and potentially vulnerable. Concern arises because, as noted above, photosynthesis can be affected by booster biocides at extraordinarily low concentrations, i.e. in the 'parts per trillion' (ng/L) range. Effects may be reversible over short exposures, but higher concentrations and long-term exposure can lead to reduced photochemical efficiency of algae (Jones, 2005). In corals this may lead to breakdown of the coral-zooxanthellae symbiosis (bleaching), demanding lengthy recovery times. This has certainly been the case following coral bleaching induced by seawater warming, for example in 1998. Hence, booster biocides can impact the base of food chains, which are linked to seafood production and many other ecosystem services.

A particularly significant aspect of booster biocides is that the most popular ones act herbicidally. Both diuron and Irgarol 1051 act at the herbicide binding site (by definition) of PSII, affecting the primary photochemical reactions of photosynthesis via the QB binding site on the D1 protein. This is a remarkably conserved area (the amino acid sequence of D1 has a 98 % homology between different higher plants and 85–90 % between PSII containing species). This conservation, and the fact that it is the base of the food chain, means that, like TBT, booster biocides can potentially have far-reaching consequences. Whereas TBT acted quite specifically in causing imposex and shell abnormalities, through endocrine disruption, the booster biocides that replaced TBT have more broad-spectrum impacts.

The wider ecological impacts of the above finding and the transition to booster biocides remain poorly understood but of considerable potential concern. The message is clear: there is a need to develop and apply non-toxic and less toxic solutions to the problem of biofouling on vessel hulls.

12.4.4 Why monitoring should continue

Monitoring should continue for several reasons: the legacy of TBT, our understanding now that booster biocides are far from 'risk free', and the recognition that developing non-toxic alternatives may take years or decades. One key lesson is that there is a need to monitor at least selected constituents of the newer antifouling agents. Both the chemical and ecological aspects are, and will remain, an important marine and environmental indicator within European waters. Monitoring design will need to be sufficiently robust to identify, and quantify, temporal and spatial trends with an appropriate degree of precaution. This is necessary to ensure that any 'clean bill of health' given to existing and new booster biocides is environmentally warranted. And while several booster biocides have already been banned in parts of Europe, monitoring of both banned and permitted antifouling agents will help determine whether further legislation is needed as an additional measure of precaution.

The present report's chapter on methyl mercury pollution in Minamata Bay, Japan, demonstrates that it is not always easy to identify pollution-free sites to serve as an 'international baseline'. For booster biocides, one possible reference area has recently been established in Chagos (Guitart et al., 2007), one of the world's essentially pristine and remotest marine areas. In Chagos, concentrations of Irgarol 1051 and other booster biocides screened for were extremely low. Over the coming years, monitoring of these antifouling agents will be necessary in both affected and reference or 'control' areas.

Price and Readman (2006) outlined an approach for establishing a monitoring procedure and an indicator for booster biocides in European waters. Essentially this could be a scaled down version of the ACE project (ACE, 2002). Sampling is recommended in sites in the regions of Norway and the Faroe Islands, the Baltic, the North Sea, the Mediterranean (north and south), the Black Sea, the Barents Sea, the English Channel, the Celtic region and Irish Sea, and the Iberian Peninsula.

Monitoring efforts should focus initially on Irgarol 1051, in view of its widespread use, marked toxicity and other factors. Extensive data are available for Irgarol 1051 and it can be traced to antifouling paints since it is not used as a herbicide (unlike diuron). The 800 samples collected and analysed during the ACE project represent a valuable resource, providing baseline data that should help determine temporal and spatial patterns in booster biocide accumulation and toxicity. Sampling from one of the world's least contaminated ocean areas (Guitart et al., 2007) might provide a valuable international standard or benchmark to determine the contamination of other marine and coastal areas.

Any future monitoring programme should be firmly linked to an action plan and catalyse management activities if contaminant levels or other metrics of ecosystem health fall to some predetermined threshold level(s). Otherwise, monitoring can easily become an essentially scientific or academic pursuit. For example, physical, chemical, ecological and visual criteria have been developed to determine when (if at all) to begin and when to end oil spill clean-up. Monitoring therefore informs clean-up, by helping determine environmental situations in which clean-up is and is not appropriate. Similar considerations may be needed for regulating and controlling biocides. On the other hand, the detection of imposex at least partly resulted from initially academic work, rather than monitoring of toxic effects. Academic activities may thus play a role, not least in identifying possible emerging issues.

12.4.5 New-age antifouling: is there a non-toxic way?

Given the undeniable (and necessarily) toxic nature of biocidal antifouling agents, there is a case for further research and fast-track development of more environmentally benign solutions. The controlled, slow release of agents regulated through polymer design (Readman, 2006) is seen as one approach. However, this represents only a 'stop-gap' and far from an optimal environmental solution given the undesirability of releasing toxic substances into the water column and environment, even slowly. Arguably, it might be better for these substances to be retained permanently in the paint, assuming they could still be sufficiently effective, to enable recovery and disposal on land.

An alternative strategy makes use of natural products (or synthesised analogues). These compounds normally act enzymatically by interfering with the metabolism of fouling organisms or dissolving their adhesive materials. Structures include terpenoids, steroids, heterocyclics, alkaloids and polyphenolics. This approach to preventing fouling has not, however, been commercially exploited (Readman, 2006). Although not all natural products are hazard-free — strychnine and aflatoxins are two examples that are not used in antifouling preparations — the release and occurrence of natural antifoulant compounds derived from marine organisms is not perceived to pose a serious environmental threat by the general public.

Non-stick fouling-residue coatings that prevent adhesion by fouling organisms are another approach. At present the choice of materials is restricted to fluoro-polymers and silicones (Readman, 2006). From an environmental perspective, this option is appealing. Results from performance tests for currently available coatings indicate modest performance, requiring relatively high speeds to remove fouling organisms. A number of such formulations are already on the market and in use for some classes of vessels. Coupled with expense, however, poor adhesion qualities to the hull and susceptibility to damage mean that widespread commercial application seems unlikely without further advances in technology (Readman, 2006).

The Biocidal Products Directive (98/8/EC) and other legal instruments give consideration to substitutes and alternatives. However, it is normally existing manufacturers of antifouling products that seek to innovate in response to such instruments and they tend to devise solutions with which they are familiar — typically more biocide. The result is incremental change, such as the shift to booster biocides after TBT use was outlawed. As noted, relatively undeveloped alternatives exist, such as non-stick coatings and polishing robots, but the companies that could develop more innovative solutions are generally unaware of the emerging market.

12.4.6 Hindsight, foresight and conclusions

Table 12.4 provides a summary of the historical use of antifouling agents and the main early environmental warnings and actions. TBT, now in demise, has been a highly effective antifouling agent but is among the most toxic synthetic compounds ever produced. Use on small crafts was banned in European waters in the late 1980s and early 1990s. Prohibition has taken longer on ships. Through an international convention, and European legislation linked to this, a total ban has come into force.

For technical and socioeconomic reasons, the extent of TBT hazards was initially underestimated. Many of the warnings serve as important reminders for booster biocides, in terms of the value of early recognition of potential environmental hazards, protocols for monitoring and appropriate regulatory measures. Uncertainties regarding the geographical scale of the problem of TBT (e.g. the limited sensitivity of analytical methods and imperfect baseline data) do not constrain understanding of antifouling residues as they did twenty or more years ago.

Recent research has demonstrated the significant toxicity of booster biocides at extremely low concentrations. Of the major booster biocides, diuron has been encountered in the highest mean concentrations, particularly in north-western Europe (ACE, 2002). Irgarol 1051 has normally been identified at lower mean concentrations, with most contamination in Mediterranean coastal environments. Globally, data are available for the biocides most commonly used in Europe, North America and Japan (i.e. diuron, Irgarol 1051 and Sea-Nine 211), while negligible data are available for other biocides. Significant endocrine disruption, the major problem associated with TBT, was not found for booster biocides (ACE, 2002). Instead, booster biocides are often photosystem II inhibitors; by impairing photosynthesis they can impact the base of food chains and their dependencies (e.g. symbiotic algae and host corals).

Despite accumulating substantial information on adverse environmental side effects, some experts (Voulvoulis et al., 2002) consider that additional data are needed to evaluate properly the risks of widespread use of Irgarol 1051, diuron, Sea-Nine 211 and chlorothalonil. They caution against using TCMS pyridine, TCMTB and dichlofluanid, again identifying a lack of appropriate data. In their initial risk evaluation, zinc pyrithione and zineb appeared the least hazardous options for the aquatic environment.

Like several other countries, the United Kingdom has taken precautionary action, introducing legislation in 2001 to restrict the use of antifouling agents in paints on small (< 25 m) vessel to dichlofluanid, zinc pyrithione and zineb. The previously popular booster biocides diuron and Irgarol 1051 were banned. Recent research (Cresswell et al., 2006) indicates that this legislation appears to have been effective in reducing environmental concentrations.

Even for prohibited (but still used) toxic substances, it is fair to assume that a release into the environment is often inevitable. The preference should always be for non-toxic, competitively priced alternative approaches, rather than adding toxic contaminants to the environment.

Booster biocides must be monitored to gather more data on accumulation, toxicity and the impact of legislation. Given the undeniable (and necessarily) toxic nature of antifouling agents, however, there appears to be a strong case and market demand for further research and fast-track development of more environmentally benign solutions to biofouling, such as natural products and non-stick coatings.

Thomas and Brooks (2010) indicate that even today DDT is used in China as an antifoulant. Meanwhile, novel compounds, such as phenylborane pyridine, Econea, capsaicin and medetomidine, are almost uninvestigated, with very little information available on them in the public domain.

In conclusion, booster biocide antifouling agents threaten a variety of habitats — from coral reefs and seagrass beds to open moorings — within the EU and globally. Their primarily herbicidal properties mean that coral zooxanthellae, phytoplankton and periphyton are particularly vulnerable. Compared to TBT — an antifouling agent with a quite specific action — booster biocides have more broad-spectrum impacts. The wider ecological effect of shifting to booster biocides remain poorly understood but of considerable concern because they may affect the base of marine food chains.

For policymakers, the challenge is to protect non-target biological communities from selective change resulting from booster biocide use. Policy has proven effective in, for example, Bermuda and the United Kingdom, where banning selected agents lowered concentrations and limited adverse ecological impacts. Clearly persistence, bioaccumulative and toxic (PBT) criteria can be used to evaluate the relative potential impact from the available biocides, and consequently target appropriate legislation. Nevertheless, lateral thinking, aiming to identify novel materials and strategies to address antifouling, could pay dividends in the future.

Table 12.4 Early warnings and actions

Early maritime to late-1600s ~ 2–3 thousand years	Ancient Greece: lead sheathing and copper nails caused no environmental concern
~ 800 AD	Arab ships: lime and mutton fat coating caused no environmental concern
Late 1400s	Columbus: pitch and tallow coating caused no environmental concern
1600s	UK navy: tar, grease, sulphur pitch coating caused no environmental concern
Late 1700s	Copper sheathing caused no environmental concern
Mid 1800s →	Copper paints caused no or limited environmental concern
Mid 1900s	Copper, arsenic and mercury paints caused no or limited environmental concern
Late 1950s/early 1960s–1990s	Organotin compounds such as tributyl tin (TBT) caused increasing environmental warnings and actions (see EEA, 2001, Ch. 13)
1989	EC Directive 89/677/EEC bans TBT on small boats (< 25 m), triggering the development and use of booster biocides
1993	First report of booster biocides in coastal waters (Irgarol 1051)
1996	First report on the toxicity of booster biocides at environmental levels (Dahl and Blanck, 1996)
1997	Previous events trigger expanded environmental research
1999	European Commission funds ACE Project (ACE, 2002)
2000	Under the Biocidal Products Directive (98/8/EC) the European Commission began reviewing all biocides used in all biocidal products, including antifouling paints. It entered into force on 14 May 2000
2000	UK Health and Safety Executive began phasing out all booster biocides except dichlofluanid, zinc pyrithione and zineb for small vessels (< 25 m)
2002–2005	Concern raised over toxicity of booster biocides to coral zooxanthellae at extremely low concentrations (e.g. Owen et al., 2002, 2003; Jones, 2005) leading to bans on specific agents in several countries
Today	Development of new technologies/non-toxic alternatives: • potential for natural products (disturbing foulant metabolism or dissolving foulant adhesives) • potential for fluoro-polymers and silicones (non-stick coatings)

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13 Ethinyl oestradiol in the aquatic environment

Susan Jobling and Richard Owen

Many decades of research have shown that when released to the environment, a group of hormones known as oestrogens, both synthetic and naturally occurring, can have serious impacts on wildlife. This includes the development of intersex characteristics in male fish, which diminishes fertility and fecundity. Although often sublethal, such impacts may be permanent and irreversible.

This chapter describes the scientific evidence and regulatory debates concerning one of these oestrogens, ethinyloestradiol (EE2), an active ingredient in the birth control pill. First developed in 1938, it is released to the aquatic environment via wastewater treatment plants. Although it is now clear that wildlife species are exposed to and impacted by a cocktail of endocrine disrupting chemicals, there is also reasonable scientific certainty that EE2 plays a significant role, and at vanishingly low levels in the environment.

In 2004 the Environment Agency of England and Wales accepted this, judging the evidence sufficient to warrant consideration of risk management. In 2012, nearly 75 years after its synthesis, the European Commission proposed to regulate EE2 as a EU-wide 'priority substance' under the Water Framework Directive (the primary legislation for protecting and conserving European water bodies). This proposal was subsequently amended, delaying any decision on a regulatory 'environmental quality standard' until at least 2016.

This is in part because control of EE2 will come at a significant price. Complying with proposed regulatory limits in the environment means removing very low (part per trillion) levels of EE2 from wastewater effluents at considerable expense.

Is this a price we are willing to pay? Or will the price of precautionary action be simply too high — a pill too bitter to swallow? To what extent is society, which has enjoyed decades of flexible fertility and will also ultimately pay for the control and management of its unintended consequences, involved in this decision? And what could this mean for the many thousands of other pharmaceuticals that ubiquitously infiltrate our environment and which could have sublethal effects on aquatic animals at similarly low levels?

13.1 Introduction

A large body of scientific data built up over many decades indicates a cause-effect link between exposure to a complex cocktail of chemicals and the feminisation and demasculinisation of wildlife species, particularly those living in or around the aquatic environment (reviewed in Lyons, 2008). Some scientists also relate exposure to hormonally active chemicals (so-called 'endocrine disruptors', including alkylphenols, bisphenol-A, phthalates, flame retardants and many other chemicals in everyday use) to declining sperm counts, increased incidence of male genital abnormalities, testicular, breast and prostate cancer in human populations (Lyons, 2008; Sharpe, 2009), breast growth in young men (Henley et al., 2007), and early onset of puberty in young girls (Den Hond and Schoeters, 2006; Jacobson-Dickman and Lee, 2009).

Over the last 50 years, since the publication of *Silent Spring* by Rachel Carson in 1962, we have learned that chemicals in food, household products, medicines and cosmetics, can be and are harmful to wildlife at very low levels. Many of these chemicals, each present at vanishingly low (parts per trillion) concentrations, can together have additive biological effects — producing 'something from nothing' in the words of Silva et al. (2002). Awareness of this reality has awoken scientists and the public to an era of possible harms from low-level, chronic chemical pollution (e.g. from human pharmaceuticals).

These chemicals may not have obvious catastrophic effects such as those observed for the endocrine disrupting anti-foulant tributyltin (TBT), which devastated commercially important oyster populations (see EEA, 2001, Ch. 13 on TBT and Gee, 2006). They can, however, have less obvious effects that nonetheless cause irreversible harm to individual organisms. This raises difficult questions concerning the relationship between these damaging but sub-lethal impacts on wildlife and their connections to ecological (e.g. population level) impacts, and to human health. It also raises issues for the precautionary principle, which states that where there is evidence of damage and irreversible harm, lack of full scientific certainty should not excuse inaction (UN, 1992). As we shall describe, the evidence suggests that it is entirely reasonable to invoke the precautionary principle and introduce regulation to limit aquatic exposure to EE2. But this is no trivial matter, and the reasons for this raise serious questions for the precautionary principle itself.

This is the story of one of these chemical pollutants, the contraceptive pill hormone 17α-ethinyloestradiol (EE2) as it has unfolded in the United Kingdom from the 1970s to today

13.1.1 The contraceptive pill

The first orally active synthetic steroidal oestrogen, EE2 ([1]), was synthesised by Hans Herloff Inhoffen and Walter Hohlweg at Schering AG in Berlin (Inhoffen and Hohlweg, 1938; Maisel, 1965) in 1938. EE2 was invented at a time when scientists across the world were intensifying their research into sex hormones as a means of controlling fertility and gynecological disorders. They were inspired by the remarkable successes achieved during the 1920s in using insulin to treat diabetes, thyroxine to alleviate thyroid deficiencies and metabolic disorders, and by the discovery of progesterone, the ovulation preventing hormone in 1934 (Sneader, 1985).

At a similar time, Edward Charles Dodds, a British medical researcher, discovered the potent oestrogenic properties of diethylstilbesterol (Dodds et al., 1938; EEA, 2001, Ch. 8) and those of bisphenol-A and 4-nonylphenol (Dodds et al., 1936), now well known endocrine disrupting chemicals. While BPA (see Chapter 10 on BPA) and 4-nonylphenol never found uses as drugs (their future was to be in plastics and detergents, respectively), for many medical practitioners and scientists there seemed no limit to the extent to which artificial oestrogens could be put to good medical use. EE2 was first marketed by Schering as Estinyl in 1943 and initially used to manage menopausal symptoms and female hypogonadism. It appeared to be readily absorbed orally and very resistant to degradation and metabolism by the gut. The stability and effects of EE2 paved the way for developing oral contraceptive pills ('the pill'), which eventually occurred in the 1950s and 1960s (Medical News, 1961).

The development of the pill was powerfully intertwined both with concerns about overpopulation and the 'sexual revolution' of the 1960s. Symbolically, it was much more than a tool for contraception. From the start it was linked with the hopes that it could curb population growth and bring about world stability. The first version of the contraceptive pill (Enovid) contained the hormones mestranol (the methyl ether of ethinyl oestradiol) and norethynodrel (a progesterone-like

([1]) 17α-ethinyloestradiol is the 17α-ethinyl analogue of the natural female hormone, 17β-oestradiol.

hormone). As Dr John Rock, a catholic obstetrician-gynecologist who ran some of the first clinical trials of the birth control pill, noted in 1967, 'If taken as it should be … it will stop ovulation 100 per cent' (CBC digital Archives, 1964).

Today the mechanisms of action of synthetic oestrogens and progestogens ([2]) are well understood. They are taken up by the cells in the reproductive system, pituitary, bone, liver and other tissues and bind to oestrogen and progesterone receptors, triggering increases or decreases in the expression of genes regulated by these hormones, in turn controlling gender, sexual development and reproduction. When taken correctly in the contraceptive pill, they interfere with the normal monthly cycle of a woman, preventing pregnancy by stopping the ovaries from releasing an egg, making it difficult for sperm to enter the womb (by thickening mucus in the cervix) and making the lining of the womb too thin for a fertilised egg to implant.

The American Food and Drug Administration approved the pill for use in the US in early 1961 and on 4 December 1961, Enoch Powell, then Minister of Health, announced that it could be prescribed through the UK National Health Service at a subsidised price of two shillings per month (Time, 1961). Take up of the pill was fast. Between 1962 and 1969, the number of UK users rose from approximately 50 000 to one million (out of an estimated 10 million users worldwide), generating an enormous social impact and earning it a place on the front cover of Time Magazine in April 1967 (Time, 1967) ([3]). The pill is hailed as playing a major role in the women's liberation movement and greater sexual freedom (Asbell, 1995; Goldin and Katz, 2002). Its availability, particularly in the developed world, has made a significant and dramatic impact on women's lives: giving unprecedented control over fertility, preventing pregnancy, and so avoiding the mortality and morbidity associated with pregnancy, childbirth and termination.

The pill now comes in 32 different forms and is used by more than 100 million women worldwide. Usage varies widely by country (UNPD, 2006; Leridon, 2006), age, education, and marital status. One quarter of women aged 16–49 in Great Britain currently use the pill — either the combined pill, progesterone-only pill or 'minipill' (Taylor et al., 2006) — compared to only 3 % of women in Japan (Hayashi, 2004; Hayes, 2009), which, in 1999, became the last country in the developed world to legalise the pill.

13.1.2 Evidence of environmental harm from 'the pill'

In the 1970s some scientists began speculating that using the contraceptive pill might cause environmental problems (e.g. Tabak and Bunch, 1970). They realised that oral medications, including contraceptives, are in fact rather inefficient methods for administering drugs to the body, since it takes a lot of drug administered orally to get a little into the bloodstream. The rest of the medicine passes right through the body and into wastewater in urine and faeces. Since water and waste treatment plants were not designed to remove pharmaceuticals (or indeed other man-made chemicals), it was likely that the contents of our medicine cabinets were unintentionally being passed on directly into the environment, and eventually, even into drinking water supplies.

EE2 is excreted as conjugates of sulphates and glucuronides, along with the natural steroid hormones oestrogens oestrone (E1), 17β-oestradiol(E2) and oestriol(E3) that occur naturally in humans. The synthetic EE2 shares a common hormonal mode of action with these natural oestrogens, which also means that, when released into the environment, the oestrogenic endocrine disrupting effects of EE2, and the natural steroid oestrogens in combination are additive. EE2, the synthetic oestrogen, is however by far the most potent of the four.

The data supporting the need for risk management of EE2 and the most potent of the three other steroid oestrogens (E2 and E1), due to their endocrine disrupting effects in the environment, are now comprehensive and compelling (Gross-Sorokin et al., 2006; Caldwell et al., 2008). Based on data amassed over many decades, the mechanism of toxicity of EE2, E2 and E1 is now well understood. They are continuously, and widely, released into the aquatic environment and are persistently present, having a half life in fresh water of between less than a day and approximately 50 days under aerobic conditions.

([2]) Progestogens (also spelled progestagens or gestagens) are a group of hormones including progesterone.
([3]) Front cover of Time Magazine's April 1967 edition can be viewed at: http://www.time.com/time/covers/0,16641,19670407,00.html.

They have been shown to cause endocrine disrupting effects at environmentally relevant concentrations in controlled laboratory studies (e.g. Lange et al., 2001; Nash et al., 2004, reviewed in Caldwell et al., 2008), in field studies of fish placed downstream of sewage treatment works with various types of secondary treatment technologies (Harries et al., 1996 and 1997) and in whole experimental lake studies dosed with EE2 (Kidd et al., 2007).

In some UK rivers, 100 % of wild male fish of the species *Rutilus rutilus* (roach, a common freshwater fish of significance to anglers) sampled between 1995 and 2002 had female characteristics (Jobling et al., 1998) and intersex has now been reported in many fish of a number of freshwater and marine species, in more than 10 countries (Tyler and Jobling, 2008; Hinck et al., 2009). Models predicting exposure of riverine fish to EE2, E2 and E1 in the United Kingdom have also been shown to correlate well with impacts observed in fish populations in the field (Jobling et al., 2006). These impacts damage fish reproductive health, for example affecting fertility and fecundity (Jobling et al., 2002a and 2002b; Harries, Hamilton et al., 2011) and are in some cases irreversible (Rodgers-Gray et al., 2001).

Risk characterisation of EE2 and the other two non-synthetic steroid oestrogens, E2 and E1, in the aquatic environment is possibly one of the most comprehensive for any chemical pollutant. Many millions of euro have been spent on this research over many decades. The chemical industry has concluded that 'endocrine disruption is undoubtedly occurring in wild fish populations' and that the evidence that wildlife has been impacted adversely following exposure to endocrine disrupting substances is 'extensive' (Webb et al., 2003). The pharmaceutical industry, in particular, has carried out and funded some of the key lab studies showing that EE2 plays a key role in causing these effects (e.g. Lange et al., 2001).

In response to this evidence, in 2004 the Environment Agency of England and Wales (EA) concluded that risk management was needed for steroid oestrogens (Gross-Sorokin et al., 2006). In 2012 the European Commission proposed EE2 as a Priority Substance (i.e. a substance requiring control across Europe) under the Water Framework Directive, one of the most important pieces of legislation for protecting European surface and ground waters, proposing regulatory limits in the aquatic environment for EE2. At present, this is only a proposal, with formal processes of agreement required before regulation can occur. In July 2012 an amendment to this proposal was tabled. This delays review of a proposal for a regulatory limit until 2016 (rather than 2012), which (if adopted) would then have to be complied with by 2027. Nevertheless nearly 75 years after its initial development, during which time some of the most comprehensive and compelling evidence of environmental impact for any chemical has been amassed, a decision to regulate of EE2 is finally under serious consideration. Why has this taken so long? And what lessons can we learn?

The example of EE2 and endocrine disruption in the aquatic environment, and the questions and dilemmas it raises, is in many ways a test case for many thousands of low-level pollutants that infiltrate our environment ubiquitously, many of which have chronic impacts that go beyond the acute polluting effects of past industrial chemicals.

13.2 Early warnings

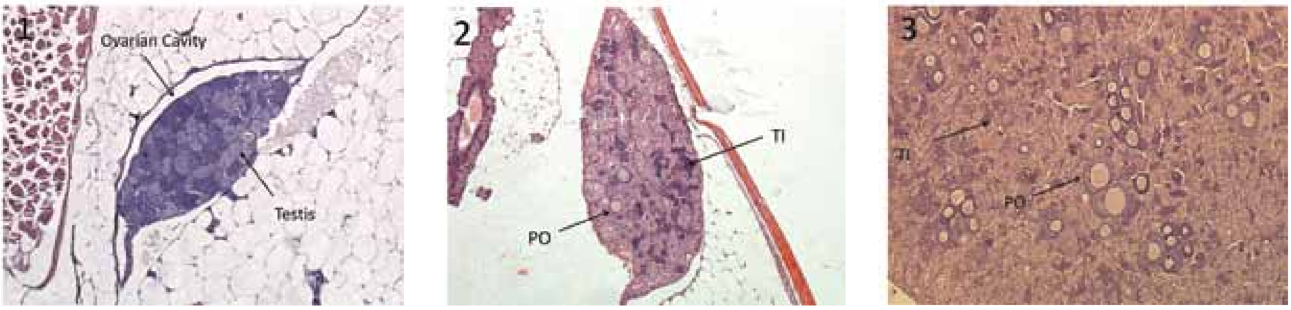
13.2.1 Early warnings from wildlife: the UK experience

The earliest concerns about possible hormone contamination of water (from contraceptive pills and other sources) related to impacts on male fish reproductive health in UK rivers. In 1978, Tony Dearsley, a Thames water area biologist in the United Kingdom, found eggs developing in the testes of five out of 26 male fish of the commonly caught species *Rutilus rutilus* (the roach) while conducting a routine health check on a small sample of fish from the River Lea.

As Dearsley's manager, Roger Sweeting, then Senior Scientist at Thames Water, noted, 'It was amazing to see macroscopically hermaphrodite fish that were both male and female all at the same time'(Sweeting, pers. comm.). It was not until a year later, however, after reading a paper by Jafri and Ensor (1979), that Sweeting telephoned David Ensor, who confirmed that the findings were highly unusual. Jafri and Ensor had reported a normal incidence of hermaphroditism of 1 in 1 000, in the same species of fish (Jafri and Ensor, 1979), more than 100 times lower than found in the fish collected from the Lower River Lea (see Figure 13.1).

Larger samples of fish confirmed the earlier observations. It was also observed that the incidence of feminisation varied with the age of the fish, with the highest proportion (20 %) found

Figure 13.1 Histological sections showing intersex phenotypes in roach



Note: Image (1) shows a female-like ovarian cavity in an otherwise normal testis. Image (2) shows a severely intersex gonad following exposure to sewage effluent with a testis containing a large number of primary oocytes at a single focus. Image (3) shows the intersex gonad of a wild fish caught from the River Aire, the United Kingdom. Tl denotes 'testis lobule'. PO denotes 'primary oocyte'.

in the older fish (aged more than six years). Roger Sweeting reported that this suggested a 'cumulative effect with time' (Sweeting, 1981).

Thames Water, at the time a government-owned company, was proactive in researching the matter further to gain a better understanding of its relevance to public health. It was reasoned that 'some risk of endocrine disturbance in human consumers of the water could be implied' (Sweeting, 1981) as it was known that the River Thames received discharges from numerous wastewater treatment plants (352 according to Williams et al. (2008)) and that it also served as a major potable water source for North London. Water abstracted from the river was purified, used by people, or industry, and then disposed of to sewage treatment works, where it was 'cleaned' before being discharged (as effluent) back into the river, only to be abstracted, used and cleaned a second or subsequent time downstream. (For this reason, it is a commonly said that when you drink a glass of water in London, the water has already passed through several pairs of kidneys).

Thames Water's concerns for public health led to further studies (never published) under a research contract given to Liverpool University. Water samples were taken directly from the River Lea at the drinking water abstraction point and transported on a train to Liverpool University, where they were given to rats to drink. Derek Tinsley (a PhD student at the time who now works for the Environment Agency of England and Wales) recalls visiting the station at regular intervals to collect the water. The studies showed clearly that giving female rats this water to drink for 12 months induced persistent oestrous.

Further studies showed, however, that water samples taken part way through the drinking water treatment process had no effects on the rats. Moreover autopsies of small mammals (water voles and wild rats) trapped around the sewage works revealed no obvious gross reproductive abnormalities. Derek Tinsley recalls that he felt 'relief that there were no signs of any effects of the treated drinking water on the rat reproductive system, and therefore no apparent risks to the consumer' ([4]).

Thames Water officials felt confident enough to present Tinsley and Ensor's results to a standing committee of the Department of Health, which, after conducting further studies, agreed that there was enough information to discount any possibility of risk to human consumers of water abstracted from the Lower Lea. It is striking that such a rapid decision was made on the basis of this small set of studies. This, as we will go on to discuss, is in stark contrast to decision-making regarding protection of aquatic wildlife from the effects of EE2 and other oestrogens, despite the many studies indicating adverse health effects related to oestrogen exposure.

The possibility that the contraceptive pill hormone might well be causing intersex in fish was not formally stated in any of the scientific reports circulated between the government and the water industry. Nor was any link made with the reports of occurrence of steroidal oestrogens in wastewater, river and potable waters (Tabak and Bunch, 1970;

([4]) Personal communication from Derek Tinsley.

Tabak et al., 1981; Aherne et al., 1985). At least one of those studies had recognised that steroidal oestrogens could potentially have adverse effects, even if none were identified:

> 'the concentrations found are far below therapeutic doses and there appears to be no evidence of adverse effects from reused water resources which may be contaminated from the normal use of such highly active therapeutic agents' (Aherne et al., 1985).

Aherne and colleagues could not have known about the Thames Water studies as they were confidential. Moreover, the significance of their work and the earlier studies by Tabak and colleagues was not recognised, because the human health agencies responsible for international drug regulation at the time usually had limited expertise in environmental issues; consideration of these was not formally required. The situation is today very different, with environmental exposure now recognised as a key consideration (for example in European Medicines Agency guidelines (EMA, 2006) ([5]). Moreover, until the 1990s, any concerted chemical analytical efforts to look for drugs in the environment achieved limited success. This is because the requisite chemical analysis tools (with sufficiently high separatory powers to identify the drugs amid a plethora of other natural and anthropogenic substances in the environment, and sufficiently low detection limits (i.e. nanograms per litre or parts per trillion)) were not commonly available.

Now there is considerable concern about the increasing amounts of pharmaceuticals that are being consumed and found in the environment (Kümmerer, 2004 and 2007; Apoteket AB et al., 2006 and 2009; EEA, 2010; German Advisory Council on the Environment 2007; Mistrapharma, 2011). With an ageing population the UK Office of National Statistics predicts that the country's medicine usage will more than double by 2050 (Nature, 2011).

13.2.2 More evidence of an environmental problem

In the mid-1980s, fisheries scientists working for the UK Ministry of Agriculture Fisheries and Food, or MAFF (Dr Colin Purdom, Dr Vic Bye and Dr Alex Scott) were asked to comment on the evidence collected to date. Quite independently, one of their colleagues, Dr John Sumpter, had found high levels of a female-specific yolk protein (vitellogenin or VTG) in the blood of male fish kept at an experimental fish farm rented by MAFF. VTG is under strict oestrogen control and as males have extremely low (often undetectable) levels of oestrogen in their blood, they can only produce VTG if they are exposed to an oestrogen (Sumpter and Jobling, 1995). The scientists wondered whether the fish were being supplied with water contaminated with oestrogens originating from the treated sewage effluent entering the river upstream of the fish farm, and whether oestrogens in the water might also explain the discovery of feminised wild male fish in the River Lea.

Field trials in the late 1980s, funded by the Department of the Environment (DoE), confirmed that VTG levels in male trout placed for just two weeks in the sewage treatment plant effluent from Rye Meads sewage treatment works (which entered the River Lea) underwent a 100 000 fold increase, reaching levels equivalent to those in mature females. These results provided the impetus for a nationwide survey of effluents (conducted between 1987 and 1990) by Brunel University (John Sumpter and Charles Tyler) and MAFF (Colin Purdom, Vic Bye, Sandy Scott and Peter Hardiman), with funding from the DoE. The results of this survey proved beyond doubt that oestrogenic effluents entering rivers were widespread throughout England and Wales (Purdom et al., 1994).

By the late 1980s, therefore, there was already evidence that wastewater from sewage treatment plants was having harmful effects on aquatic wildlife, and that at least one possible culprit was EE2. This information was not widely circulated beyond government and industrial organisations. Indeed, the results were not published until 1994 (Purdom et al., 1994), because of the contractual agreement between the DoE, MAFF and Brunel University. There was little action: policymakers of that era perhaps preferred to wait until the level of proof linking cause with effect was beyond reasonable doubt, reflecting a wider resistance at the time to precautionary action in the absence of higher levels of proof.

Subsequent research has proven EE2's presence in effluents and natural waters, and established that it

([5]) More recent guidance from the European Medicines Agency states that if the estimated environmental concentration (i.e. predicted surface water concentration) of a medical product is below 0.01ppb and 'no other environmental concerns are apparent' then no further actions are needed in terms of environmental risk assessment, i.e. no action needed by a pharmaceutical company.

is highly likely that it is contributing significantly to the damaging effects seen in wild fish (Caldwell et al., 2009). Moreover, studies carried out in Canada have confirmed large effects associated with very low concentrations in a multi-year study in which fish living in a large experimental lake were exposed to introduced EE2 (Kidd et al. (2007): 6.1 ng/L (+/– 2.8) during the first year, 5.0 ng/L (+/– 1.8) during the second year and 4.8 ng/L (+/– 1.0) during the third year of. This low level introduction of oestrogen provoked a large surge in fish plasma VTG levels, followed by complete collapse of the fish population. The fundamental conclusion, that EE2 and other hormones in wastewater, both natural and synthetic, are harming aquatic wildlife, particularly downstream of wastewater plants with low dilution, has not changed since the late 1980s. Only the level of uncertainty has reduced.

13.2.3 *Widespread endocrine disruption in wild fish and growing evidence of problems in other wildlife*

The discovery in the 1980s that oestrogenic effluents were widespread led logically to more caged fish trials that illustrated the extent of the oestrogenic pollution at greater distances from the sewage treatment works (Harries et al., 1996 and 1997). Extensive field trials in the United Kingdom between 1995 and 2000 also showed unequivocally that intersex in wild roach was widespread and especially prevalent up to 10 km downstream of medium- to large-sized sewage treatment works (serving populations of 50 000 to 675 000) and where dilution of their effluents in receiving river waters was less than 10-fold (Jobling et al., 1998).

In addition, studies on estuarine species of fish illustrated clearly that the effects of oestrogenic contaminants extended beyond the rivers into estuaries (Lye et al., 1997 and 1998; Allen et al., 1999) Feminisation and sub-fertility were also reported in additional wildlife species, especially those living in or around the aquatic environment (reviewed in Lyons, 2008). Specifically:

- amphibians were found to have abnormal production of VTG by males and ovotestes/intersex features;
- reptiles were found to have abnormal production of VTG by males: sex hormone disruption; ovotestes; smaller phallus in alligators and shorter estimated penis length in turtles; decreased hatching; and decreased post hatch survival;
- birds were found to have abnormal VTG production in males; deformities of the reproductive tract; embryonic mortality; reduced reproductive success including egg-shell thinning and poor parenting behaviour;
- otters and mink were found to have reduced penile bone length; smaller testes; and impaired reproduction;
- seals and sea lions were found to have impaired reproduction (including implantation failure, sterility, abortion, premature pupping);
- cetaceans were found to have reduced testosterone levels; impaired reproduction; and hermaphrodite organs;
- polar bears were found to have intersex features and deformed genitals; reduced testes and baculum length; low testosterone levels in adult males; and reduced cub survival.

In none of these cases was a link with exposure to EE2 investigated and/or proven.

13.2.4 *Wildlife as sentinels for human reproductive health*

Beyond the aquatic environment, the feminising syndromes found in wildlife appeared to mirror reports of male infertility, genital abnormalities and testicular cancer observed in the human male population, collectively termed Testicular Dysgenesis Syndrome (TDS; see Box 13.1). If testicular dysgenesis syndrome was occurring in humans due to environmental pollutants, then genital disruption should have been found in wildlife exposed to those pollutants. This did indeed seem to be the case. The question arose whether the effects seen in wildlife and in humans shared a common cause: environmental oestrogens including EE2. There had already been evidence of human health impacts associated with another synthetic oestrogen created in the same year as EE2: diethylstilbestrol (DES). From the 1940s to the early 1970s, pregnant women in the US (and beyond) were commonly prescribed DES in the mistaken belief that it could prevent miscarriage. Some of the sons of these DES mothers developed low sperm counts, undescended testicles and deformations of the penis (Ibaretta and Swan, 2001).

The steepest declines in male reproductive health appear to have taken place in most countries between the 1960s and the 1980s, coinciding not only with the introduction and take up of the contraceptive

Box 13.1 Human health concerns

The first indications that something might be wrong with human sperm came in 1974, when Kinloch Nelson and Bunge produced a small study of the semen quality of men who were about to undergo vasectomies. They found that only 7 % had sperm concentrations above 100 million (Kinloch Nelson and Bunge, 1974), which is well below the 65 % reported earlier by pioneering andrologist, John Macleod (MacLeod and Heim, 1945).

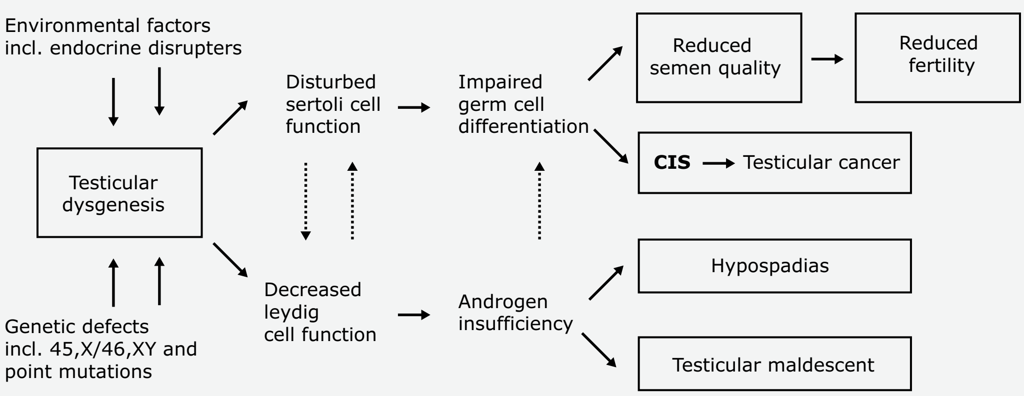
Kinloch Nelson and Bunge speculated that 'an environmental factor to which the entire population has been exposed' might be causing the low sperm counts. These studies were discredited by John MacLeod himself in 1979. While acknowledging a decline in sperm counts in fertile males since the 1930s, MacLeod and Wang (1979) rejected the notion of a larger, overall decline, citing analytical errors in the Nelson and Bunge study and suggesting a concentration of 20 million per ml should be the lower limit for the normal sperm count. This limit was adopted in the WHO guidelines for semen analysis in 1980 (WHO, 1980).

Nothing more was reported until 1992, when Danish clinician Niels Skakkebaek and Elizabeth Carlsen published their ground-breaking paper on studies of sperm counts around the world. In 61 studies going back as far as 1938, they found a decline in average sperm density from 113 million per millilitre in 1940 to 66 million in 1990 (Carlsen et al., 1992). These findings made some scientists wonder whether the human species was approaching a fertility crisis. Debate on this issue was intense and opinion was divided regarding the validity of the apparent fall in global sperm counts (e.g. Swan et al., 1997; Paulsen et al., 1996; Fisch et al., 1996).

The approach taken in Europe (led by Skakkebaek) followed the reasoning that 'if sperm counts have fallen then the average should be lower in men born most recently than they were in the past'. More recent investigations in seven European countries involving more than 4 000 young men have shown that in most of the countries investigated 20 % or more of young men have a subnormal sperm count (less than 20 mn per ml) and the average sperm count is 45–65 million (Jorgensen et al., 2006). This is consistent with sperm counts having fallen, as suggested by the meta-analysis studies. More importantly, it shows that male subfertility is likely to be a common issue for current and future generations, with widespread societal and economic consequences.

The importance of declining semen quality lies partly in its possible link with other problems of male reproductive organs, especially the rise in the incidence of testicular cancer (Adami et al., 1994; Wanderas et al., 1995; Bergstrom et al., 1996; Moller, 2001; McGlynn et al., 2003; Richiardi, 2004) and in congenital malformations of the male reproductive system such as cryptorchidism (undescended testis) and hypospadias (penis malformation) (Hohlbein, 1959; Sweet et al., 1974; WHO, 1991; Matlai and Beral, 1985; Paulozzi et al., 1997; Lund et al., 2009). These diseases often occur together (Prener, 1992; Berthelsen, 1984; Petersen et al., 1999; Schnack et al., 2009) and may have the same underlying pathology — testicular dysgenesis syndrome (TDS) (Sharpe and Skakkebaek, 1993; Skakkebaek, 1998) with a common origin in fetal life (see Figure 13.2).

Figure 13.2 Testicular dysgenesis syndrome



Source: Sharpe and Skakkebaek, 1993.

Box 13.1 Human health concerns (cont.)

Unlike in the case of intersex in fish, there has never been one widely accepted theory regarding the cause of the decline in male reproductive health. Instead, a bewildering array of hypothetical culprits have been posited, including not only the residues of birth control pills in drinking water or inadvertent pill taking during pregnancy, but also a range of anti-androgenic industrial chemicals (male hormone lowering or blocking) and non-chemical stressors that have been shown in laboratory studies to induce TDS when exposure takes place during early pregnancy (Sharpe, 2009). The research in this field has been challenged by the lack of human exposure information and the absence of results of past testing of industrial chemicals for endocrine disruption and other adverse effects that may affect the development of the male reproductive system. Even if animal testing is performed, the results cannot directly be translated to humans because, for example, a chemical may reduce sperm counts by 80–90 % in rats before male fertility is affected.

The net result is that no systematic effort has been made to prevent infertility, despite the substantial potential societal consequences associated with its widespread occurrence. Indeed, the official WHO response to male infertility has been to redefine the ill people as 'normal' by changing the lower reference value for a 'normal' sperm concentration first from 60 mn/ml in 1940s to 20 mn/ml in 1980 and then to the current 15 mn/ml (WHO, 2010), making it of little use in helping society recognise that there is a problem (Skakkebaek, 2010).

pill but also with the entry of many other synthetic chemicals into the environment, the Clean Water Act in 1972 and subsequent upgrading of sewage treatment plants to secondary treatment. Thus, endocrine disruption in the developing child could have occurred through the inadvertent consumption of pills in the first trimester of pregnancy (Smithells, 1981, although refuted by Joffe, 2002). Alternatively, or additionally, it could have resulted from drinking water containing residues of contraceptive pill hormones and a whole plethora of industrial chemicals. Or it could have resulted from inadvertent exposure to these chemicals via application to the skin (cosmetics), inhalation or diet. A more recent report highlights a relationship between modern contraceptive pill use and prostate cancer (Margel and Fleshner, 2011), another hormone-dependent male reproductive disease.

In the case of the contraceptive pill, one might expect the exposure to have been higher in the 1960s, 1970s and 1980s than in later years as the first pill formulations contained up to 100 µg of oestrogen, at least five times higher than current formulations. If exposure to the contraceptive pill was a significant risk factor in causing TDS, the effects should show up in statistics on male reproductive health.

Examination of historical contraceptive pill usage in various countries does indeed suggest higher rates of use (allowing a 30–35 year time lag between exposure of the developing child and the later appearance of testicular cancer) in some countries where rates of testicular cancer and hypospadias are higher, such as Denmark, Germany, Hungary, the United Kingdom and USA, than in countries where rates are lower, such as Bulgaria, Finland, Italy, Poland, Portugal, Romania and Spain and Japan (Leridon et al., 2006). These associations may well be coincidental, however, as the available evidence in support of the oestrogen theory is not entirely convincing (Raman-Wilms et al., 1995; Toppari et al., 1996; Martin et al., 2008). Indeed, recent animal experimental studies suggest that industrial chemicals that block the action of male hormones (anti-androgens) are more likely culprits of declines in male reproductive health and could even act in combination with oestrogens to induce a proportion of the cases of TDS seen in humans. So far, however, 'there is no human or experimental animal data to support this' (Sharpe, 2009). The lack of cause-effect, especially in human epidemiological studies, could easily be wrongly interpreted as ruling out involvement of endocrine disruptors in TDS. Several factors complicate analysis, including the long latency between exposure and effect and the possibility that the effects may be caused by multiple chemicals in combination, while exposure to each chemical individually may not be insufficient to cause damage. This is also why Bradford Hill's criteria, when invoked in the 2002 WHO report on endocrine disruption (WHO, 2002), rejected the hypothesis of an impact on male reproductive function. These criteria are not suited for determining causation by environmental toxicants because such exposures are simply too complex. Perhaps we should abandon the unrealistic hope of achieving more certainty prior to policymaking about human male reproductive health and use wildlife as sentinels instead?

The case for endocrine disrupting chemicals causing male sterility in humans and wildlife, showing wildlife were sentinels for human health, was beautifully presented in the British Broadcasting Company's award-winning Horizon documentary 'Assault on the male', written and produced by Deborah Cadbury and screened in 1993. The world began to sit up and take notice. Mounting concern in Europe was such that between 1998 and 2007 the European Commission invested over EUR 150 million into researching endocrine disruption. This research provided the basis for testing both existing chemicals and those planned for introduction to the market in the future for their endocrine disrupting effects. It also furthered understanding of the effects of mixtures of endocrine disrupting chemicals, identification of vulnerable life stages and impacts on male reproductive health. The new data showed that a wide range of chemicals could have endocrine disrupting effects, with a wide range of health impacts.

13.3 The hunt for the culprit chemicals

Against the backdrop of growing global awareness of endocrine disruption, attention focused on the chemicals responsible for the feminised male fish observed in UK rivers. Laboratory studies showed clearly that male fish were extremely sensitive to the presence of EE2 in the water at low ng/L concentrations (Sheahan et al., 1994). Until the mid-1990s, however, few were convinced that this or any other hormone was present in wastewater in sufficient amounts to cause the effects seen in fish.

Coincidentally, during that time information was emerging from the US that, in addition to pharmaceuticals, industrial chemicals in everyday use could mimic oestrogens. Although this was first shown by Charles Dodds in the 1930s (Dodds et al., 1936), widespread awareness of this possibility was instigated by John McLachlan, one of the pioneers of research into environmental oestrogens and the organiser of the first meeting on the topic in 1979 (McLachlan, 1980).

It now seemed possible that effects seen in aquatic and other wildlife were actually more likely to be a result of exposure to cocktails of 'endocrine-disrupting' industrial chemicals, (Clement and Colborn, 1992) than to the contraceptive pill hormone. In 1988 Theo Colborn, in her research on the environmental condition of the North American Great Lakes, showed that persistent, man-made chemicals were being transferred from top predator females to their offspring, undermining the construction and programming of their youngsters' organs before they were born. In 1991, Theo convened a meeting ('The Wingspread Meeting') of 21 international scientists from 15 different disciplines to share relevant research on the topic and it was during this meeting that the term 'endocrine disruption' was coined.

It was also in 1991 that Dr Ana Soto published a paper about the oestrogenic effects of nonylphenol, a chemical compound used in manufacturing a large group of industrial detergents (Soto et al., 1991). Some detective work by Susan Jobling (then a student of John Sumpter) at Brunel University revealed that the environmental chemist Walter Giger had identified these chemicals in sewage treatment works effluents, sewage sludge and river water (Giger et al., 1984) at concentrations that Jobling later confirmed were oestrogenic to fish exposed to the chemicals in the laboratory (Jobling and Sumpter, 1993; Jobling et al., 1996).

An earlier report of the oestrogenic activity of 4-nonylphenol, was published in 1936 by Charles Dodds when he was trying to synthesise one of the first synthetic oestrogens, diethylstilbesterol ([6]). The detergent industry may have been unaware of this literature when it embarked on the largescale manufacture and sale of nonylphenol ethoxylates as detergents in the 1940s, leading to the contamination of many rivers and estuaries with these oestrogenic chemicals.

While the causal links between exposure to industrial chemicals and endocrine disruption in most wildlife species were still unclear in the 1990s, further research in the United Kingdom and other European countries showed that nonylphenolic chemicals were causing at least part of the problem in wild fish in some, but not all, areas (Sheahan et al., 2002a and 2002b). However, more sophisticated studies employing chemical fractionation and screening of effluents using an *in vitro* oestrogenicity screen showed that naturally occurring and synthetic steroid oestrogens (EE2, E2

([6]) Interestingly, Dodds identified another controversial compound at the same time — the environmental endocrine disruptor bisphenol-A (Dodds, 1938). See also Chapter 10 on BPA.

and E1) were in fact the most potent oestrogenically active substances present in domestic effluents (Desbrow et al., 1998; Routledge et al., 1998; Snyder et al., 2001), responsible for much of the oestrogenic activity found in wastewaters and rivers throughout most of the world. Of these, EE2 was by far the most potent: the pill was once again under the spotlight.

13.4 Government and industry action in the 1990s

Enormous efforts were made in the 1990s to assess and manage the risks of alkyphenols, not only because of their endocrine disrupting effects but also their wider toxicity to aquatic life:

Following recommendations of the UK Chemicals Stakeholder Forum, the UK government negotiated a voluntary agreement with the suppliers of nonylphenols, octylphenols, and their respective ethoxylates. Suppliers thereby agreed not to promote octylphenol (another endocrine disruptor also found in sewage effluent) as a substitute for nonylphenols, not to manufacture or import new formulations or products containing those substances, and to reformulate existing products to remove those substances as a matter of urgency. This was a constructive application of the precautionary principle (Lokke, 2006), which has not been extended to EE2.

Similarly, in mainland Europe, the European Union undertook a risk assessment of nonylphenols and, as a result, restrictions on using nonylphenol have been imposed across Europe.

At the same time, continued uncertainty about exposure to chemical pollutants in the environment and their effects on the human population (particularly regarding reproductive health) were highlighted during discussions at a major European workshop at Weybridge, the United Kingdom ([7]), on endocrine disrupting chemicals held in December 1996 and jointly sponsored by the European Commission, the European Environment Agency, the European Centre for Environment and Health and the WHO (EU, 1996). An EU strategy on endocrine disruptors was launched in 1999 to begin to address the problem (EU, 1999) but still no action was taken on EE2.

13.5 The last decade of research

Since the mid-1990s, oestrogenic sewage-treatment works effluents have been identified more widely across Europe, and globally, e.g. in Denmark (Bjerregaard et al., 2006), Germany (Hecker et al., 2002), the Netherlands (Vethaak et al., 2005), Portugal (Diniz et al., 2005), Sweden (Larsson et al., 1999), Switzerland (Vermeirssen et al., 2005), China (Ma et al., 2005), Japan (Higashitani et al., 2003) and the United States (Folmar et al., 1996). More extensive evidence has also emerged from around the world showing widespread endocrine disruption in fish in rivers (Hinck et al., 2009; Bjerregaard et al., 2006; Blazer et al., 2007; De Metrio et al., 2003; Hinck et al., 2009; Penaz et al., 2005; Vajda et al., 2008), estuaries (Allen et al., 1999) and oceans (Cho et al., 2003; Ohkubo et al., 2003; Fossi et al., 2004; Kirby et al., 2004; Scott et al., 2006 and 2007).

In general, the situation in other countries appears to match that found in the United Kingdom. The incidence and severity of endocrine disruption appears to relate largely to the size of the sewage works (treatment type is also important), most importantly, and the dilution of its effluent in the receiving water. This leads to generally lesser effects in fish inhabiting large rivers with high dilution factors (a common scenario in the US and parts of Europe, for example) compared with those in smaller rivers with little dilution (a common scenario in the United Kingdom and other parts of Europe). In Japan, where contraceptive pill hormone use is probably the lowest anywhere in the developed world and where endocrine disruption in fish is reported to be quite rare (Tanaka et al., 2001; Higashitani et el., 2003), the greater mean river flow, and hence available dilution per capita (five times more than in the United Kingdom), suggests that combined steroid estrogen potency will be less across its rivers than in the United Kingdom. Even if the Japanese population were to take up the contraceptive pill to the extent of use in England then widespread endocrine disruption in fish would still not be predicted because of the large amount of available dilution (Johnson et al., 2012).

A growing body of evidence also shows that the harm caused by exposure to endocrine disrupting chemicals early in development is, in many cases, irreversible. In fish, as in humans and rodents, feminisation of the male reproductive tract occurs early in development and produces a fish with

([7]) In 2006 the 10th anniversary of Weybridge was marked with a conference organised by the Academy of Finland, the European Commission (DG Research), and the EEA. The EEA has updated and published the papers from that meeting (EEA, 2012).

both an oviduct and a sperm duct. Depuration in clean water does not correct this condition, indicating that feminised ducts seen in wild roach are likely to be a permanent feature (Rodgers-Gray, 2001). Considerable evidence also shows that both the prevalence and the severity of feminisation in wild roach increases with age (Jobling et al., 2006), in extreme cases resulting in a 100 % female population after three years of continuous exposure to treated sewage effluents or EE2 (Lange et al., 2009).

Population-relevant effects of EE2 have also been documented, including a complete fish life cycle test carried out by the original manufacturers of EE2, Schering (Lange et al., 2001), which showed inhibition of breeding at concentrations exceeding the environmentally relevant concentration of 2 ng/L and full sex reversal of males producing an all female population at 4 ng/L. This effect was corroborated by Kidd et al., (2007), who (as we have already noted) dosed an entire lake with EE2, causing a population collapse at concentrations of approximately 5–6 ng/L.

Improvements in analytical power, lower analytical instrument detection limits and innovative modelling approaches have led to the discovery of other steroid oestrogens in the environment, such as equine oestrogens used in hormone replacement therapies (Tyler et al., 2009). There are now also more accurate measurements (Williams et al., 2003; Kanda and Churchley, 2008) and credible modelled estimates (Hannah et al., 2009) of steroid oestrogen concentrations present in sewage effluents and in rivers . This has caused a mixture of doubt and amazement at the possibility that EE2 could be causing endocrine disruption at the very low concentrations at which it is present.

The last decade has also brought the realisation that risk assessments for mixtures of hormonally active chemicals are not adequately protective if based on data for individual substances. Mixtures of synthetic and natural oestrogens (EE2, E2, E1) each at or below their individual 'no effect' concentration were shown to be particularly potent when present in combination (Silva et al., 2002; Thorpe et al., 2003; Brian et al., 2005 and 2007) or with other industrial chemicals with anti-androgenic (male-hormone blocking) activity. These findings confirmed concerns originally mooted by Rachel Carson in 1962 in her book, *Silent Spring*.

More recent reports show an almost concurrent incidence of anti-androgenic chemicals and oestrogens in treated wastewater throughout the United Kingdom. Statistical modelling of exposure and effect data suggest that these chemicals (although not yet identified) could play a pivotal role in causing feminising effects in male fish in UK rivers. Until now it was thought that such effects were caused only by oestrogens found in contraceptive pills and some industrial chemicals (Jobling et al., 2009).

There may be a further twist in the story. Synthetic progesterones (which complement synthetic oestrogen in the contraceptive pill) have been identified in natural waters (Standley et al., 2008; Kuster et al., 2008) and reported to cause effects in fish when present at ng/L concentrations (Paulos et al., 2010; DeQuattro et al., 2012). Ironically, despite the history of their combined use, oestrogens and progesterones have yet to be tested in fish 'in combination', despite the fact that human females have been carrying out this 'test' for 50 years.

13.6 From risk assessment to risk management

In 2004, some 25 years after initial observations of intersex in fish, the UK government accepted the weight of evidence that EE2, E2 and E1 in combination posed a significant risk to aquatic life through their endocrine disrupting effects (Gross-Sorokin et al., 2006). The long journey to this point was passionately championed by Geoff Brighty, Science Manager at the Environment Agency of England and Wales. His team, in collaboration with others, built and defended the evidence-based case against steroid oestrogens and other endocrine disrupting chemicals in UK rivers.

As Brighty remarked in 2004, 'We now have enough data to act as a policy trigger for taking action' (ScienceBlog, 2004).

End-of-pipe treatment of effluent by water companies was chosen as the risk management approach, in comparison to alternative approaches (such as pharmaceutical industry action to develop substitutes for the active ingredient (EE2) in the pill). This may have partly reflected awareness of the public health benefits of the oral contraceptive, the fact that both naturally-excreted and synthetic oestrogens posed risks via their endocrine disrupting effects (i.e. that both would need to be removed) and that other priority hazardous chemicals would also be reduced with the end-of-pipe treatment approach.

This would place the responsibility for risk management on the water industry and (ultimately) the cost of treatment of the tax paying public. In

2007 the Environment Agency began to develop a (draft) technical environmental quality standard (EQS) — a target concentration which could be used for regulatory compliance for EE2- based on a predicted no effect concentration of 0.1ng/L (Young et al., 2004, Figure 13.3). The Environment Agency also identified the EU Water Framework Directive (WFD) as an appropriate legislative mechanism within which the EQS could be enforced. Options for control under the WFD might be to propose EE2 either as a nationally important 'specific pollutant, or an EU-wide 'priority substance' requiring control across Europe. The WFD is the most important EU legislation for managing water resources and had already been used to regulate other endocrine disrupting chemicals such as TBT and nonylphenol. Since additional endocrine disrupting chemicals were likely to be proposed as 'specific pollutants' or 'priority substances' in order to decrease their overall environmental burden, this was a reasonable option for the steroid oestrogens. At this point, no other country in the world had Environmental Quality Standards for any of these substances ([8]).

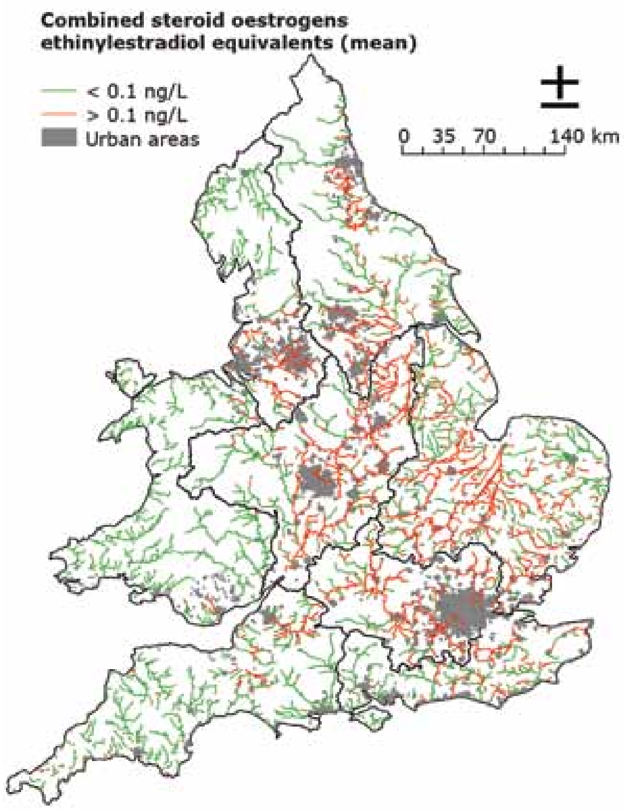
Before introducing risk management of this type there is an important step known as risk evaluation, which quantifies the wider consequences and costs to society of the proposed management approach and balances them against the benefits. The various options on how to proceed are then evaluated and a decision made. For example, a regulatory impact assessment may be undertaken to evaluate the implications of bringing in regulation and implementing an EQS.

In the case of EE2 and the other two steroid oestrogens it was necessary to understand the efficiency of various treatment approaches in removing these substances from sewage treatment plant final effluents. The approaches included both existing and new (advanced) treatment methods: these would need to be quantified in terms of both financial and carbon costs.

In 2004 the UK water industry, in collaboration with the Environment Agency and the UK government, and under the watchful eye of the independent auditor Ofwat, commenced a comprehensive and lengthy work programme to address this goal. The so-called 'National Demonstration Programme' (Gross-Sorokin, 2006) was budgeted at GBP 25–40 million and was not welcomed by the UK water industry, which financed most of the costs. All ten water companies in England and Wales were involved.

In the first phase of the programme fourteen sewage treatment plants were used to evaluate the efficiency of oestrogen removal through 'conventional' treatment technologies. These consisted of primary or chemically aided primary sedimentation with secondary treatment by nitrifying, non-nitrifying activated sludge (ASP) or biological filtration and in some cases tertiary sand or biologically aerated filtration. In the second phase, two so-called 'full-scale' plants were used to evaluate the most promising new technology as an additional

Figure 13.3 UK rivers and streams exceeding the Predicted No Effect Concentration (PNEC) for EE2



Note: In rivers and streams coloured red the suggested Predicted No Effect Concentration (PNEC) for EE2 of 0.1 ng/L is exceeded. In rivers coloured green the combined concentrations of steroid oestrogens (in EE2 equivalents) are less than the suggested PNEC.

([8]) In the US, for example, the FDA regulates pharmaceutical manufacture and the EPA regulates discharge under the Clean Water Act. However, these limitations may not be strict enough to protect the environment because they are technology-based and do not rely on environmental data. As explained later, there is no treatment technique currently available that comprehensively deals with EE2.

advanced tertiary effluent treatment: granular activated carbon (GAC).

The first phase of the Demonstration Programme was completed in mid-2008 (UKWIR, 2009). Results showed that while existing treatment approaches were effective for removal of oestrone and oestradiol, particularly using nitrifying activated sludge treatment, EE2 was far harder to remove. The most efficient treatment, nitrifying ASP, removed some 54 %, with tertiary treatments accounting for a further reduction of 0–38 % of that remaining, depending on the form of tertiary treatment.

These results are completely in line with the consensus seen in current international scientific literature, as comprehensively reviewed by Racz and Goel (2010). Wastewater treatment plants with long retention times (greater than 10 days), especially those performing nitrification, seem to be generally more effective at removing oestrogens because they allow the enrichment of slow-growing bacteria, such as nitrifying bacteria, and the establishment of a more diverse ecological community including species capable of degrading EE2. For this reason, expensive membrane bioreactors with microfiltration and ultrafiltration as well as long retention times have been shown to effectively degrade and reduce the concentrations of oestrogens in effluents, including EE2.

In general, however, EE2 is not nearly as easily biologically removed as the other oestrogens. The ethinyl group of EE2 is thought to hinder EE2 sorption and metabolism. Furthermore, EE2 often exists in the aquatic environment at concentrations below those at which a substrate can support bacterial growth. Biodegradation studies at EE2 concentrations greater than those found in natural environments (mainly conducted at such concentrations due to limitations in analytical chemistry techniques) may therefore lead to erroneous conclusions about the occurrence, rates and products of microbial transformation of EE2 and the other steroid oestrogens.

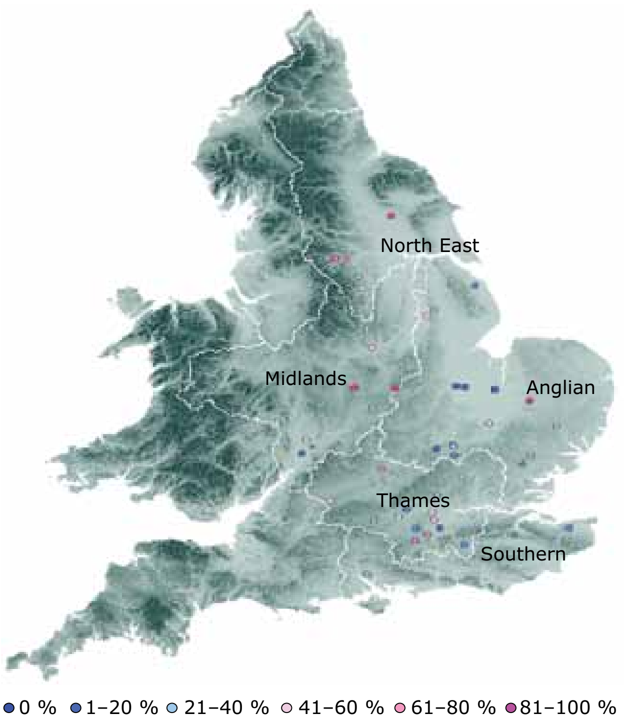
As a consequence of removal inefficiencies, the proposed EE2 Predicted No Effect Concentration (PNEC) of 0.1 ng/L is exceeded in many UK final effluents entering the aquatic environment, irrespective of conventional treatment type (see Figure 13.3). The results of the second phase of the UK Demonstration Programme were reported in May 2010 (NDP, 2010). They showed that additional treatment using a novel approach called granular activated carbon (GAC) can be effective at removing EE2, producing final effluents below the EE2 PNEC and with no significant induction in fish VTG or intersex (Filby et al., 2010; Baynes et al., 2012). GAC could therefore offer the most promising route for preventing EE2's entry into the aquatic environment at harmful levels (noting that in one study reproduction in fish was slightly, but significantly impacted by effluent subjected to GAC treatment). The Demonstration Programme showed, however, that GAC suffers from a fundamental problem: it is expensive to implement.

For a small town with a 50 000 population equivalent (PE) sewage treatment plant, the capital costs alone of setting up additional GAC were calculated as being over EUR 3 million. That rose to over EUR 8 million for a 250 000 PE works serving a large town such as Swindon, which was one of the sites chosen in the United Kingdom for assessing the technology. Operating costs per annum were calculated as being EUR 800 000 for a 250 000 PE sewage treatment plant, but this would depend on the life of the granular activated carbon. Costs were calculated to approximately 14 kg of CO_2 per person per year. Provisional estimates by the UK government showed that, in total for England and Wales, this would translate into costs of between EUR 32 and 37 billion for the approximately 1 360 sewage treatment works that would require additional treatment (Owen and Jobling, 2012). Again, these findings are in line with the findings of Racz and Goel (2010), who concluded that 'Much attention has also been placed on studying methods of removing oestrogens prior to discharging effluent or disposing waste sludge. While advanced treatment systems such as chemical removal, activated carbon, chlorination, ozonation, ultraviolet irradiation, membrane separation, and other novel approaches may be effective, their current capital and operation costs may make them not viable options.'

Faced with this information, those tasked with implemention of an EQS for EE2 (for example as a 'priority substance' under the Water Framework Directive, see below) increasingly began to worry about two important considerations: technical feasibility and disproportionate cost. It confirmed what they had suspected for many years: EE2 was potent and hard to get rid of.

Evaluation of risk management costs, which have to be calculated at a national scale given the widespread nature of endocrine disruption (Figure 13.4), is however only one half of the cost benefit equation. They must be balanced against the (often intangible) benefits of risk management to key stakeholders, such as the angling community,

Figure 13.4 Extent of sexual disruption in roach in English rivers



Note: Intersex was present at 44 (86 %) of 51 sites surveyed, with an aggregate incidence of intersex of 23 % of sampled males. Coloured symbols indicate incidence of intersex at the different river sites surveyed.

Source: Taylor et al., 2005.

and the public, who will ultimately have to pay for it. This has been a highly contested and often acrimonious area of debate, with highly charged discussions about what constitutes harm at the level of individual fish and what it means for (more ecologically important) fish populations. Adding to this debate is the fact that the costs associated with removing EE2 and E2 should not be seen in isolation: treatment such as GAC would also quite possibly serve to reduce/remove other substances posing risks to the environment and requiring control. Why should such removal costs not be considered for all such chemicals as a whole: is it scientifically incorrect to blame just EE2 for the costs?

Another consideration is how such costs might scale at an EU-wide level, where EU-wide regulation might occur. One European Commission estimate for this is EUR 11–18 per person per annum (EC, 2012). EUREAU (European Federation of National Associations of Water and Wastewater Services) however estimates that these costs are much higher; 25–50 % of the current annual sewerage charges per year (EUREAU initial position paper on amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy). There is clearly considerable uncertainty here.

The costs at an individual country level are likely to vary on a country by country basis, for example varying with the population density, status of wastewater treatment and size of rivers. In some cases individual country costs may be substantially lower than those estimated for the United Kingdom (e.g. see EU project Neptune and the Swiss project Micropoll; Eawag, 2009). Many European countries have lower population densities and much greater dilution of effluents in their receiving rivers than seen in the United Kingdom. Consequently, the total national costs of complying with any regulation concerning EE2 could be considerably lower in these countries than in the United Kingdom. In addition, the quality of treatment plants in mainland Western Europe is in general higher than in the United Kingdom. In Germany, for example, most sewage treatment plants have three stages and some even have a fourth stage, whilst in the United Kingdom, two stages are most commonly encountered. As we have already noted, the addition of a third stage, whether it be GAC, mild ozonation or simple sand filtration could cause dramatic reductions in estrogen concentrations and their biological effects on fish. As recently demonstrated by Baynes et al. (2012) using biological effects rather than chemical concentrations as measures of effective risk reduction, sand filtration following activated sludge treatment was almost as effective as GAC at preventing the feminisation of male fish albeit it was two thirds cheaper.

For a number of years the decision of whether or not to regulate EE2 appeared to stall in the still waters of cost-benefit analysis, with little chance of resolution and little movement forward. Then, in January 2012, the European Commission proposed a revised list of 'priority substances' for the Water Framework Directive (EC 2012). This included the oestrogens 17β-oestradiol and 17α-ethinyloestradiol. The proposed regulatory EQS for EE2 was 0.035 ng/L for inland surface waters (e.g. rivers and lakes): this is the annually-averaged limit in these water bodies. If this proposed EQS is adopted (a first vote on which occurs in the European Parliament's Environment, Public Health and Food Safety Committee in November 2012), it could be taken into account in the 2015 updated River Basin Management Plans and associated 'Programmes of Measures' across Europe, with enforcement required by 2021. But even now, nearly 75 years after its initial manufacture in 1938, and decades of research concerning its environmental endocrine disrupting effects, this remains a proposal requiring agreement: the decision to regulate or not is yet to be made and may be stalled by recent representations to the EC from both the water and pharmaceutical industries (EUREAU, 2012).

Indeed in July 2012 an amendment to this proposal was tabled, stating 'It is appropriate not to specify the EQS for certain substances of pharmaceutical relevance that have been added to the list of priority substances' and that 'The Commission should propose the EQS for these substances in the next review of the list in 2016, and appropriate measures should be introduced…with the aim of meeting the EQS by 2027' ([9]).

13.7 Late lessons

Ethinyloestradiol, the active ingredient in the birth control pill, has allowed women to control their fertility reliably on a global scale. But it has come at a price to the environment. As mixtures, EE2 and other oestrogens, both synthetic and natural, have been shown to have serious impacts on wildlife — impacts that can be associated with early life exposure but manifest themselves later in adult life. Such impacts are often sub-lethal but may be permanent and irreversible. They may also serve as sentinels for impacts on human health via environmental oestrogen or other endocrine disrupting chemical exposure.

Since wildlife is exposed to a cocktail of endocrine disrupting chemicals, it is naive to conclude that EE2 alone is the culprit. It is, however, the most potently oestrogenic of the steroid oestrogens, occurring widely in effluents entering the environment, at concentrations that can frequently exceed the Predicted No Effect Concentration of 0.1 parts per trillion (UKWIR, 2009). There is reasonable certainty, based on sufficient scientific evidence, that EE2 plays a significant role in causing the reproductive health impacts observed in fish. The need for risk management has been accepted by both the Environment Agency of England and Wales (Gross-Sorokin et al., 2006) and by the European Commission through its proposal for EE2 to become a priority substance requiring control (EC, 2012).

But this is a story that is far from over, and is one that continues to raise important questions that will apply not only to EE2 but to any other pollutants exerting damaging but often sub-lethal effects at very low concentrations. For a decision to regulate EE2 has not been agreed. A critical question is whether we as a society are willing to pay a potentially very high premium to be precautionary and exclude EE2 from the environment. Alternatively, would we, as a society, prefer to live with the impacts of EE2 and other oestrogens on wildlife; are they acceptable risks? To what extent is society, which ultimately bears the benefits of flexible fertility but also the costs of cleaning up its unintended consequences on the environment, having a say on this decision?

This historical retrospective allows us to identify several important lessons, which are central not only to regulation of EE2 and other steroid oestrogens but also for many other low-level chemical pollutants in the environment with sublethal effects, alone or in combination, now and in the future.

13.7.1 Lesson 1: for low-level pollutants in the environment, is the price of being precautionary simply too high?

With regulation of EE2 now a serious proposal in Europe, the water industry, regulators and national governments are faced (as will be the case with many other low-level pollutants) with risk management that will be a costly process if EE2 is to be removed from sewage treatment works final effluents to the vanishingly low levels that will be required for compliance. The target level proposed by the EC for EE2 as an annual EQS has been set at 0.035 ng/L for inland surface waters (e.g. rivers and lakes). This is the regulatory concentration *in the water body itself*, not in the final effluent discharged from the sewage treatment works. However, as the UK Demonstration Programme has shown, reducing levels of EE2 in final effluents via end-of-pipe treatment to enable compliance with this EQS (e.g. for those water bodies with low dilution receiving large volumes of oestrogenic effluent) will be extremely difficult, The most promising technology, granular activated carbon, might achieve this, but it is expensive and may have a potentially large carbon footprint. Mild ozonation may also be

([9]) Draft report on the proposal for a directive of the European Parliament and of the Council amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy (17.07.2012). Proposer Richard Seeber, European Member of Parliament.

effective, but this will still be expensive in terms of capital set up costs (10).

Measuring compliance with the low EQS for EE2 and E2 will also be a significant challenge. The techniques available to measure such very low levels of EE2 in natural waters and effluents are hardly routine. Some efforts have been made to develop more amenable enzyme-linked immunoassay analysis methods but these have been fraught with issues around selectivity and sensitivity at the very low levels of detection required. This leaves both the water industry and regulators with a fundamental problem: it will be costly to remove EE2 to enable compliance with the target EQS, and costly to monitor and demonstrate legal compliance itself. So while it is technically possible to develop an EQS, in practice it may be very hard to implement. The widespread nature of contamination has only added to the problem: this is unlikely to be an issue in one isolated location, but one with significant cost implications across Europe and beyond.

What other options might there be? Since EE2 is both the most potent of the steroid oestrogens and, seemingly, the most difficult to remove by conventional sewage treatment, could there be an argument for substituting this as the active ingredient in the contraceptive pill, leaving the remaining oestrogens to be removed conventionally at less cost? But what would replace it? If there were sufficient demand or need, the pharmaceutical industry could continue to provide women with access to birth control and reproductive choice while substantively altering the design of pharmaceuticals to protect the environment from unnecessary harm. This would represent a constructive precautionary approach (11). Is this option preferable?

13.7.2 *Lesson 2: low-level pollutants with sublethal effects present fundamental issues for the precautionary principle*

A number of definitions and interpretations of the precautionary principle exist (see Weiner and Rogers, 2002; Gee, 2006), of which the Rio Declaration (UN, 1992) is one that is widely cited:

> 'Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation' (12).

The chapter on the precautionary principle (PP) in this volume, provides different definitions of the PP taken from other international treaties and the European Court of Justice, including the working definition proposed by the EEA which is designed to improve common understanding about the meaning and application of the PP.

However, for this chapter it will be useful to consider the constituent parts of the Rio definition, the first of which deals with threats of serious or irreversible damage.

It is not in dispute that intersex in fish represents both serious and irreversible damage to fish and that exposure to environmentally relevant levels of EE2 has adverse effects on fish reproduction, an ecologically relevant measure of impact. Uncertainties remain, particularly around fish population level effects, but the precautionary principle aims to promote action in the face of such uncertainties, when there is evidence of serious environmental damage that is irreversible. In fact, the level of scientific certainty concerning the risks (or threats) posed by oestrogens as mixtures to aquatic life, mediated through their endocrine disrupting effects is extremely high and there seems to be little or no doubt that there is sufficient evidence to justify applying the precautionary principle (Gross-Sorokin et al., 2006). Responding to this evidence of harm, the water and chemical industries (and indeed some scientists) have increasingly asked the question, 'so what?' There may be male fish with eggs in their testes and this might be unpleasant, irreversible and widespread. But does it seriously damage fish populations? (Webb et al., 2003). Why pay potentially vast sums

(10) It should be noted that some European countries have decided to clean up wastewater, even in the absence of regulation of EE2 and E2, but in recognition of contamination of wastewater by pharmaceuticals, pesticides and endocrine disruptors. Full-scale treatments will be installed on more than 100 Swiss WWTP treating about 80 % of the Swiss municipal wastewater. The first full-scale ozonation plant will go in operation in Spring 2013 and will cost only 5 EUR/person/year including both capital and operational costs, because sand filtration already exists on this plant.

(11) There has been some research towards development of contraceptive formulations such as the progesterone-only pill, which do not contain oestrogen and instead target the female reproductive cycle more specifically (Lakha et al., 2007).

(12) A European Commission Communication on the Precautionary Principle (EC, 2000) sets out guidance on when to apply the precautionary principle e.g. 'where there are reasonable grounds for concern'. The Communication sets out a set of general principles underpinning application of the PP This includes 'examining costs and benefits' which 'entails comparing the overall cost to the Community of action and lack of action, in both the short and long term. This is not simply an economic cost-benefit analysis: its scope is much broader, and includes non-economic considerations, such as the efficacy of possible options and their acceptability to the public' (p. 4). It also includes the need for the decision-making process to be 'transparent'.

of money for risk management when the seriousness of such population — level effects is uncertain? These populations might collapse in the future, as indicated in the Great Lakes study of EE2 (Kidd et al., 2007), but maybe they will not. Is intersex an unpalatable but acceptable harm?

But even if the seriousness of the harmful threats is accepted, the precautionary principle's Achilles heel, however, as defined in the Rio Declaration, lies in the words 'cost effective'. The central issue for oestrogens (and quite possibly for many other chemicals that cause sublethal impacts at very low levels) is that any risk management measures are likely to be very costly, and as we have discussed above, this may be a price too high to pay.

The potentially high costs of risk management have combined with protracted debates about what constitutes acceptable harm to seriously delay decision-making about the regulation of EE2 and other steroid oestrogens. This has been compounded by a precautionary principle whose definition includes issues of disproportionate cost and cost effectiveness, either explicitly or implicitly ([13]). Defined in this way the precautionary principle may be logical and rational, but it can also paradoxically become a perfect excuse for inaction or, at best, seriously delayed action. It is therefore perhaps no surprise that eight years after the UK government officially recognised EE2 and other steroid oestrogens as posing a risk to wildlife that should be managed, and some 30 years after the first observations of their effects in wild fish populations, that the regulation of EE2 is still undecided. And even if the EC proposal is agreed, it will not come into force until at least 2015.

Such long delays have, one might argue, been completely within the spirit of the precautionary principle at least as defined in the Rio declaration. The precautionary principle is well intended and should expedite decision-making in the face of uncertainty. But in reality decision-making has been painfully slow. We are left with the uncomfortable knowledge of a serious environmental issue that has been, and continues to be, unresolved: one which we may have to live with if the price of precaution is deemed too high. This is a bitter pill to swallow.

13.7.3 *Lesson 3: the need for an open debate on precaution and decision-making*

Our environment is full of low-level pollutants present as mixtures that cause sublethal effects. The European Inventory of Existing Commercial Chemical Substances (EINECS) lists over 100 000 chemical compounds and little is known about the toxicity of about 75 % of them. Several hundred new substances are marketed each year after some basic premarket toxicity testing and these are registered in the European List of Notified Chemical Substances (ELINCS), which currently contains about 2 000 chemicals.

In 2007 the new chemicals EU regulation, REACH (Registration, Evaluation, Authorisation and restriction of CHemicals) was enacted. This reformed chemicals laws and set up procedures and responsibilities to address the backlog of untested chemicals, focusing on some 30 000 substances now being evaluated by industry and the new EU chemicals agency ECHA. Hazard identification and quantification is challenging however, and implementing monitoring programmes and conducting risk assessments for this whole 'chemicals universe' is unfeasible. Moreover, we do not have the tools to fully analyse how mixtures of these chemicals behave. The only logical way forward seems to be to reduce exposure as much as possible — to be precautionary. But this comes at a price and raises ethical questions of where responsibility should lie. Do we want the water industry to reduce exposure through costly treatment? Do we want the pharmaceutical industries to invest in developing new, less harmful contraceptive pills? Either way, are we as a society, prepared to pay for it? Do we care?

The average fish in a stream or person in the street now has hundreds of novel compounds in their bodies that were not there 60 years ago. We can measure them in adult and foetal tissue. We know they have detrimental effects such as intersex in fish. We have changed the chemical environment of the developing organism. EE2 is a perfect case study of how we are responding as a society to difficult decisions regarding the need for, and challenges of, risk management for these low-level pollutants with chronic sublethal effects.

([13]) The EU communication on the precautionary principle also recommends an 'Examination of the benefits and costs of action and lack of action'. This 'examination of the pros and cons should include an economic cost benefit analysis where this is appropriate and possible.However, such an 'examination of the pros and cons cannot be reduced to an economic cost-benefit analysis'. It is wider in scope and includes non-economic considerations (EC, 2000). The EEA working definition of the PP also uses the broader 'pros and cons' rather than 'costs and benefits' for similar reasons, including the importance of the non-quantifiable 'cons' such as the melt down of public trust in scientists and policticians which occurred in the BSE saga (see EEA, 2001, Ch. 15 on BSE).

A key observation from this case study is that the public has been and continues to be silent witnesses. A key lesson learnt from previous case studies (EEA, 2001; Gee, 2006; Lokke, 2006) has been that the process of applying precaution must encourage public participation, such that the costs of action (e.g. risk management) and potential costs of inaction are debated. This enables value judgements and decisions to be made in an open and democratic way. Transparency of decision-making and the need to involve all interested parties as early as possible is a central tenet of the European Commission communication on the precautionary principle (EC, 2000), which states that:

> 'All interested parties should be involved to the fullest extent possible in the study of various risk management options that may be envisaged once the results of the scientific evaluation and/or risk assessment are available.'

The US National Academy of Sciences has also repeatedly stressed the importance and need for stakeholder involvement at all stages of the risk-based decision-making process (NAS, 2009.) Prior to this, in 1998 the UK Royal Commission on Environmental Pollution published a report on Setting Environmental Standards (RCEP, 1998) in which it emphasised that decisions must be informed by an early understanding of peoples values, with a process that ensures transparency and openness. This is a view that is shared by the chemicals industry (Webb et al., 2003).

The Royal Commission also identified specific mechanisms by which this could be achieved. It stated that those affected have a right to make their views known before a decision is made and that 'it is no longer acceptable for decisions to be negotiated privately between the regulator and polluter' (RCEP, 1998). This was fully endorsed by the UK government in their response to the Commission's report. But this endorsement is yet to translate into action. Opportunities for engagement and consultation that do exist are insufficient ([14]).

Decisions regarding regulation of EE2 and its sister oestrogens, and the dilemmas and issues these pose, have been, and continue to be undertaken in a poorly understood, closed process that has little engaged the public. It is vitally important that decision-makers understand about the acceptability of risk, appetite for precaution and the willingness to pay for being precautionary. The views and concerns of the public have to date however gone largely undocumented. This is not an academic exercise: it is fundamental to making a decision on such a complex and potentially costly issue, a point emphasised by the Royal Commission in 1998 and the European Commission in 2000. Without public support the costs of risk management, of regulation of EE2, may be seen by policy makers as disproportionate. It might be that the weight of evidence suggests that public opinion is not on the side of risk management, that we are prepared to live with endocrine disruption in the environment as collateral damage associated with flexible fertility in our own species. But what is very clear is that without asking the public it will be far easier to come to a conclusion based largely on costs alone. This loads the dice before they are thrown.

([14]) For example in the development of the next round of River Basin Management Plans across the EU under the Water Framework Directive.

Table 13.1 Early warnings and actions

1938	17α-ethinyl estradiol (EE2) synthesised
1943	EE2 marketed as a contraceptive
1962–1969	USFDA approve the birth control pill and the United Kingdom allows it to be prescribed through its National Health Service
1970	Pill users increase in number from 50 000 to 1 million
1976	First speculation that oral contraceptives might pass through sewage treatment works (STWs) into the aquatic environment
1979	Kinloch Nelson and Bunge publish a study showing low sperm counts in 93 % of men about to undergo vasectomies
1982	Routine health checks of male fish (roach) in a UK river show the presence of oocytes in testes (intersex). The rate of hermaphroditism is very high in comparison to the norm
Mid-1980s	First reports of contraceptive pill hormones in river water
1985	High levels of female-specific yolk protein (vitellogenin) found in blood of male fish in a fish farm receiving effluent containing river water
1985	Nonylphenols discovered in sewage effluents and in sludge
1991	National survey shows that oestrogenic effluents are widespread in England and Wales
1991	4-Nonylphenol is rediscovered as an oestrogen
1992	Meta-analysis of 61 studies shows sperm counts have declined 50 % in the preceding 50 years
1993	Theo Colborn and Clement publish 'The Wildlife Human Connection' suggesting widespread endocrine disrupting effects in wildlife and humans as a result of exposure to chemicals
1994–1996	Sharpe and Skakkebaek publish a hypothesis that testicular cancer, hypospadias, cryptorchidism and lowered semen quality are part of a syndrome caused by exposure to environmental oestrogens during foetal life
1993	BBC Horizon screens the award-winning documentary 'Assault on the male'
1995–1996	Surveys show that intersex is widespread in roach and is especially prevalent downstream of STWs with low effluent dilution. Feminising syndromes in other wildlife species are reported
1996	Major European workshop on endocrine disruptors are held, jointly sponsored by the European Commission, the European Environment Agency, the European Centre for Environment and Health and the World Health Organization
1998	Steroid oestrogens, and EE2 in particular, are shown to be the most potent oestrogenically active substances in domestic effluent
1998	Royal Commission on Environmental Pollution publishes a report *Setting environmental standards*, in which it emphasises that decisions must be informed by an early understanding of people's values. It is endorsed by the United Kingdom government
1999	European Union launches a Strategy on endocrine disrupters
2001	Feminisation is shown to be a permanent phenomenon that is progressive with age i.e. duration of exposure
2001	Schering publish a whole life-cycle study showing EE2 causing full sex reversal of males to females at concentrations > 2 ng/L
2002	Silva et al. show additive effects of oestrogenic endocrine disrupting chemicals *in vitro*: 'something from nothing'
2002-2003	More widespread surveys show intersex fish are present throughout the United Kingdom. Widespread anti-androgenic activity is discovered in sewage effluents
2003	Nonylphenol and nonyphenol ethoxylates are banned in the European Union as a hazard to human and environmental safety. Serious evaluations of other endocrine disruptors such as BPA take place
2004	Predicted No Effect Concentration (PNEC) of 0.1 ng/L derived for EE2
2004	UK Endocrine Disruption Demonstration Programme commences, evaluating the efficiency of removing oestrogens from sewage treatment processes
2007	Draft environmental quality standard for EE2 prepared by the Environment Agency of England and Wales
2008	Experimental lakes study in Canada reports a population crash of fish after exposure to EE2 at 6 ng/L
2009	UK Demonstration Programme reports first phase results showing difficulty removing EE2 to the PNEC using conventional sewage treatment approaches
2012	European Commission publishes proposals to regulate EE2 as a 'Priority Substance' under the EU Water Framework Directive, which if accepted may come into force after 2015. An amendment to this proposal is tabled in July 2012 which proposes delay of setting EQS until 2016, with the aim of meeting this by 2027'

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14 Climate change: science and the precautionary principle

Hartmut Grassl and Bert Metz [1]

The first scientifically credible early warning about the possible dangers of climate change due to carbon dioxide (CO_2) emissions from burning fossil fuels came in 1897. While the basic physical principles of global warming are simple, however, the more detailed science of climate change is exceedingly complicated. Even now, more than a hundred years since the first early warning, many important details of climate change cannot be predicted with certainty. It is therefore unsurprising that the science of climate change and questions about the true value of burning fossil fuels have fostered sustained scientific and political controversy.

When the first volume of *Late lessons from early warnings* was drafted there appeared to be too much legitimate controversy about climate change for the issue to be included. A case study could have led to arguments that distracted attention from the valuable and robust lessons from more established issues such as asbestos, polychlorinated biphenyls (PCBs), chlorofluorocarbons (CFCs) and the ozone-hole, X-rays and acid rain. This decision was taken despite the then widespread acceptance that 'the balance of evidence suggests a discernible human influence on global climate' (IPCC, 1995a).

Over a decade later and after two more reviews by the Intergovernmental Panel on Climate Change (IPCC) of a much greater volume of climate change science it seemed appropriate to include climate change in this volume, despite some continuing controversy. The evidence that human activities are having a dangerous impact on the climate has strengthened since 1995. By 2007, the IPCC was able to conclude with 'very high confidence that the global net effect of human activities since 1750 has been one of warming' (IPCC, 2007a). Given the size and irreversibility (on human time scales) of many of the harmful effects of human-induced climate change, there is an urgent need for action to reduce CO_2 emissions and other greenhouse gases. Some contrarian views persist, however, as the authors illustrate.

This chapter summarises the history of growing knowledge about human-induced climate change and of the main actions, or inactions that accompanied it. Like many other chapters, it reflects the lifelong commitment of both authors to trying to understand and mitigate the effects of human-induced climate change. It concludes with some lessons and insights that are relevant to many other environmental and health issues.

Also included is a panel text describing how the IPCC's approach to assessing uncertainty evolved between its first to its fifth assessment reports.

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14.1 Introduction

The climate provides the background for the development of human civilisation. Historically, it has been a decisive factor determining where and how people live, what they eat, how they clothe themselves, how they structure their activities, where and why they travel, what hazards they face, and how they organise their response to those hazards. In fact, almost every aspect of human and social life is closely linked to climatic factors.

At the same time, the goal of becoming less dependent on the climate's vagaries has been an important driver for the development of human civilisation. Humans have learned how to construct shelters to protect themselves and their belongings from cold and rain, how to build irrigation systems that allow food production despite erratic rainfall, how to conserve and store food to prevent starvation at times when there are few natural food sources available, and so on.

Growing use of fossil fuels since the industrial revolution has arguably been the key factor enabling humankind to separate decisions about where and how to live from the local climatic conditions. Today, fossil fuels allow a significant fraction of humankind to heat or cool a building at the press of a button, to pump water over long distances and even between watersheds, to transport food across continents, often in artificially cooled environments, and to fly to holiday destinations with particularly attractive climates.

During recent decades, a rapidly increasing body of scientific knowledge has identified unexpectedly close links between these two major driving forces of social and economic development: the climate and burning fossil fuels. We now know that the use of fossil fuels, which has allowed the wealthy part of humankind to become less dependent on climate factors, is substantially changing the radiative properties of the atmosphere. It is thereby causing changes to the global climate system that are unprecedented at least since the end of the last ice age.

Ironically, or tragically, the societies that have contributed most to the problem of anthropogenic (i.e. man-made) climate change are generally least affected by its impacts, and vice versa. The massive use of fossil fuels — and the economic wealth that typically goes with it — allow fossil fuel-intensive societies to largely protect themselves from the vagaries of climate variability and weather extremes. In contrast, poor people who use little fossil fuels and who have contributed least to the problem have limited resources to cope with the hazards brought about by anthropogenic climate change. Worse still, they often live in regions with an already marginal climate.

It is not surprising that the strong links between these two fundamental drivers of human societies and their evolution have brought about an unprecedented level of interest, debate and conflict in the public, the media and at all political levels. Climate change policy has become a key item on the agenda of many high-level international meetings. In fact, the fifteenth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP15) in Copenhagen in December 2009 was the second largest assembly of Heads of State and Heads of Government ever to occur outside the New York Headquarters of the United Nations (after the Earth Summit in Rio de Janeiro in 1992).

Anthropogenic climate change is in many ways a unique problem. First, the anticipated (and increasingly observed) effects of climate change and of climate protection policies are very large and widespread. Second, the expected 'winners' and 'losers' from climate change and from climate policies are very unequally distributed across the world and across time, which raises difficult questions of international and intergenerational equity. Third, the science of climate change and its interactions with other social and economic developments is extremely complex, which prevents clear-cut answers on many questions of particular relevance for decision-makers (e.g. on specific local and regional impacts of climate change).

Against the backdrop of an increasingly charged public and political environment, the science of climate change is continuously developing, producing robust results and identifying key uncertainties. In parallel to the evolution of science, unique institutions have been created to facilitate the transfer of scientific knowledge to decision-makers. Other forces have developed to obstruct this knowledge transfer by creating unfounded confusion even around robust scientific findings. As a consequence, climate scientists find themselves in an increasingly politicised environment.

Climate change is, of course, not the only global problem undermining the planet's ecosystems and economies. The loss of biodiversity, increasing water scarcity, dispersion of toxic chemicals, loss of productive land due to erosion and overgrazing, and the depletion of natural resources are, like climate change, the result of human societies' unsustainable practices. A global response was formulated at the UN Conference on Environment and Development (the Earth Summit) in Rio de Janeiro in 1992, with the adoption of Agenda 21 for sustainable development (UN, 1992). The subsequently adopted Millennium Development Goals (UN, 2000) establish a clear link between eradicating widespread poverty (Goal 1) and ensuring environmental sustainability (Goal 7). This development dimension is fundamental to dealing effectively with climate change, although in practice much of the scientific and policy discussion on climate change has been narrowly focused.

This chapter attempts to shed light on the co-evolution of climate change science and international climate policy by presenting key events, important actors and institutions, and the main conflicts. The focus is on the science-policy interface, the role of the precautionary principle in helping to deal with scientific and social uncertainties of long-term climate change, the link with the broader sustainable development agenda and the lessons that can be drawn so far.

14.2 Early development of the scientific knowledge base on human-induced climate change until the 1970s

First hints of the greenhouse gas effect

The greenhouse effect, as currently understood, is described in Box 14.1. The first hint of its existence dates back to the 1800s. Based on observations by Saussure from the late 18th and early 19th century, the Frenchman Joseph Baptiste Fourier correctly understood the observed atmospheric vertical temperature gradient (i.e. the observation that upper layers of the atmosphere are colder than lower layers) to be similar to the observed strong heating caused by a glass plate on an insulated box (Fourier, 1824). Up until that time, the absorption properties of atmospheric gases had been completely unknown.

Absorption of heat radiation by atmospheric trace gases

Nearly 40 years later, in 1863, John Tyndall, an Irishman working in Great Britain, published a remarkably precise description of the atmospheric greenhouse effect, which comes close to modern definitions:

> 'The solar heat possesses the power of crossing an atmosphere, but, when the heat is absorbed by the planet, it is so changed in quality that the rays emanating from the planet cannot get with the same freedom back into space. Thus the atmosphere admits the entrance of the solar heat but checks its exit, and the result is a tendency to accumulate heat at the surface of the planet' (Tyndall, 1863a).

Tyndall based his definition on his own observations of the absorption characteristics of atmospheric trace gases, including the key absorption bands of water vapour and carbon dioxide, which account for about 80 % of the total atmospheric greenhouse effect according to current knowledge.

The first scientist identifying fossil fuel use as a potential reason for climate change

In 1896, the Swede Svante Arrhenius used the knowledge of carbon dioxide absorption bands published by American scientist Samuel Langley to

Box 14.1 The greenhouse effect (IPCC definition)

Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface-troposphere system. This is called the *greenhouse effect*. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, – 19 °C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, + 14 °C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called *enhanced greenhouse effect*.

Source: IPCC, 2007d.

argue that increased combustion of coal — at that time mainly in Great Britain — could lead to higher surface temperatures. He stated:

> 'if the quantity of carbonic acid [i.e. carbon dioxide] increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression' (Arrhenius, 1896).

The modern formulation of this still valid relationship is that 'the temperature increase is proportional to the logarithm of the carbon dioxide increase'. Arrhenius's estimate that the global surface temperature would rise by 3–5 °C if atmospheric carbon dioxide concentrations doubled is close to present day knowledge. For example, the Intergovernmental Panel on Climate Change (IPCC, 2007a) has projected a 2.0–4.5 °C increase.

Arrhenius was not alarmed about the warming due to an enhanced atmospheric greenhouse effect, since his initial concern was the negative consequences for Scandinavia if cooling were to occur.

Early anthropogenic climate change debates until 1940

The issue of anthropogenic climate change was raised in the late 19th century by Eduard Brückner, although his interest was not the greenhouse effect. Instead his focus was the effects of deforestation and cultivation of land on the reflectivity of the land surface and its evaporation, given the huge changes people have made to vegetative cycles (Penck and Brückner, 1901–1909). Arrhenius, as already described, was the first to consider anthropogenic emissions and the greenhouse effect but the lack of accurate measurements of trace gas concentrations prevented a continuing debate except for a few follow-up papers by Arrhenius (e.g. in 1899). Even some decades later Callendar (1938) was only able to give a range of 274 to 292 parts per million volume (ppmv) for the atmospheric CO_2 concentration at the turn of the century.

Guy Stewart Callendar's 1938 paper published in the Quarterly Journal of the Royal Meteorological Society marked a milestone in the history of understanding anthropogenic climate change. He was the first to establish the full link from trace gas concentration change, observed only for carbon dioxide, via changed radiation fluxes from the atmosphere to the surface, to observed global mean warming for the period from 1900 to 1938. The following year he went further, stating:

> 'As man is now changing the composition of the atmosphere at a rate which must be very exceptional on the geological time scale, it is natural to seek for the probable effects of such a change. From the best laboratory observations it appears that the principal result of increasing carbon dioxide […] would be a gradual increase in the mean temperature of the colder regions of the Earth' (Callendar, 1939).

Callendar's paper failed to raise a major scientific debate even though the first (albeit rather inaccurate) measurements of CO_2 concentration changes were available, a major global mean warming episode had occurred between 1900 and 1940, and spectroscopy of trace gases had advanced. One reason why Callendar did not succeed in spreading his message, even among the scientific community, was because his meteorological colleagues did not believe the CO_2 concentration changes he claimed to have been observed ([2]). A second reason was the poor knowledge that most meteorologists then had of radiative transfer of heat radiation (also called terrestrial, or thermal infrared, or long-wave radiation) through the atmosphere.

From theoretical considerations on the transfer of energy in the global atmosphere to quantification in computer models

While the mechanisms underlying the transfer of energy around the global atmosphere are simple to understand in principle, quantifying this in a computer model remains far from easy. Accurate radiative transfer calculations in a spherical atmosphere require sophisticated numerical codes, as the basic equation fully established by Chandrasekhar (1950) is a so-called integro-differential equation that can only be solved numerically, demanding high performance computing facilities. Even today a comparably large amount of computing time is devoted to the 'brute force' calculation of a still very simplified radiative transfer in a climate model.

([2]) For accurate trace gas measurements, groups of laboratories have to measure concentrations of gases in samples given to them within an international comparison in order to eliminate larger systematic errors. Reliable change estimates for CO_2 were not available until the 1960s and data for the other two naturally occurring long-lived trace gases, N_2O and CH_4, were not available until the late-1980s.

Chandrasekhar's work allowed a more accurate calculation (at first only in atmospheres without clouds) of the increased downward thermal radiation and hence the global mean warming estimates, following any increase in greenhouse gases. In the second half of the 1950s and early 1960s such estimates for a doubling of CO_2 concentrations evolved steadily from original estimates without cloud influence reaching 2.5 °C (Plass, 1956). Adding the influence of clouds reduced this to less than 2 °C (Kaplan, 1960) but attempts to account for water vapour influence, via fixed relative humidity led to very high temperature increases (Möller, 1963). These were strongly disputed because the positive water vapour effect amplified the estimated impact of a doubling of CO_2 concentrations to nearly 10 °C warming.

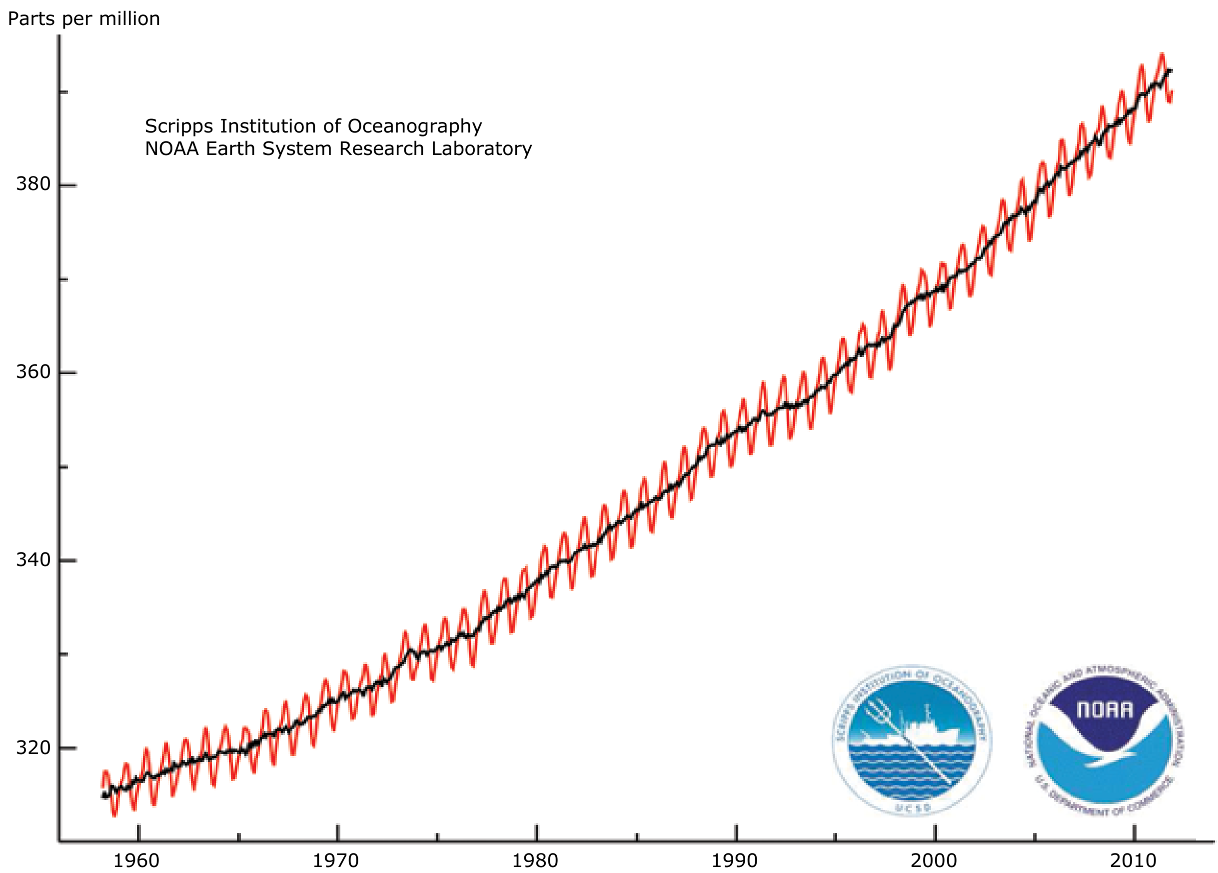
Establishment of long-term time series of greenhouse gas measurements

The International Geophysical Year from 1957 to 1958 marked the start of long-term monitoring of the most important anthropogenic greenhouse gas, carbon dioxide (CO_2). The US scientist David Keeling established two monitoring stations in very remote locations — Mauna Loa on Hawaii (Figure 14.1) and Antarctica — to measure the background concentration of CO_2 without the influence of nearby anthropogenic sources. These time series soon revealed the annual seasonal 'breathing' of the northern hemisphere (caused by the growth of biomass during the warm months and its decay during cold months). This annual cycle is weak at the South Pole, at the point furthest from the seasonal influence. It was this time series which, by 1970, had demonstrated a clear rising trend in global CO_2 concentration of some 0.4 % per year. The full trend curve can be found in NOAA (2011).

First calculations with global circulation models

Computers have had a huge impact on our ability to understand the atmospheric greenhouse gas effect. The advent of the first global three-dimensional atmospheric general circulation

Figure 14.1 Carbon dioxide (CO_2) mixing ratio at the Mauna Loa station on Hawaii



Note: The yearly averages and the annual cycle rise continually in the 50 year period. The annual cycle is caused by biomass growth during the Northern Hemisphere summer and the decay of biomass in the winter.

Source: NOAA, 2011.

models (AGCMs) for weather forecasting came with the first electronic computers in the late 1950s. By the early 1960s, an AGCM roughly representing the present day climate had also been run with doubled or quadrupled atmospheric CO_2 concentration.

These AGCMs rapidly reached a new higher equilibrium for surface temperature because the effect of the ocean, represented merely as a rather thin boundary of several 10s of metres in the model, was a poor representation of reality. Oceanic circulation — particularly vertical mixing — has a major impact, delaying the rise in global mean warming by at least several decades under present CO_2 concentration increases. Climate system sensitivity — the change in temperature resulting from a net change in incoming and outgoing energy at the top of the atmosphere ([3]) — has been investigated ever since such the first AGCM efforts of the mid-1960s.

The role of clouds

Simulations by AGCMs consistently indicated a surface temperature increase of around 1 °C for a net increase in energy flux of one watt per square metre at the top of the atmosphere, if the effect of clouds were trivial. Clouds cover more than 60 % of the Earth's surface, however, and their effect is far from trivial. They can reflect up to 80 % of solar radiation and they decouple thermal infrared emission from the surface into space. High clouds very often add to the greenhouse effect but low clouds lower it. Schneider (1972) was the first to realise that increasing cloud top height by 600 m is equivalent to a temperature increase of 2 °C. Reducing cloud cover by 8 % has a similar effect. Clouds are also influenced by air pollution, leading to higher reflectivity for geometrically thin water clouds and lower reflectivity for geometrically and optically thick water clouds, if they contain some black carbon.

It rapidly became evident that understanding cloud properties and the consequences of any changes in these, was a crucial element in predicting greenhouse gas effects. However, it proved very difficult to quantify what the net effect of these various changes would be.

Air pollution and climate change

The absence of obvious atmospheric warming from the late 1940s until the 1970s, despite the increase in greenhouse gases, revealed yet another facet of the anthropogenic climate change 'puzzle': that surface cooling could occur as a result of increased atmospheric turbidity, both in clear and cloudy atmospheres. This is because turbidity arising from anthropogenic air pollution affects the radiative transfer of energy in the following, sometimes unexpected, ways:

- it increases local planetary albedo (reflectivity) over dark surfaces like the ocean but decreases local planetary albedo over bright surfaces like sand dunes and snow (Yamamoto, 1972; Eschelbach, 1973);
- it strongly reduces solar irradiance at the Earth's surface — also called 'global dimming';
- it enhances cloud reflectivity for water clouds, especially for weakly absorbing minute, so-called 'aerosol' particles — the Twomey effect (Twomey, 1972 and 1974) — and reduces cloud reflectivity for optically thick water clouds, if black carbon or soot particles are part of the aerosol particles (Grassl, 1975).

As stated in IPCC's fourth assessment report (IPCC, 2007a), the latter two effects have remained a key uncertainty within the anthropogenic climate change debate, and are now estimated to mask the enhanced greenhouse effect by about one third.

Summary

By the end of the 1970s, it was known that the CO_2 concentration in the atmosphere was increasing by about 0.4 % per year; that a doubling of CO_2 concentration in climate models would lead to a mean global warming of several degrees centigrade; and that the water cycle contains two positive feedbacks (increasing the key greenhouse gas, water vapour, and lowering the reflectivity of earlier ice and snow surfaces), which act as an amplifier.

With that, most of the main elements of our current technical understanding of the issues were in place. It was not known, however, whether systematic

([3]) Radiative forcing is the rate of energy change per unit area of the globe as measured at the top of the atmosphere or at the tropopause level (the latter has been adopted by IPCC), if a certain radiatively active constituent of the atmosphere is altered and others remain fixed. It is measured in watts per square metre (Wm^{-2}), and positive values lead to surface warming. According to the IPCC, 'The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.'

changes of methane (CH_4) and nitrous oxide (N_2O) concentrations were taking place. Nor could CO_2 concentrations before industrialisation be determined.

14.3 Scientific breakthroughs regarding human-induced climate change during the 1980s

The 1980s brought scientific breakthroughs with respect to a number of the remaining uncertainties. As outlined below, these included historical greenhouse gas concentrations derived from air bubbles in ice cores, the emergence of coupled three-dimensional ocean-atmosphere-land models, and the clear signal of observed global mean warming in near-surface temperatures. These breakthroughs were largely the result of global change research coordination, as discussed in Section 14.4.

Trace gas history from air bubbles in ice cores
The air inside a snow pack in areas without summer melt, i.e. in the large inner parts of the two major ice sheets in Greenland and Antarctica, is trapped in small air bubbles within older snow that becomes progressively compacted. These tiny bubbles still exist in deep layers of an ice shield after several hundred thousand years.

During the 1980s, Swiss and French scientists (Neftel et al., 1985; Jouzel et al., 1987) were the first to determine the CO_2 concentration in these air bubbles of ice cores with enough precision to reconstruct the long-term history of greenhouse gases (CH_4 and N_2O concentrations could also be determined later). These findings established the strong correlation between CO_2 concentrations and the temperature at precipitation formation. However, the processes causing this correlation are still debated today. Greenhouse gases were clearly a global player in glacial cycles but the lower and upper limits of CO_2 concentration at about 190 to 200 ppmv for glacial maxima and about 280 ppmv during interglacials are still unexplained today.

It also became clear that the start and end of 'glacial' periods were initiated by the insolation changes in the Northern Hemisphere caused by long-term changes in the Earth's orbit around the sun. The consequences of these changes in the Northern Hemisphere climate are then amplified and made global by changing levels of greenhouse gases and by the ice-albedo feedback (Hansen, 2010).

Emergence of coupled atmosphere-ocean models
At the end of the 1980s, the first coupled atmosphere-ocean models emerged. These models included a three-dimensional representation of the ocean, which for the first time allowed simulations of the dynamic interactions between atmosphere and ocean under increasing greenhouse gas concentrations. The models, based on natural laws, are the only way for a look into the future, based on assumptions about human behaviour with respect to population changes, energy supply systems, land use change and global economic development.

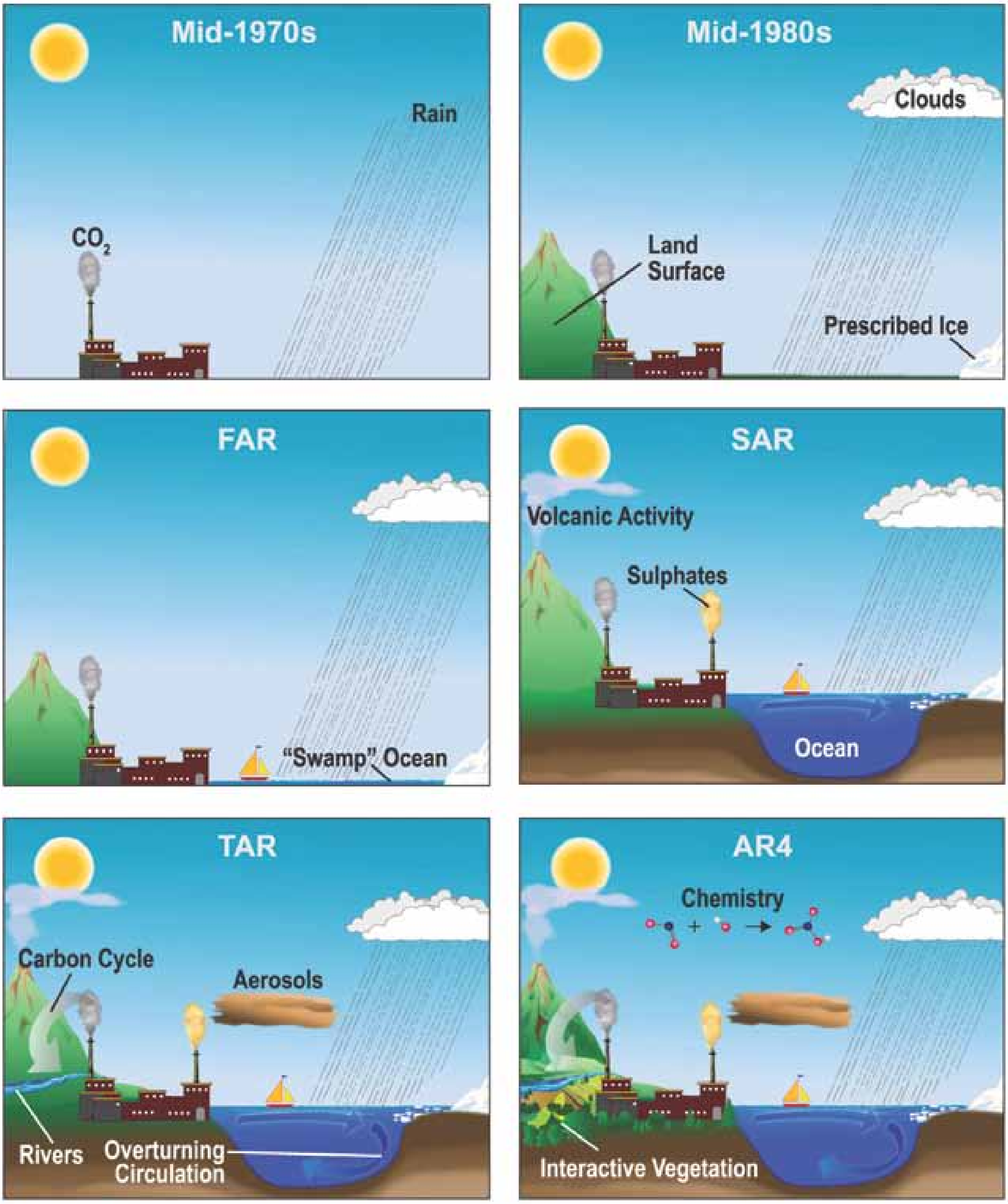
These first coupled models were, however, in need of 'flux corrections'. Flux corrections imply deliberately changing the energy and momentum fluxes at the air-ocean interface to prevent climate drift, i.e. a change in climate, in a constant greenhouse gas concentration scenario. It was not until the IPCC's third assessment report in 2001 that these flux corrections were no longer needed by some more advanced climate models.

One robust and anticipated result of these early coupled models was the delay of the full climate change signal by many decades compared to AGCMs due to the high heat capacity of the ocean. The models predicted that in a period with strong greenhouse gas concentration increase, such as now, less than two thirds of the mean warming that is inevitable due to the past concentration increase can be seen. Another important implication of the considerable inertia in the global climate systems is that the effects of policy measures taken now can only be detected after several decades. The progress in climate modelling during recent decades is depicted in Figure 14.2.

Detection of increased global mean air temperature
A further major development during the 1980s concerned temperature trends. While various regional air temperature trends had been published over the years, the first global trend analyses covering a full century only emerged during the 1980s (Groisman et al., 1987; Hansen et al., 1988). They were still rather uncertain, partly because there were gaps in the 'quality assurance' of observations from thousands of stations. Temperature time series can be inhomogeneous for many reasons, including changes in instrumentation, changed vegetation or buildings in the neighbourhood of the station, changed observers and infrequent calibration.

Other developments
Also in the mid-1980s, the 14th Ozone Report (WMO, 1984) provided the first more or less comprehensive list of the many artificial substances found in the atmosphere, subsequently known as the 'greenhouse gang', that apparently were very

Figure 14.2 Evolution of global climate change models



Note: The complexity of climate models has increased over the last few decades. The additional physical, chemical and biological processes incorporated in the models are shown pictorially by the different features of the modelled world.

Source: IPCC, 2007a.

strong greenhouse gases. Amongst them were the chlorofluorocarbons (CFCs), which were later found to be responsible for the hole in the ozone layer over Antarctica. That phenomenon became widely known only in 1985, although it had started several years earlier. That 14th Ozone Report could not, however, quantify the increase of methane and nitrous oxide concentration because the monitoring time series were too short given the accuracy of concentration measurements at that time.

14.4 Start of global coordination or climate change research and dissemination of findings on human-induced climate change

During the 1980s the climate change issue 'broke out' from being a largely scientific issue to a matter of concern for environmental policymakers. That is not to say that governments had totally ignored the issue previously. Much of the research on climate change had, in fact, been funded by governments. However, the warnings of global anthropogenic climate change by groups of leading scientists, speaking as an increasingly coordinated and unified voice, often reinforced and broadcasted by environmental non-governmental organisations such as the Climate Action Network, played a crucial role in raising the issues prominence. This knowledge transfer from science to policy became formalised with the establishment of a then unique, remarkable and authoritative scientific global climate change assessment body — the IPCC — in November 1988.

14.4.1 World Climate Research Programme

The first World Climate Conference in 1979, organised by the World Meteorological Organization (WMO), a specialised UN agency, agreed a World Climate Programme (WCP). Its research component, the World Climate Research Programme (WCRP), started in 1980 based on an agreement between WMO and the International Council for Scientific Unions (now named the International Council for Science) to organise and co-finance the first global change research programme.

The International Geosphere Biosphere Programme (IGBP), established in 1986, together with WCRP, now provides the main global organising and coordinating framework underpinning the bulk of scientific progress in understanding the functioning of the global system. A large part of the research assessed today by the Intergovernmental Panel on Climate Change (IPCC), was initiated in 1980 under the WCRP, which, for example, had by 1997 completed the first global survey of the physical status of the world oceans via its World Ocean Circulation Experiment (WOCE). The observations from this survey in turn allowed it to determine that the oceans absorb about 2 billion tonnes of carbon from anthropogenic carbon dioxide emissions per year, as presented in the IPCC's third assessment report (IPCC, 2001a, 2001b and 2001c).

14.4.2 Villach Conferences in 1980 and 1985

After two scientific conferences in the Austrian town of Villach in the early and mid-1980s, groups of high-ranking scientists issued initial warnings of the potential consequences of anthropogenic climate change. The scientists had been invited to Villach by the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO) and the International Council for Scientific Unions. In October 1985, these warnings culminated in the observation that:

> 'Many important economic and social decisions are being made today on long-term projects [...], all based on the assumption that past climatic data, without modification, are a reliable guide for the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions' (WMO, 1986).

This paragraph captured one of the key threats of global climate change, namely that important features of our society, such as key infrastructure, may no longer be well adapted to prevailing climate conditions. Scientists, such as Scientific Committee on Problems of the Environment (SCOPE 29, 1988) highlighted that anthropogenic climate change could affect not only average conditions but also climate variability and weather extremes. Many extreme weather events might become more frequent and even new, more devastating extremes might occur as a result of changes in the distribution of climate parameters.

Box 14.2 Why do most policymakers accept IPCC statements as the most authoritative voice on climate change?

In all areas of science, reviews by authoritative groups of established scientists have for a long time been the preferred method of informing the scientific community and the public at large about the current state of knowledge. In the case of the IPCC, however, such assessments were lifted to a level never reached before in any field of science. The reasons primarily structural but also related to individuals, most notably the first IPCC chairman, Bert Bolin.

The structural advantages of the IPCC include the following:

- it is sponsored by well accepted institutions of the United Nations: the World Meteorological Organization (WMO), a technical agency in charge of climate matters, and the United Nations Environment Programme (UNEP);
- it is intergovernmental, i.e. government representatives are members of the national IPCC delegations;
- scientists and governments select the groups of authors for each chapter drawing from lists given by countries and accepting contributions by other experts in a certain subsector of climate research;
- the reviewing process is elaborate and involves the scientific community first and government-named experts in a second round, with all critical remarks and proposals for improvement judged by established scientists who are not authors of the chapters themselves.

A further essential part is the approval of the summary for policymakers 'sentence by sentence'.

14.4.3 Establishment of the Intergovernmental Panel on Climate Change

The IPCC originated from proposals of presidents of national meteorological services, put forward at the Tenth Congress of the World Meteorological Organization (WMO) in Geneva in May 1987. That Congress established an intergovernmental mechanism charged to deliver an authoritative assessment of knowledge about anthropogenic climate change, without which government attention was unlikely.

The Executive Council of WMO proceeded jointly with the United Nations Environment Programme (UNEP) towards establishing an intergovernmental panel of experts. This led, in November 1988, to the first meeting of the IPCC at the Geneva Congress Centre. Three working groups were formed. Working Group I assesses the physical scientific aspects of the climate system and climate change. Working Group II assesses the vulnerability of society and nature to climate change, and means of adaptation, while Working Group III examines mitigation measures for limiting or preventing the effects of greenhouse gases.

More specifically the IPCC's tasks are:

- to identify human induced influences on the climate and to compare these with other external influences and natural variability.

- to address, through process studies and observations, effects on the climate system of important feedbacks, both positive (enhancing change) and negative (reducing change), for instance those due to water-vapour, clouds and ocean circulation.

- to combine these influences and effects by means of numerical computer models simulating past and present climates and projecting future climate.

- to compare model simulations from different modelling groups with observations related to past and present climates, and so estimate the contributions to climate change from natural and human induced influences, together with their associated uncertainties. These computer models provide the only means of adding together all the non-linear processes involved in the evolution of climate.

- to describe the likely future impact on human communities and ecosystems.

All chapters of IPCC reports are reviewed, first by a limited number of expert scientists, then by the international community of climate scientists and others with an interest in reviewing, and finally by governments.

When the working groups meet in plenary, they consist of government representatives, generally both scientists and policymakers, which is a remarkable development in itself. However, the actual assessment work is done by selected scientists only. The overall IPCC structure has been judged successful and has been retained (see Bolin, 2008) although in 2010–2011 several changes were implemented to address criticism (see Section 14.6.4).

The creation of the IPCC represented a decisive turning point in recognition of the scale of the climate change problem, at least amongst technical and policy experts. The IPCC was immediately under pressure to publish its first full assessment of knowledge on (anthropogenic) climate change in time for the Second World Climate Conference (SWCC), scheduled for October 1990.

The IPCC first assessment report, 1990

The IPCC finished its first assessment report in June 1990. The report stated that:

- there is a natural greenhouse effect of the atmosphere which already keeps the Earth warmer than it would otherwise be;
- there is a strong increase of concentrations of all three long-lived naturally occurring greenhouse gases (CO_2, CH_4, N_2O), which is due to anthropogenic activities;
- global mean near-surface air temperature has risen by 0.3 to 0.6 °C during the 20th century;
- in the past there has been a strong correlation between greenhouse gas concentrations and the global mean temperature, as shown by concentrations of greenhouse gases in air bubbles from the last 160 000 years contained in ice cores in Antarctica.

In addition, the IPCC report also pointed to other observed changes in the climate system, including a rise in the mean sea level, the retreat of mountain glaciers in most regions, changes in the regional redistribution of precipitation, and other significant changes in climate parameters. On the basis of the evidence before them, however, and the level of proof that is required to conclude that observed climate change is significantly beyond the level of natural variability, the IPCC could not yet state that observed climate change has a man-made origin.

The IPCC Response Strategies Working Group concluded in 1989 that the potentially serious consequences of climate change justified the immediate adoption of response strategies, such as limiting emissions and preparing adaptation measures. The Working Group suggested that the United Nations agree on a framework convention that later could be supplemented with specific protocols, following the approach taken with the Vienna Convention on Protecting the Ozone layer and its Montreal Protocol. It also suggested setting goals for reducing emission levels in an equitable manner and listed many specific options for doing so across economic sectors.

The IPCC second assessment report, 1995

In 1995, the IPCC published its second assessment report. The Working Group I volume (IPCC, 1995a), agreed in November 1995, stated that 'The balance of evidence suggests a discernible human influence on global climate.' This was the first time that scientific evidence enabled the human-induced change signal to be perceived against the background of natural climate variability. This conclusion strengthened the urgency of calls to address climate change.

Box 14.3 Evidence of anthropogenic climate change

In March 1995, a pre-print of a peer-reviewed scientific paper (Hegerl et al., 1997) claiming that anthropogenic climate change had been detected was announced at a press conference in Hamburg, Germany. The founding director of the Max Planck Institute for Meteorology, Klaus Hasselmann, presented the work of his research group, which was based on four types of evidence: time series of long-lived greenhouse gas concentrations, observed geographical patterns of temperature anomaly time series, transient runs of a coupled atmosphere-ocean-land model, and the so-called fingerprint method (Hasselmann, 1997) searching for anomaly patterns attributable to distinct processes. The wide media coverage of this very unusual event emphasised the significance of the findings.

The Working Group II volume, covering impacts, adaptation and mitigation of climate change (IPCC, 1995b), presented a wealth of information. It indicated that impacts of anthropogenic climate change were already occurring and would pose serious risks in the future.

The Working Group III report, covering the economic and social dimensions of climate change, showed that there were many options available, both in terms of low-emitting technologies and available policy instruments to reduce GHG emissions significantly in all countries and economic sectors. The report also pointed to the importance of early mitigation efforts to improve flexibility in stabilising atmospheric greenhouse gas concentrations as a risk management approach.

The IPCC third assessment report, 2001

The IPCC published its third assessment report in 2001 (IPCC, 2001a, 2001b and 2001c). The role of human activity in causing climate change was further clarified: 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.' Evidence of climate change impacts around the world had strongly increased and projections of climate change impacts in the future were much more serious than in the past. The potential for strong reductions in global GHG emissions was clearly demonstrated and the costs of these reductions were shown to be modest compared to the projected increase in wealth. Insights into effective climate policies had grown significantly.

The IPCC fourth assessment report, 2007

On 2 February 2007 Working Group I of IPCC (2007a) stoked the political debate by clearly pointing out humankind's responsibility for the observed mean global warming:

> 'The understanding of anthropogenic warming and cooling influences on climate has improved since the third assessment report, leading to very high confidence that the global net effect of human activities since 1750 has been one of warming, with a radiative forcing of 1.6 Wm^{-2} (uncertainty range 0.6 to 2.4 Wm^{-2})'.

This statement strengthened the claim that an anthropogenic climate signal had been detected in the second and third assessments. The IPCC's Working Group II report in April 2007 (IPCC, 2007b) concluded that the extent of climate impacts on natural systems had further increased and that risks of future impacts were considered higher than in previous assessments, including an onset of negative impacts at lower temperature changes (see also Smith et al., 2009) than previously assumed. It included for instance the observation that:

> 'Approximately 20–30 % of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5–2.5 °C.'

In May 2007 Working Group III on mitigation of climate change (IPCC, 2007c) made it clear that global emissions need to peak not later than 2015 to have a 50 % chance of keeping long-term temperature increase below 2 °C above pre-industrial levels. If peaking were delayed to 2025 the world would be committed to at least 3 °C warming in the long term. The report confirmed that ample options for reducing GHG emissions are available at modest costs. The report also suggested that the costs and benefits of mitigation are broadly comparable, even for the most stringent stabilisation of GHG concentrations studied (i.e. 450 ppm CO_2-eq.).

The *Stern review on the economics of climate change* (Stern, 2007) published at about the same time was more unequivocal. It stated that the costs of aggressive mitigation action are substantially lower than the costs of climate impacts and adaptation measures. It should be noted that the benefits of avoided climate change are notoriously difficult to estimate, since many impacts cannot easily be translated into monetary terms. In addition, co-benefits of reducing emissions, such as health benefits due to reduced air pollution from coal or increased energy security due to lower imports of fossil fuels, are not included in these calculations.

The outcomes of the Stern review were influenced by the choice of discount rates, which determine the weighting of future benefits and costs in decision-making. The Stern review employed very low discount rates and argued why that was the right choice. Not all economists agree with the approach used (e.g. Nordhaus, 2007).

One of the reasons for the stark messages about the urgency of reducing emissions was the higher estimate for so-called 'climate sensitivity', compared to previous reports. Working Group I stated that the 'best estimate' for a doubling of the CO_2 concentration compared to pre-industrial levels is a 3 °C increase in the mean global temperature, with a lower bound of + 2 °C and an upper bound of + 4.5 °C at two standard deviations. More recent studies confirmed this range (Rummukainen et al., 2010). The third assessment report had estimated climate sensitivity as 2.5 °C (without providing upper and lower bounds). As a consequence, GHG concentration levels for avoiding a particular temperature increase have to be lower than previously indicated. In particular, the European Union had originally estimated that a CO_2 concentration of 550 ppmv would be compatible with its goal of limiting the increase in global mean temperature to 2 °C above preindustrial levels. According to the new assessment, staying within this temperature limit requires greenhouse gas concentrations to remain below about 450 ppm CO_2-eq., which in turn implies a maximum concentration for CO_2 alone of about 400 ppm (compared to measured 380 ppm in 2007). To achieve that, CO_2 emissions would have to be reduced by 50–85 % from 2000 to 2050 globally, and by 80–95 % in industrialised countries.

Such a goal may appear Herculean. Nevertheless, many scenarios have been developed that achieve such a low carbon future using different portfolios of measures. Some scenarios still allow for relatively high shares of fossil fuels (coal and gas) for electricity production but require power plants to be equipped with CO_2 capture and storage. Other scenarios rely on a large share of nuclear power and yet others bring emissions to very low levels by moving to producing 80–100 % of electricity from renewable sources (e.g. WBGU, 2003; Greenpeace/EREC, 2007; van Vuuren, 2007; IEA, 2009 and 2010; IPCC, 2011).

IPCC special report on renewable energy sources and climate change mitigation

The Working Group III special report, *Renewable energy sources and climate change mitigation* (IPCC, 2011), is an assessment of the literature on the scientific, technological, environmental, economic and social aspects of the contribution of six renewable energy sources to mitigating climate change, published in 2011. Some of the main messages are:

- 'A significant increase in the deployment of renewable energy by 2030, 2050 and beyond is indicated in the majority of the 164 scenarios reviewed in this special report';

- In 2008, total renewable energy production was roughly 64 EJ/year (12.9 % of total primary energy supply) with more than 30 EJ/year of this being traditional biomass. The global primary energy supply share of renewable energy differs substantially among the scenarios. More than half of the scenarios show a contribution from renewable energy in excess of a 17 % share of primary energy supply in 2030 rising to more than 27 % in 2050. The scenarios with the highest RE shares reach approximately 43 % in 2030 and 77 % in 2050.

14.5 Emerging climate change policy

The foregoing sections of this chapter presented the evolution of science regarding the enhanced greenhouse gas effect and its projected impacts. The remainder focuses on how the political process dealt with this emerging scientific knowledge base. The power to determine the ends and means of public policy is widely though not equally shared, and different groups will of course seek to shape perceptions of truth, information or analysis (Gregory, 1989). Among the various stakeholders that seek to influence government policy development are environmental NGOs and business organisations. Their influence is mentioned briefly here but is not analysed in detail in order to limit the length of the chapter.

Some environmental NGOs like the Climate Action Network (CAN, 2012) aim to influence the United Nations Framework Convention on Climate Change (UNFCCC) policy process directly by providing detailed feedback through newsletters during the negotiations. Others focus on awareness campaigns (e.g. Greenpeace, 2012) and others provide summary information on scientific aspects (e.g. WWF, 2012). Some businesses (e.g. parts of the fossil fuel industry) have aimed to influence the negotiations directly or through lobby groups (e.g. the former Global Climate Coalition) or have questioned the underlying science (as discussed below). Other businesses have focused on the opportunities provided by climate policy, for example members of the World Business Council on Sustainable Development (WBCSD, 2012). It appears that the perspective of many businesses has changed somewhat over the years from being against action on GHG emission reductions to being in favour of measures such as regulation, either to provide investment security or because certain industries see opportunities (e.g. the renewable energy industries).

14.5.1 The 1980s: initiatives to stimulate political debate on how to deal with climate change

The late-1980s saw several initiatives to stimulate political debate on how to deal with climate change. There was intense public debate in some industrialised countries on climate change, illustrated by reports from some national advisory bodies to governments and legislative bodies, such as in Germany (WBGU, 1993) and other countries (Oppenheimer and Petsonk, 2005). In 1987, scientists and policymakers discussed matters at workshops in Villach and Bellagio, leading to recommendations to formulate policy targets (Oppenheimer and Petsonk, 2005).

Two conferences in Toronto (1988) and Noordwijk (1989) provided opportunities to enhance the scientific input into political decision-making and came up with proposals that would become the heart of the legal climate change regime later on. This was made possible by the mix of government representatives, international agency staff and scientists participating in these conferences.

Encouraged by the international agreement on the Montreal Protocol on protecting the ozone layer in 1987, which set targets for phasing out ozone-depleting substances, many of which are also powerful greenhouse gases (IPCC, 2005a), the Canadian government hosted an international conference in Toronto in 1988. The Toronto Declaration (WMO, 1989) makes extensive reference to the signals of a changing climate and the projections of future changes. It calls for an action plan, including a framework convention on climate change and the stabilisation of GHG concentrations in the atmosphere, and calls for domestic action on reducing CO_2 emissions. The action plan set a political target of a 20 % reduction of global CO_2 emissions by 2005 from 1988 levels, with industrialised countries taking responsibility for most of it. It further called for the establishment of a global atmosphere fund.

The Noordwijk conference, bringing together a group of 67 concerned countries at ministerial level in November 1989, was provided extensive scientific information on climate change, its impacts and strategies to bring it under control. This led to a ministerial declaration, which called for atmospheric GHG concentrations to be stabilised 'within tolerable limits', reflecting the concern about increasing negative impacts of climate change. It asked the IPCC (which was working on its first assessment) to report on the best scientific knowledge to help define what that level should be. It also stated that GHG emissions should be reduced and sinks increased to a level consistent with the natural capacity of the planet, allowing for ecosystems to adapt naturally, food production not to be threatened and economic activity to develop in a sustainable manner (Oppenheim and Petsonk, 2005). This would provide the foundation for the later United Nations Framework Convention on Climate Change.

These events demonstrate the willingness of some political actors to take action based on emerging, but certainly not complete knowledge on climate change and its impacts: the precautionary principle in action.

14.5.2 The 1990s: establishment of the framework of international law for dealing with climate change

In the field of climate policy, the 1990s saw the establishment of the framework of international law for addressing climate change.

United Nations Framework Convention on Climate Change

The IPCC finished its first assessment report in June 1990 and was asked to present its findings at the Second World Climate Conference (SWCC), which took place in Geneva, Switzerland, in October 1990. The World Meteorological Organization (WMO) had changed the earlier main topic of the SWCC, climate variability, to anthropogenic climate change, indicating the increasing priority being given to the issue. The presentation of the first full assessment of scientific knowledge on climate change by the IPCC during the first part of SWCC in 1990 had a major impact on the later ministerial part.

As a result, ministers from 134 countries called for a framework convention on climate change, to be ready for signature at the Earth Summit in Rio de Janeiro, in June 1992. They urged the inclusion of a global objective of stabilising GHG concentrations in the atmosphere at a level that would prevent 'dangerous interference with climate' (language used in the Noordwijk Declaration) and, as a first step, to halt the growth of global GHG emissions.

As a result of the Ministerial declaration of the SWCC, the UN General Assembly decided in December 1990 to set up an international negotiating committee, consisting of government representatives of all UN member countries, to work out an agreement. To serve the negotiations, the IPCC brought out a supplementary report in early 1992 (IPCC, 1992) to provide a synthesis of the latest scientific knowledge about climate change. The work of the negotiating committee resulted in agreement on the text of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) in May 1992, just before the World Summit in July 1992, where it was signed by 153 countries and the European Communities.

Interestingly, the Convention explicitly mentions several underlying principles, including, in Article 3.3, the precautionary principle:

> 'The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.'

The central goal (or 'ultimate objective') of the UNFCCC reads as follows:

> 'The ultimate objective of this Convention […] is to achieve […] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.'

This article clearly shows the central role given to science, which was supposed to inform politics about the level of action to be taken. Specifically, this article raises four major questions (Box 14.4). Science had not progressed to provide definite and clear information on all these questions, so they were essentially unanswered when the UNFCCC came into force.

Operationally, the UNFCCC contains clauses in which industrialised countries commit themselves to:

> 'adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs. These policies and measures will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions consistent with the objective of the Convention, recognising that the return by the end of the present decade to earlier levels of anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol would contribute to such modification'.

This text is a complicated and not really legally binding way of saying that developed countries will try to stabilise GHG emissions by the end of the century at the level of some prior year. The vague formulation already reflected the trouble of getting all industrialised countries (and particularly the US) to agree on a binding formulation to stop the growth of emissions. Box 14.5 sets out the other key elements of the Convention. The UNFCCC was rapidly ratified. It became binding on 21 March 1994, 90 days after the threshold of 55 countries had been reached on 21 December 1993.

Box 14.4 Four major science questions associated with the central goal of the UNFCCC

- What is dangerous interference with the climate system? In other words, what climate change impacts constitute a danger? This is obviously a value judgement that cannot be made on scientific grounds alone but science has an important role to play in providing relevant information.
- How fast may the climate change while still allowing for ecosystems to adapt naturally? This seems largely a scientific question. However, any level of change will cause responses in ecosystems. Whether these responses are still considered as 'adaptation' or already as 'impacts' is partly a value judgement, which in turn may be influenced by considerations about how much these responses matter — e.g. fish stocks that we eat versus marine species that we do not.
- At which redistribution of precipitation and at which warming level is food production threatened? Again, it initially seems a scientific question but in effect it also requires value judgements, asking for political decisions related to e.g. food distribution and the population size of an area facing food insecurity.
- At what degree and rate of climate change is economic development going to be affected negatively? But also, what is the speed at which emissions reduction and adaptation measures can be taken so as to avoid disrupting economic development? Here scientific and economic knowledge is needed to inform politics.

Box 14.5 Key elements of the UNFCCC

Principles:
- 'common but differentiated responsibility'
- special consideration for vulnerable developing countries
- 'precautionary principle'
- 'polluter pays'
- promoting sustainable development

Goals: the ultimate goal (Article 2) is to 'stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.'

Participation: almost universal (191 countries and the European Union, as of 1 September 2008).

Actions required:

- All countries must minimise emissions and protect and enhance biological carbon reservoirs, so called 'sinks'. Industrialised countries ('Annex I countries') must take action to stop growth of emissions before 2000.
- All countries must promote development, application and transfer of low-carbon technologies. Annex I countries must assist developing countries.
- Cooperate in preparing for adaptation.
- Promote and cooperate in research and development.
- Report on emissions and other actions (so called 'national communications'), annually for Annex I countries and less frequently for others.
- Rich industrialised countries ('Annex II countries') must assist developing countries financially in their actions.

Compliance: reports are reviewed by the secretariat and by visiting expert review teams.

Institutions:

- The Conference of the Parties (COP) is the supreme decision-making body. Its rules of procedure for decisions have never been agreed.
- The Bureau (comprising officials elected by the COP) is responsible for overall management of the process.
- Two subsidiary bodies (for implementation and for scientific and technological advice) prepare decisions of the COP.
- The financial mechanism is operated by the Global Environment Facility of the World Bank, the United Nations Development Programme (UNDP) and UNEP, and replenished by Annex II countries on a voluntary basis. Two special funds — a least developed country fund and a special climate change fund — mainly finance adaptation plans and capacity-building but also provide for technology transfer and economic diversification.
- Expert groups exist on technology transfer, developing country national communications, least developed country national adaptation plans.
- The Secretariat is located in Bonn, Germany.

Other elements: a requirement to review the need for further action regularly.

Source: Metz, 2010.

Kyoto Protocol

At the time the UNFCCC entered into force (end-1994), the IPCC was still working on its second assessment report. Enhanced scientific understanding of climate change and stronger evidence of its man-made causes was becoming more widely known. At the first session of the Conference of the Parties to the UNFCCC (COP1), in Berlin from end-March to the early-April 1995, the vague and not legally binding commitment of industrialised countries to try to stabilise emissions by 2000 was recognised as being far from sufficient.

The Conference of the Parties therefore adopted the so-called Berlin Mandate, which contained as its key provision the need for a legally binding intergovernmental agreement to reduce greenhouse gas emissions by industrialised countries, ready in time for COP3 in 1997.

Developing countries pushed hard to be left out of this strengthening of commitments. Under the UNFCCC they are only subject to general obligations on matters such as taking national action to combat climate change and reporting their emissions. Their arguments were based on the principle of 'common but differentiated commitments and respective capabilities' in UNFCCC Article 3.1. The COP agreed that in the UNFCCC context this approach implied that industrialised countries should take the first step but that all countries would step up their commitments to address the problem over time, albeit maintaining proper differentiation of actions.

The demand expressed in the 'Berlin Mandate' for a binding legal agreement for greenhouse gas emission reductions was met at COP3 in Kyoto, Japan, with the unanimous adoption of the Kyoto Protocol to the UNFCCC by more than 150 countries on 10 December 1997 (UNFCCC, 1997). Industrialised countries agreed to reduce their GHG emissions, using a basket of six GHGs, to about 5 % below their 1990 level by the 2008–2012 period. This was a substantial deviation from the business as usual situation which, despite the commitments made in the UNFCCC, still showed strongly increasing GHG emissions from industrialised countries. The aggregate 5 % reduction was to be achieved by differentiated emission targets for each country, taking into account specific national circumstances. The principles of the Convention, including the precautionary principle and the principle of 'common but differentiated responsibilities and respective capabilities' apply to the Protocol. Other key elements are presented in Box 14.6.

Implementation of the Kyoto Protocol

Four years of negotiations and four further sessions of the Conferences of the Parties to the UNFCCC (COP4 to COP7) were needed to get the full 'small print' of the Kyoto Protocol finalised. It was not until ratification by the Russian Federation on 16 February 2005 that the 1997 Kyoto Protocol became binding, which required ratification by 55 countries representing more than 55 % of the total emissions in 1990 from countries with reduction commitments. Ratification by Russia was critical for the Kyoto Protocol to enter into force after the single most important emitter, the US, withdrew from the Protocol in 2001.

Will industrialised country ('Annex B') Parties achieve their collective target of reducing greenhouse gas emissions by 5 % below 1990 on average over the 2008 to 2012 period? Projected emission levels in the period 2008–2012, based on country reporting as of 2007 show that, other than Canada and New Zealand, most Parties are likely to meet their targets after accounting for emissions and removals from land-use change and credits from the Kyoto flexible mechanisms (UNFCCC, 2011a). Emission levels in 2009 of all Annex B Parties to the Protocol were about 22 % below the base year, in part due to the economic recession of 2008 (Figure 14.3).

The EU-15 ([4]) is on track to achieve its commitment under the Kyoto Protocol of reducing emissions by 8 % compared to base-year levels. This is due to a combination of domestic measures, EU-wide policies and measures, carbon sinks and Kyoto mechanisms. The closing of coal mines in the United Kingdom in 1985 and the German reunification after the fall of the Berlin wall in 1989 have helped these countries deliver on their respective 12.5 % and 21 % individual reduction targets. In recent years emissions were also reduced because of the short-term effects of the global economic crisis.

EU actions have included establishing the EU Emissions Trading Scheme; promoting renewable energy sources; promoting energy efficiency increases in the energy, transport and industry sectors; reducing methane from landfills; and cutting emissions of industrial fluorinated gases (EC, 2010; EEA, 2010; EEA, 2011).

Countries of the former Soviet Union and eastern European countries are significantly overachieving their targets because emissions fell dramatically after the breakup of the Soviet bloc and the expected rebound of emissions after economic recovery did not occur as a result of changes in their economic structure and modernisation of their industries. Collectively they are at around 35 % below their 1990 level.

([4]) The EU comprised 15 Member States when it agreed to a collective 8 % reduction target in 1997. That is still the basis for compliance with the Kyoto Protocol obligations, although the EU now has 27 Member States.

Box 14.6 Key elements of the Kyoto Protocol

Principles: same as the Convention

Goals: same as the Convention

Participation: 180 countries and the European Union (United States are not a Party)

Actions:

- Annex I countries jointly reduce emissions to 5 % below the 1990 level, on average over the period 2008–2012. Specific emission caps are set for individual countries (UNFCCC, 2012).
- Option to use flexible mechanisms, i.e. international trading of emission allowances (not to be confused with domestic emission trading systems), using the emissions reductions from projects in developing countries (through the Clean Development Mechanism, CDM) or other Annex I countries ('Joint Implementation').
- Option to develop coordinated policies and measures.
- Strengthened monitoring and reporting requirements for countries with reduction obligations.

Compliance: failures to achieve emission reduction targets are to be compensated in the period after 2012, with a 30 % penalty.

Institutions:

- COP of the UNFCCC, acting as the Meeting of the Parties of the Protocol, serves as the primary decision-making body.
- All other UNFCCC institutions are used.
- Compliance Committee, with consultative and enforcement branch.
- Executive Board for the Clean Development Mechanism.
- Joint Implementation Supervisory Committee.
- Adaptation Fund, managed by the Adaptation Fund Board and administered by the GEF. The Fund gets its money from a 2 % levy on CDM projects.

Other elements: a requirement to review the need for strengthening actions.

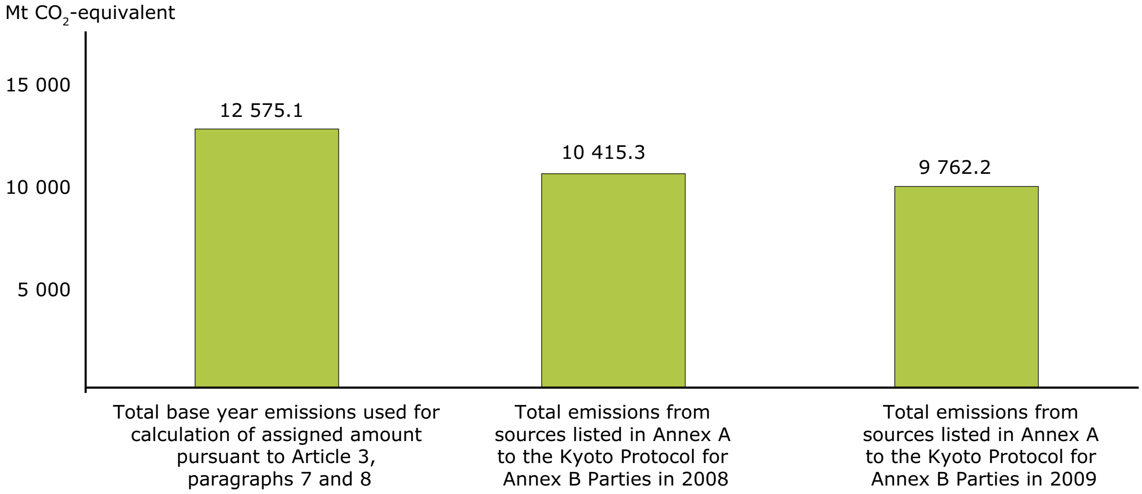
Source: Metz, 2010.

At the same time, however, global emissions increased from about 38 Gt CO_2-equivalent in 1990 to about 50 Gt CO_2-equivalent in 2010 (UNEP, 2011b), largely because developing countries increased their emissions as a result of spectacular economic growth. Compared to developing country emissions growth, the fact that the US stayed out of the Kyoto Protocol played a minor role in aggregate emissions growth. The global increase till 2012 was deliberately accepted (although underestimated at the time) in the design of the Kyoto Protocol, in line with the 'polluter pays' principle and the need to deal with equity concerns on the side of developing countries. The expectation was that in subsequent periods all countries would strengthen their actions to bring global emissions under control.

The Clean Development Mechanism of the Kyoto Protocol was increasingly employed. It allows developing countries to 'sell' reductions obtained from specific projects to industrialised countries and aims to support sustainable development in the 'selling' developing country. As of 1 January 2009, there were 4 474 CDM projects in the pipeline (i.e. either submitted to or registered by the CDM Executive Board). Of these, 1 370 had been registered and 465 certified emission reductions (CERs) had been issued. Together they equate to a reduction of about 0.3 Gt CO_2-equivalent per year in the period 2008–2012 and about 0.7 Gt CO_2-equivalent per year from 2013 to 2020. Given their relatively low price, it is very likely that Annex I countries will buy all the CERs originating from the CDM to meet their obligations.

To put things in perspective: the 0.3 Gt CO_2-equivalent per year is about 50 % of the total emission reduction (compared to the base year) that Kyoto Annex I countries are supposed to achieve. In other words, domestic emissions reductions in these countries will be only half of what they would have been without the CDM, if all available CERs are indeed bought (Metz, 2010).

Figure 14.3 Emission levels of Kyoto Protocol Annex B Parties in 2008 and 2009 (excluding land-use change emissions), compared to the base year



Source: UNFCCC, 2011b.

CDM projects cover a wide range of mitigation activities. The number of projects on renewable energy is the highest, with much smaller numbers for landfill gas (methane) recovery and destruction of HFC-23 at HCFC plants and N_2O at chemical plants. In terms of tonnes of CO_2-equivalent reduction expected before the end of 2012, however, renewable energy projects represent 36 % and HFC-23 and N_2O projects 26 %, which reflects the high global warming potential of HFC-23 (Metz, 2010).

Although the CDM is one of the successes of the Kyoto Protocol there are also some weaknesses. An example is the approval of some renewable energy projects (e.g. hydropower) but also efficient ('super critical') coal-fired power plants projects, where it is hard to prove that emission reductions are 'additional'. In other words, these projects possibly would have happened anyway without CDM credits. Another example is the approval of various industrial destruction projects of HFCs, which are emitted as a by-product of manufacturing the refrigerant gas HCFC-22, for companies that thus made profits selling credits. Such weaknesses are being addressed in current negotiations on a new international agreement for the period after 2012.

The US went its own way in dealing with climate change, as did Australia until December 2008 when it ratified the Protocol. Domestic climate action at federal level was given low priority in the US until the Bush administration concluded at the end of 2008. Although some action was taken at State and local level across the US, GHG emissions kept rising and net emissions were about 15 % above 1990 levels in 2008 (EPA, 2010b). After the election of President Obama at the end of 2008 there was hope that federal US GHG emission reduction policy would change, but this has not happened. Australia, although not part of the Kyoto Protocol until December 2008, nevertheless took domestic action in line with its Kyoto commitment. Australia is more or less set to meet its Kyoto target.

The ultimate objective of the UNFCCC and the EU two-degree target

It seems highly probable that the statement that 'The balance of evidence suggests a discernible human influence on global climate' in the IPCC second assessment report and the information on climate impacts and emission reduction options both played a strong role in facilitating the adoption of the Kyoto Protocol in 1997 by all countries attending the third session of the Conference of the Parties to the UNFCCC. The resistance that emerged in the US Congress prior to COP3 was primarily focused on the design of the Protocol, particularly its exemption of countries like China, and on the perceived risk for the US economy if significant emissions reductions were made (Byrd-Hagel Resolution, 1997).

In terms of the precautionary principle, political action was indeed strengthened at a time when scientific knowledge had improved but was still far from certain on the causes of climate change, the expected impacts and the feasibility and costs of emission reductions. It was not possible, however, to achieve political agreement on the exact meaning of the ultimate objective of the UNFCCC, i.e. what constitutes a 'safe' level of GHG concentrations in the atmosphere. In other words, there was no clear idea how big the challenge actually was and how fast global emission reductions would have to occur.

In 1996 an important decision was taken by the Council of Environment Ministers of the European Union. They decided that in the light of the scientific evidence as reflected in the IPCC second assessment report, global average temperatures should not be allowed to rise more than 2 °C above the pre-industrial level. This was a political decision, based on scientific evidence about the risk of expected climate change impacts on one hand and the perceived feasibility of deep emission reductions on the other. It would become the focus for EU climate policy for the next decade and beyond.

The decision was based on the following global risk management approaches (Metz, 2010):

- **Cost-effectiveness approach**: first determine what a 'tolerable' risk of climate change impacts is (a political judgement based on scientific evidence), then determine how this level can be achieved at the lowest possible costs, and finally consider whether this is politically feasible.
- **Cost-benefit approach**: perform a cost-benefit analysis that attempts to compare the monetised climate change damages with the cost of taking action, ensuring that the benefits of an action exceed its costs. As noted in Section 14.4.3, estimating these future costs and benefits poses some significant challenges.

The EU's 2 °C decision was arguably based on a mix of the two approaches. It was obvious that a 2 °C warming would still mean a significant increase of the risks of climate change with serious consequences in vulnerable countries. It was regarded as unrealistic, however, to turn around global emission trends fast enough to limit the temperature increase further. It was also felt that setting a maximum tolerable level of warming should not be based on an uncertain and disputed comparison with the monetised costs of climate change impacts. The precautionary element was to set a clear limit, despite the continuing scientific uncertainty about climate change impacts, and the costs and feasibility of drastic emission reductions.

Scientific literature published since the IPCC second assessment report confirmed that limiting global warming to less than 2 °C above pre-industrial temperatures would considerably reduce the risk of triggering irreversible large-scale changes in the climate system, such as a complete melting of the Greenland ice sheet, which would lead to large adverse impacts in many world regions. Nevertheless, significant risks would remain even in the event of a 2 °C increase above pre-industrial temperatures (IPCC, 2007b; CCSEG, 2010). This recently led to a large group of developing countries challenging the adequacy of the 2 °C limit, arguing for the necessity of a 1.5 °C limit, as discussed in the next section.

14.6 Debate on further international action after 2012

14.6.1 The post-Kyoto UNFCCC process

At COP11 in 2005 a decision was taken to start two processes: a negotiation among Kyoto Parties about a second commitment period (following the first period from 2008–2012), and a so called 'dialogue' among all UNFCCC Parties about the future evolution of international climate action under the UNFCCC.

The IPCC published its fourth assessment report in 2007 and was awarded the Nobel Peace Prize in November 2007, together with Al Gore. With the messages from IPCC being discussed widely, it was possible at COP13 in Bali in December 2007 to formally start negotiations on a new agreement for the period after 2012. A complex two-track negotiating structure emerged. The negotiations on a second commitment period of the Kyoto Protocol continued with all countries except the US. A new track was also started, known as the 'long-term cooperative action', which covered all countries and aimed to enhance national and international action to achieve the ultimate objective of the UNFCCC. COP13 agreed the 'Bali Action Plan', which called for negotiations to be completed at COP15 in Copenhagen in December 2009.

14.6.2 Copenhagen 2009

COP15 in Copenhagen failed to reach agreement on a legally binding agreement for the post-2012 period, jeopardising effective global action. The COP 'took notice' of the Copenhagen Accord (UNFCCC, 2010), a political declaration by more than 140 countries. The Accord includes the goal of keeping global temperature increase below 2 °C or possibly even 1.5 °C, it promises substantial financial resources from industrialised countries, and it contains an annex in which countries can include their intended national actions.

Although the COP did not formally endorse the Accord, it does reflect some significant progress regarding the policy response to climate change, including the endorsement of the 2 °C limit. It demonstrated the almost unanimous support for the 2 °C limit first proposed in 1996 by the EU. And the Accord even recognises that the climate change risks implied in this limit may already be going beyond what vulnerable regions, countries and people can tolerate and that a 1.5 °C limit might be needed.

The specific actions that have subsequently been pledged by almost 100 industrialised and developing countries show the intent of many countries to take domestic action to combat climate change. The EU specified internally agreed climate and energy targets to be met by 2020: reducing EU greenhouse gas emissions to at least 20 % below 1990 levels; providing for 20 % of EU energy consumption from renewable resources; and reducing primary energy use by 20 % compared with projected levels, to be achieved by improving energy efficiency (EU, 2012). It also pledged a 30 % reduction of emissions, provided other major emitters would made comparable efforts.

Unfortunately, the sum of these national emission reduction pledges for 2020 does not add up to what is needed to be on track to limit global temperature increase to 2 °C. In fact, current pledges imply a 2.5–5 degree trajectory, depending on how pledges for 2020 are implemented and what happens after 2020 (UNEP, 2010a and 2010c).

In Figure 14.4, the top coloured bands illustrate emission pathways over the 21st century, generated using integrated assessment modelling (IAM). The pathways were grouped based on ranges of likely temperature increase in the 21st century. Emissions corridors correspond to the 20th to 80th percentile range of emissions. The median of the Copenhagen Accord Pledge cases in 2020 is represented by the black bar.

The two bottom figures illustrate temperature increases associated with the different emissions pathways in the years 2020 (left) and 2050 (right): Thick, black lines show the median values, dark shaded areas represent the 20th to 80th percentile range, and light shaded ones the minimum/maximum range.

14.6.3 Cancun and Durban

COP16 in December 2010 took place in Cancun, Mexico. It was the culmination of a year of very active diplomacy and consensus was reached among all Parties to the UNFCCC on a series of decisions that formalised the elements of the Copenhagen Accord as official UNFCCC decisions and agreed a number of organisational provisions on finance and technology transfer. This meant that the long-term goal for limiting global warming and the pledges made by countries to reduce their emissions were formally decided. However, the most contested issues in the negotiations, such as the future of the Kyoto Protocol, the legally binding character of a new treaty, commitments from major developing countries, the provisions on monitoring, reporting and verification and the provision of financial support to developing countries, were not addressed.

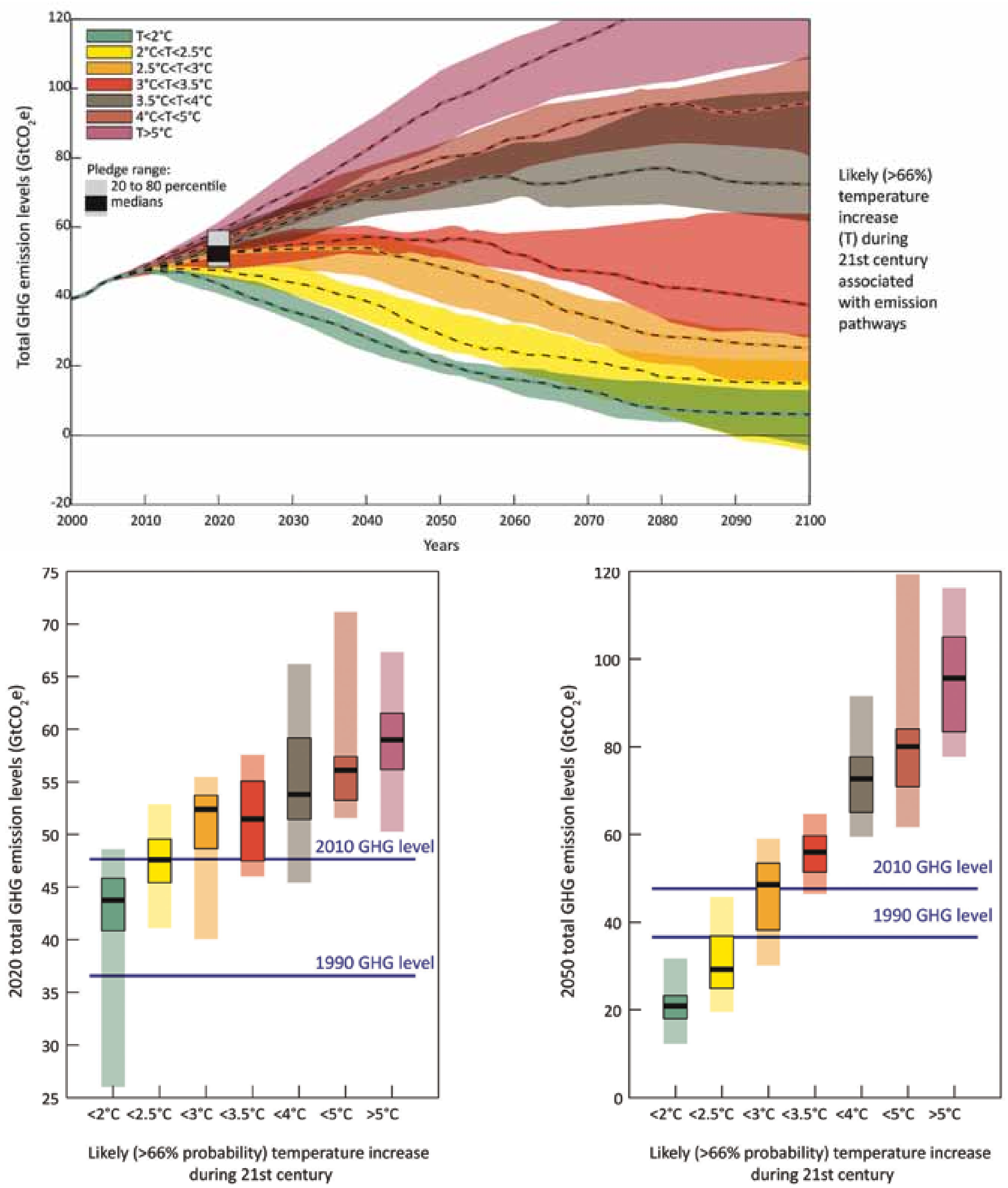
Despite difficult preparations, the next COP17 in Durban in 2011 delivered a series of decisions, although these did not include a new agreement for the period 2012–2020. Many countries were satisfied with the voluntary pledges that had been made in Copenhagen and Cancun. Only some Annex B countries agreed to put these pledges into a second commitment period under the Kyoto Protocol. It was agreed to hold workshops to clarify the pledges and were encouraged to strengthen the pledges, since the existing commitments would lead to a 3–4 °C trajectory, making it impossible to meet the 2 °C limit (UNEP, 2011b).

COP17 decided to start negotiations for a new legally binding agreement that would cover the period after 2020 and to complete negotiations by 2015 (UNFCCC, 2011d). Businesses require long-term agreements extending beyond 2020 to inform their investment decisions. Governments likewise need time to translate international agreements into national legislation and policies. In the short term, however, there is also a need for more ambitious action in the period up to 2020 if the 2 °C limit is to be taken seriously.

14.6.4 Creating doubt on the scientific knowledge base

Looking back at the 2000–2010 decade we see that international political action on climate change is moving forward only slowly. This is at odds with the increasingly strong messages from the scientific community about the man-made causes of climate change, the current and expected impacts of climate change, the urgency of deep reductions of global

Figure 14.4 Projected emission pathways over the 21st century



Note: In the above figure, the top coloured bands illustrate emission pathways over the 21st Century, generated using integrated assessment modelling (IAM). The pathways were grouped based on ranges of likely temperature increase in the 21st Century. Emissions corridors correspond to the 20th to 80th percentile range of emissions. The black bar represents emissions in 2020 resulting from pledges.

The two bottom figures illustrate temperature increases associated with the different emissions pathways in the years 2020 (left) and 2050 (right): Thick, black lines show the median values, dark shaded areas represent the 20th to 80th percentile range, and light shaded ones the minimum/maximum range.

Source: UNEP, 2011b.

GHG emissions and the feasibility of specific actions and technologies to realise such reductions.

One factor that caused this, although not the only one, is the doubt that was created about scientific knowledge on climate change. Other reasons, such as global economic and political developments and the growing ineffectiveness of the current approach to international agreements, have certainly contributed but are beyond the scope of this chapter.

Proper scientific conduct requires assumptions and findings to be challenged continuously in order to advance scientific knowledge. The IPCC has invested a lot in accurately reflecting in its assessments the certainty of findings and the continuing uncertainties (see Panel 14.1 on the IPCC and Uncertainty) — and it is important that these uncertainties be explored. While scientific method demands close scrutiny of certainties and uncertainties alike, however, honest scientists would not blatantly deny where the preponderance of evidence leads (Schneider, 2009). That is precisely what 'climate change deniers' or 'contrarians' are doing.

The science of climate change in general and the conclusions of the IPCC in particular have often been attacked by interested political actors and in the past years increasingly through a range of internet blogs, often in order to create doubt about the scientific basis for climate protection policies. These attacks have occurred despite significant scientific progress and despite the IPCC having stimulated research on topics that were identified as key uncertainties in earlier IPCC reports. Political lobbies supported by very few scientists — mostly from fields unrelated to climate change and without a publication record on climate issues — have often received prominent attention in the media, merely by opposing settled knowledge. Media in Anglo-Saxon countries have been much more inclined to support such attempts than in other countries (Painter, 2011). These campaigns have been able to delay the political process, in particular in the US, but also at the global level. It seems that the message that nothing has to be done is preferred to a call for global action.

The fossil fuel industry, for example, financed the 'Global Climate Coalition' in the US from 1989 to 2002. This group ran multi-million dollar advertising campaigns just before the Kyoto negotiations, which certainly had an impact on public opinion. These efforts have continued in different forms until now, the latest incarnation being a full 'denial industry' (Hoggan and Littlemore, 2009; Dunlap and McCright, 2010). Parallels between the climate change debate and earlier controversies over tobacco smoking, acid rain and the hole in the ozone layer have been identified, showing that spreading doubt and confusion was a basic strategy of those opposing action in each case (Oreskes and Conway, 2010).

Another line of attack on addressing climate change has come from economists who argue that climate change is not the most important problem ('not the end of the world') and that tackling it would divert scarce resources from resolving problems such as poverty, hunger, malaria and HIV/AIDS that claim more lives (Lomborg, 2007; Copenhagen Consensus Center, 2009).

Just before COP15 in Copenhagen, another attack on climate science was launched, accusing climate scientists that had worked for the IPCC of manipulating their results and keeping unwanted papers from scientists with different views out of the IPCC report. This accusation, dubbed 'Climategate' in the press, was based on a series of hacked emails from the computers of the University of East Anglia (UEA) in the United Kingdom. This attack was followed soon by the discovery of two mistakes in the Working Group II contribution to the 3 000 page IPCC fourth assessment report. Due to an erroneous statement on the melting rate of Himalayan glaciers, this problem became known as 'Glaciergate'. Attackers suggested that IPCC authors had deliberately manipulated the assessment to make it scarier than was warranted. A delayed and defensive reaction from the IPCC management to these accusations made things worse.

A number of different investigations in the United Kingdom of the behaviour of the involved scientists at the Climatic Research Unit (CRU) of the UEA cleared them from scientific misconduct (Russell et al., 2010; Oxburgh et al., 2010; House of Commons Science and Technology Committee, 2010). One of the recommendations given by the investigators was that climate scientists should take even more steps to make all their supporting data available — right down to the computer codes they use — in order to make research findings properly verifiable. The CRU (and other organisations) have meanwhile started activities to make more climate data accessible (e.g. UEA, 2010).

Investigations of the claimed mistakes in the IPCC report showed that only very few things needed correction and that they did not have any impact on the major conclusions contained in the Synthesis Report and the summaries of the working group reports (e.g. NEEA, 2010; EPA, 2010a). A review of the IPCC procedures and management structure requested by the UN Secretary-General and the IPCC suggested several changes to avoid similar problems in the future (InterAcademy Council, 2010).

Panel 14.1 The evolution of the IPCC's approach to assessing 'uncertainty'

Malcolm MacGarvin

Dealing with uncertainty has been a fundamental issue in assessing and communicating climate change. The IPCC generally distinguishes between 'statistical', 'value' or 'probabilistic' uncertainty (referred to as 'quantifiable risk' in *Late lessons from early warnings*) and 'systemic' or 'structural' uncertainty (termed 'unquantifiable uncertainty', 'ignorance' and 'indeterminacy' in *Late lessons from early warnings*).

The first and second IPCC assessments use terms such as 'almost certain', 'likely' and 'doubtful' inconsistently, even within each assessment. In preparation for the third assessment report, the IPCC therefore produced guidance for authors addressing the issue of reporting uncertainty. This included material on underlying theory, the practical pitfalls for authors and editors, and the communication of uncertainty to the wider world. The IPCC has since revisited its guidance on uncertainty for both the fourth and fifth assessments. This panel charts the various landmarks in the IPCC's evolving approach to uncertainty.

Guidance for the third assessment

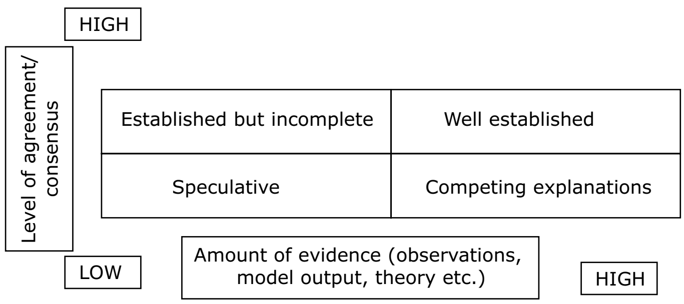
The third assessment report's guidance on uncertainties (Moss and Schneider, 2000) — which lists 37 reviewers, including some still influential in IPCC work — noted that uncertainty results from a lack of information, and disagreement about what is known or even knowable. Uncertainty exists even in carefully controlled laboratory studies. For climate research, however, this is compounded by factors such as the global scale and low frequency variability, with characteristic times greater than the length of most instrumental records; the impossibility of before-the-fact experimental controls; and the (particularly tricky) issue of long time lags between climate forcing and response. According to the third assessment report guidance, assessing the probability of events will inevitably be subjective. It reflects the 'degree of belief that exists among lead authors and reviewers that the event will occur, given the observations, modelling results and theory currently available.'

Other challenges include how best to represent differences in expert opinion; how to alert readers to 'long tail' events (outcomes believed to be unlikely but with serious implications should they occur); and 'poorly managed' projected ranges in impact assessments that may propagate a 'cascade of uncertainty'. Evidently there are communication and credibility challenges in emphasising quantified probabilities, while simultaneously communicating these as provisional and liable to (perhaps dramatic) change. The guidance stresses that it is vital that the specialists should **quantify** the probabilities to the best of their abilities because otherwise others, less expert, would do so on their behalf. The guidance introduced a five-point scale to categorise quantitative probabilities (presented on the left side of Figure 14.5).

The guidelines acknowledged that some reviewers and potential users of the guidelines were 'uncomfortable' with the quantitative ranking of uncertainty. It therefore proposed a qualitative scheme, based on the amount and strength of evidence of various types, and the level of consensus between experts (as shown on the right side of Figure 14.5). Together, these could be used to express high, medium or low confidence in particular findings, with specific formulations of words for various combinations. The guidance maintained, however, that this should be supplementary to the quantitative assessment, because qualitative terms 'do not always map well onto a quantitative scale', increasing the likelihood of inconsistent usage.

Figure 14.5 Quantitative and qualitative expressions of uncertainty as categorised in the third assessment report guidance

(0.95)–(1.00) 'Very High Confidence'
(0.67)–(0.95) 'High Confidence'
(0.33)–(0.67) 'Medium Confidence'
(0.05)–(0.33) 'Low Confidence'
(0.00)–(0.05) 'Very Low Confidence'



Source: Moss and Schneider, 2000.

Panel 14.1 The evolution of the IPCC's approach to assessing 'uncertainty' (cont.)

A separate practical dimension of the third assessment report guidelines is their acknowledgement of human shortcomings in producing assessments. The guidance notes that the means for ensuring consistency in assessing and reporting on uncertainty had not previously received much attention in IPCC reports and that lead authors need to be aware of bias. Group dynamics add complexity to report drafting and that lead authors 'need to guard against the potential for 'gaming' or strategic behaviour' from contributors negotiating a text. Uncertainty within a group arising from conflicting strongly held individual views is qualitatively different from that of a group of collectively uncertain individuals, and report users need this information. Moreover, lead authors should be aware of history, that overconfidence biases experts' judgements: experts 'are correct less often than their confident assessments imply'.

For all these reasons, the third assessment report guidelines advise the preparation of a 'traceable account', describing the 'reasons for adopting a particular probability distribution, including important lines of evidence used, standards of evidence applied, approaches to combining/reconciling multiple lines of evidence, explicit explanations of methods for aggregation, and critical uncertainties.' For particularly important outcomes, the guidelines suggest the use of formal decision analytic techniques, which may achieve 'a more consistent assessment of the subjective probability distribution'.

Learning from third assessment report and preparing for the fourth

Following the third assessment report, an IPCC workshop on uncertainty and risk again reviewed the issues (Manning et al., 2004). The workshop report states that:

> 'probability is the basic language of uncertainty and was originally developed to describe the chance of different outcomes for processes that are stationary over time (such as throws of dice) where observed frequencies are equivalent to probabilities. In general, assigning probabilities to future outcomes cannot assume stationarity or be based entirely on past observations. This leads to the subjective view of probability as a statement of the degree of belief that a person has, that a specified event will occur given all the relevant information currently known by that person. Such subjective probabilities have wider utility and are more relevant to the climate change context.'

Nevertheless, 'cognitive bias' will exist, influenced by a person's (selective) awareness of past events and future expectations; the roots of their perceptions; and the analogies that spring to their mind. A distinction was also drawn between 'likelihood' and 'levels of confidence'. Likelihood was 'the chance of a defined occurrence or outcome' whereas the 'level of confidence' refers to a broader 'degree of belief or confidence in a science community of the amount of evidence or information available and the degree of consensus in the interpretation of that information'.

The workshop also reported on how the third assessment report working groups had diverged from the guidance. Working Group I (addressing the physical science basis) had generally used mathematical-statistical methods and estimates of uncertainty in raw data, using likelihood 'as a basis for approaching uncertainty focused on the probability of outcomes'. It 'was clearly intended to be interpreted in that way despite the definition in the Working Group I Summary for Policymakers as 'judgemental estimates of confidence''. Working Group I never used the qualitative confidence terms introduced in the guidance because of 'discomfort' with the wording. Members agreed, however, that it was appropriate to provide separate indications of the amount of information and the degree of unanimity in the expert community on its interpretation.

Working Group II (addressing impacts, adaptation and vulnerability) addressed less material based on statistical methods, instead giving levels of confidence focused on the degree of understanding and consensus among experts. At times this was used as a proxy for the probability of outcomes. Chapter authors had exercised discretion in using qualitative or quantitative assessments.

Working Group III (addressing mitigation of climate change) did not adopt the guidelines, asserting that it was challenging for economists and social scientists to attempt to use a scale such as those employed by Working Groups I and II, and that there was very little literature to support such estimates for mitigation potentials and estimates of future emissions or drivers.

Panel 14.1 The evolution of the IPCC's approach to assessing 'uncertainty' (cont.)

According to the workshop report, 'structural' uncertainty had not been adequately addressed in the third assessment report. This applied to physical measurements (such as interpreting temperature trends from satellite data) and to biological consequences (such as significant differences between crop yield models, indicating structural uncertainties). Even less account had been taken of structural uncertainties for natural (unmanaged) ecosystems. Similarly, socio-economic structural uncertainties underlying future scenarios and the treatment of adaptive and mitigated capacity had not been explained well in the TAR.

While acknowledging that assessing structural uncertainty 'is generally more difficult and can normally only be done to a limited extent', the workshop concluded that there had nevertheless been a demonstrable tendency for it 'to be overlooked by expert groups'. Indeed 'structural uncertainties associated with analysis techniques … were not considered explicitly. This may have lead to more apparent certainty being given to results where only one or very few independent analyses had been carried out'. There is 'an obligation to identify what we are unlikely to be able to know before the changes actually occur'. So far 'the assessment community has not done very well' in addressing this point.

The workshop was clear that decision-makers need to be aware of events with low probabilities but large impacts, even though these are 'necessarily based on subjective views, usually of a group of experts, on how the future may evolve'. Qualitative explanations of uncertainties associated with costs and benefits, mitigation and adaptation potentials, and scenarios, may be more appropriate than quantitative confidence or likelihood estimates. Providing context will sometimes be more relevant to policymakers than trying to quantify the uncertainties. This includes indicating how robust predictions are, under different assumptions; identifying and explaining sources of uncertainty, including how the variables are defined; assumptions regarding system boundaries; and competing conceptual frameworks. Indeed, giving statements about confidence in probabilistic projections of likelihood raises basic issues, such as how do we measure confidence in unfalsifiable probabilities of future climate change, and to what extent convergence of models can actually be assumed to indicate increasing confidence. Given such deep uncertainties, it was argued, robust strategies that appear to work reasonably well across a wide range of outcomes should be favoured.

Fourth assessment guidance

Following the workshop, the *Guidance note on addressing uncertainties for the fourth assessment report* (IPCC, 2005) was drafted. In part drawing on the earlier work, the fourth assessment guidance was intended to 'assist' lead authors to have a consistent approach to uncertainty 'where possible', while acknowledging that there will be a 'diversity of approaches'. These, the guidance suggested, should be considered early, using a balanced process that reflects any divergence of views, and addressing value and structural uncertainty as well as fundamental unpredictability. Where expert judgements are made, their basis and the critical assumptions, should be traceable. Lead authors should be aware of group dynamics converging and becoming overconfident in an expressed view, or unjustifiably anchored on previous versions or values.

The guidance noted that the appropriate level of precision should be used to describe findings and it proposed a six-point **linear 'typology of uncertainties'**. This ranged from (A) 'Direction of change is ambiguous or the issue assessed is not amenable to prediction' to (F) 'A probability distribution can be determined for changes in a continuous variable either objectively or through use of a formal quantitative survey of expert views'. Three sets of terminology were given 'to describe different aspects of confidence and uncertainty and to provide consistency across the fourth assessment report':

- The first was essentially the same qualitative assessment of confidence (evidence versus level of agreement) set out in the third assessment report guidance, although this time accompanied by instruction that this should only be used to supplement quantitative assessment.
- Similarly, the second was the five-point quantitative confidence scale ranging from 'very high confidence' to 'very low confidence' from the third assessment report guidance. This could 'be used to characterise uncertainty that is based on expert judgement as to the correctness of a model, an analysis or a statement'.
- The third was a 'likelihood' scale, intended to serve as 'a probabilistic assessment of some well defined outcome having occurred or occurring in the future', based on 'quantitative analysis or expert views'. This ranged from 'virtually certain, greater than 99 % probability of occurrence' to 'exceptionally unlikely, less than 1 % probability'.

Panel 14.1 The evolution of the IPCC's approach to assessing 'uncertainty' (cont.)

The guidance did not specify how to ensure that the third assessment report's weaknesses in addressing structural uncertainty were rectified in the fourth report, other than to repeat the third assessment report guidance that 'structural uncertainty tends to be underestimated by experts'. Indeed, the proposed linear 'typology of uncertainties' proposed has the potential to contribute to this confusion as any classification will contain contingent elements of structural uncertainty. A situation classified as (F) inevitably includes elements of classification (A) — categorisation is neither linear nor exclusive.

That such dilemmas exist should not lead to policy paralysis, nor necessarily mean that the best option is further research to 'reduce' uncertainty. Moss and Schneider (2000), the 2004 IPCC workshop report, volume 1 of *Late lessons from early warning*s and the general literature on uncertainty all contain numerous proposals, such as weighing up the pros and cons of action or inaction.

Inter-Academy Council (IAC) review

Following 'Climategate', a critical Dutch review, and the revelation of an error regarding the fate of Himalayan glaciers (actually raised but unaddressed during the fourth assessment report review process) the IPCC asked the IAC to review the IPCC process. Issues raised (IAC, 2010) relevant to uncertainty included the need to improve on transparent selection criteria for authors; demonstrably improved and formalised handling of alternative viewpoints; the advantages of an open review process; policies and resources for handling the volume of comments likely to arise, including any orchestrated efforts, by those with strong views, to overwhelm the system; and demonstrable independence of the review process. Structural uncertainty was not raised.

The IAC recommended that all working group reports should use the qualitative level-of-understanding scale in their summaries for policymakers and technical summaries, 'as suggested in' the fourth assessment report guidance. Actually the guidance was ambiguous on this (c.f. paragraphs 7 and 11–12).

The IAC concurred with the IPCC's aspiration that the basis of the assessments should be fully traceable — although this has resource implications for expert authors and for recovering the information if queried. The IAC also argued that requiring quantitative levels of overall confidence, and a likelihood scale for specific observations, was redundant, noting 'One could have high confidence that obtaining two sixes when rolling a pair of fair dice is extremely unlikely. But why not just say that obtaining two sixes when rolling a pair of fair dice is extremely unlikely'.

Fifth assessment guidance

The IPCC has now produced a *Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties* (Mastrandrea et al., 2010), taking into account the recommendations of the IAC review. The guidance states that:

'The fifth assessment report will rely on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).'

To avoid any doubt about the strength of this guidance, the IPCC subsequently stated, in a response to the IAC report (IPCC, 2011), that working groups were now 'instructed to make this evaluation of evidence and agreement the basis for any key finding, even those that employ other calibrated language (level of confidence, likelihood), and to provide a traceable account of this evaluation in the text of their chapters.' This, nominally at least, represents a significant evolution in the approach to uncertainty by IPCC since the third assessment report guidelines.

The approach to communicating the certainty of key findings in the fifth assessment report is presented in Figure 14.6. The accompanying explanation in the guidance describes this as 'A depiction of evidence and agreement statements and their relation to confidence.

Panel 14.1 The evolution of the IPCC's approach to assessing 'uncertainty' (cont.)

Confidence increases towards the top-right corner as suggested by the increasing strength of shading. Generally, evidence in most robust when there are multiple, consistent independent lines of high-quality evidence.'

Whereas the fourth assessment report guidance employed three sets of terminology to describe confidence and uncertainty, this is reduced to two for the fifth assessment. The five-point quantitative confidence scale is deleted, leaving only the likelihood scale to 'provide calibrated language for describing quantified uncertainty'.

Figure 14.6 Fifth assessment report scheme for communicating confidence in key findings

Confidence scale

Agreement →			
	High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
	Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
	Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Evidence (type, amount, quality, consistency) →

Source: Mastrandrea et al., 2010.

For the first time, the fifth assessment report guidance asks authors to 'be aware that findings can be constructed from the perspective of minimising false positive (type I) or false negative (type II) errors'. Traditionally, academic science places its emphasis on avoiding false positives (falsely concluding that a result is significant, when it is not), and these form the basis of most statements of quantitative likelihood or confidence. Although the fifth assessment report guidance does not discuss it in such terms, from a precautionary perspective one is also interested in type II errors (concluding that a result is not significant, when it is), which requires a different approach. In essence, it can mean assuming that it is more important to be safe than to be right.

In other respects, as might be expected given the earlier effort, the fifth assessment report guidance largely reflects previous IPCC guidance, with some differences of emphasis and re-ordering of text. The guidance again refers to the importance of communicating low probability outcomes with significant impacts; the need to communicate the full range of views where expressing collective viewpoint is inappropriate; the need to make expert judgements and provide a traceable account of their derivation; the tendency of groups to converge on a viewpoint and become overconfident in it; the need to be wary of how the wording of statements affects interpretation by the reader; and the need for lead authors to ensure that they have considered all 'plausible' sources of uncertainty and to be aware that experts underestimate structural uncertainty arising from incomplete understanding.

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The IPCC has started implementing reforms based on these suggestions. In May 2011 the IPCC adopted guidance on a communications strategy; recommendations on how best to handle 'grey' literature; protocols on how to handle scientific uncertainties and corrections of errors in reports; and a conflict of interest policy. The IPCC also agreed to establish an Executive Committee to strengthen the overall management structure (IPCC, 2010).

Polls have shown that these attacks and other developments have had an impact on public opinion regarding the urgency of taking action, even though the accusations were shown to be unsubstantiated. In Europe in 2011 only 34 % of citizens consider climate change to be one of their five major concerns, compared to 57 % in 2007 (EC, 2011a), although 95 % of EU citizens still feel that protecting the environment is important to them personally. Media coverage of climate change has also decreased since 2009, although there are differences across the world (CSTPR, 2011). A survey in 15 countries (covering about 50 % of the global population) shows that climate change was still one of the top three concerns in 2010 (HSBC, 2010). But doubts about the reality of climate change have increased in the general population, and the pressure on politicians to take action on climate change has decreased.

This is not to say that the scientific community is completely free of blame for the situation. Scientists and the IPCC should be open to consider criticism seriously, even if it appears to be scientifically unfounded. In the attacks on the IPCC mentioned above, the response of the IPCC and individual scientists was defensive, which was one reason why the Inter-Academy Council recommended a more transparent communication practice for IPCC. Scientists in general are not necessarily good communicators, lacking understanding on how to communicate effectively to decision-makers and the general public. A lot can be improved here (Bowman et al., 2010).

14.7 Discussion

Can the evolution of climate change policy be understood as an application of the precautionary principle?

Climate change science has evolved over time. The IPCC was established to provide comprehensive policy-relevant assessments of the scientific knowledge relevant for developing climate change policies. These developments clearly had an effect on climate policymaking. IPCC assessment reports played an important role in raising awareness of risks as well as explaining potential solutions and their estimated costs.

At the international level, however, this science-policy dialogue can only be regarded as a partial success. Current policies will not achieve the emission reductions that scientists consider necessary to achieve the ultimate objective of the UNFCCC, as confirmed in the Cancun agreements concluded at COP16. Hence, the sum of international political action over the last 20 years is inconsistent with a strict interpretation of the precautionary principle, which would require taking necessary action in the absence of full information.

A key question is the level of scientific certainty that the international policymaking community needs to act to address climate change. The five criteria presented below correspond to increasing evidence that humankind is significantly altering the climate on a global scale, starting with the most basic criterion and ending with the most demanding one. The more society and its leaders are willing to adopt a precautionary approach, the fewer criteria have to be fulfilled before actions are implemented.

- Criterion 1: Observation of a long-term increase of long-lived greenhouse gas concentrations in the atmosphere.
- Criterion 2: Observation of mean global warming derived from nearly global long-term nearsurface air temperature measurements.
- Criterion 3: Paleo-climatic evidence of global warming caused by an enhanced greenhouse effect of the atmosphere.
- Criterion 4: Detection of a significant anthropogenic contribution to observed mean global warming using validated climate models and statistical fingerprint methods.
- Criterion 5: Attribution of specific aspects of climate change to anthropogenic causes. Examples include attributing thermal expansion of ocean water, the most important contribution to sea level rise, to mean global warming at the surface and strong cooling of the upper stratosphere and the mesosphere due to increased CO_2 concentration.

Criterion 1 was satisfied as far back as the late-1960s, although only for CO_2. For concentration increases of the other two long-lived greenhouse gases, CH_4 and N_2O, the 1990 report of IPCC Working Group I (climate science) presented the evidence. The halocarbons as new, artificial long-lived greenhouse gases became known as contributors to the enhanced greenhouse effect in the ozone assessment reports by WMO and NASA (WMO, 1986).

Criterion 2 was satisfied by the first assessment report of IPCC (IPCC, 1990). Criterion 3 was arguably also fulfilled by the first IPCC report from 1990, which showed very high correlation between greenhouse gas concentrations and temperatures (during snow-formation) for a 160 000 year record of air bubble composition and oxygen isotope content in Antarctic ice cores.

Criterion 4 was fulfilled by the sentence 'the balance of evidence suggests a discernible human influence on global climate', published in December 1995 in the Working Group I's summary for policymakers in the IPCC's second assessment report.

Criterion 5 was fulfilled by the IPCC's third assessment report in 2001. This report showed that the observed cooling in the lowest stratosphere is predominantly caused by depletion of ozone as a consequence of chlorofluorocarbon decomposition in the stratosphere and less by the enhanced greenhouse effect, which is the key reason for cooling in the upper stratosphere (above 30 km height) and mesosphere (above 50 km height). In addition, the IPCC fourth assessment report of Working Group I, published in February 2007, cites several new links such as 'sea level rise is largely a consequence of the warming of sea water in the upper ocean layers' (IPCC, 2007a).

An important factor in the IPCC successfully fulfilling the criteria above was the development of guidelines for assessing and expressing uncertainty systematically. As a result, important statements on the knowledge about changes in the climate system could be given qualifications such as 'as likely as not' (33–66 % probability it is true), 'likely' (67–90 % probability), 'very likely' (90–99 % probability) or 'virtually certain' (99–100 % probability).

In summary, for all these criteria scientific proof is by now largely or completely available at a high confidence level. Hence we are far beyond the knowledge level where the precautionary principle would still be needed for any action in the global climate change context — at least, if the precautionary principle is interpreted as referring to major anthropogenic changes to the global climate system.

Obviously, the list above considers neither the impacts of changes in the climate system on humans and ecosystems nor the costs and impacts of climate change policies. Some would say that attempts to consider the costs and impacts of alternative policies (including doing nothing) go beyond the precautionary approach — instead being characteristics of a comprehensive risk management approach. However, most authorities accept that precautionary policy actions need to take account of the pros and cons of action and inaction (See Chapter 27 on the precautionary principle).

It seems that when the precautionary approach has been applied in environmental policymaking in the years since the Rio Declaration, it has mostly occurred at regional scales and addressed air and water pollution. The stakes were much lower than in the case of global climate change and those implementing policies were generally also the ones benefitting from them. Global climate change is very different in many ways:

1. Climate change and climate policies have strong impacts on all of us. There is no readily available solution that could easily reduce the problem to a safe level.

2. Climate change is a global problem and efforts to reduce GHG emissions are cost-effective only if they are part of an agreement with others to act in a comparable manner. Furthermore those countries and population groups most negatively affected by climate change are generally poor countries and population groups who have contributed little to its causation. Hence, the motivation for reducing greenhouse gas emissions can differ substantially depending on the underlying ethical perspective. In the particular case of climate change, it appears that increasing information on the expected distribution of impacts, i.e. on expected 'winners' and 'losers', has unfortunately decreased the momentum for international climate policy.

3. Climate change is a problem characterised by the very long atmospheric life times of many greenhouse gases (from a decade to millennia) and a long inertia in the climate system (mostly due to the large heat capacity of the ocean). As a result, emissions reductions of long-lived greenhouse gases now will only have significant climatic effects after several decades. Hence, the moral dilemma outlined in the previous bullet point is even larger: the costs and benefits of emission reductions are not only unequally distributed across countries but also over time. Primarily self-interested high emitters have little incentives for costly emission reductions because they will experience only a small fraction of their benefits, if their scope is only the present

> generation. However many emission reductions provide substantial non-climatic benefits in the short term, including reduced air pollution and reduced costs for importing fossil fuels. Contrastingly, self-interested motivation is particularly low for GHG reduction measures such as carbon capture and sequestration that do not provide large non-climatic benefits.

Apparently the precautionary principle did play a role when the UNFCCC was agreed after the IPCC first assessment report in 1990 (criteria 4 and 5 above were not yet fulfilled). If the UNFCCC had already contained binding emission reduction goals for industrialised countries, it would have provided evidence of full acceptance of the principle in the climate change context. The influence of the precautionary principle diminished however with subsequent actions. Now precautionary arguments appear to have only little, if any, effect on internationally coordinated climate policy action.

Is a risk management framework better for understanding the evolution of climate policy?

The history of climate change policy suggests that arguments based on a risk management framework had a much stronger impact on political action than arguments based mainly on a precautionary framework. In a risk management framework, it is necessary to know the risks of climate change impacts and the risks, costs and benefits of taking mitigation and adaptation action, including their distribution across regions and over time. Countries have only committed to significant action at the national level (in the context of the Kyoto Protocol and the subsequent pledges under the Copenhagen Accord) after having satisfied themselves that emissions reductions are technically feasible, and that they can be implemented at reasonable costs and in a politically acceptable way. In addition, cost-benefit analysis (such as the Stern review) is sometimes applied to evaluate how far mitigation measures should go in the light of the avoided climate change impacts.

So risk management approaches have been applied but other key factors are also important, including the perception of risk. Risks, costs and benefits of climate change depend on assumptions about future social, economic and technical developments and on the evaluation of uncertainties that cannot be presented in strict scientific terms. Perceptions of risks, costs and benefits of climate change and climate protection policies vary significantly across different people and stakeholders. In addition, risk perception depends on factors such as how the scientific community communicates its findings and interacts with stakeholders, how credible it is perceived to be, how the media handle the information, as well as human psychology and behaviour, cultural background, world views and political affiliations (Weber and Johnson, 2012; McCright and Dunlap, 2011).

The importance of risk perception became obvious in the uproar surrounding the attacks on climate science and the IPCC in 2009–2010. The public in several countries became less concerned about climate change and this affected the political prioritisation of action. The 'blogosphere' generates a huge amount of (dis)information, in which scientific arguments often are characterised as 'just another opinion'. This undermines the authority of bodies like the IPCC (Giddens, 2009), further altering risk perception. Misperceptions of risk partially, but not wholly, explain why climate change policy has so far been inadequate.

From threat to opportunity

Perhaps the biggest problem with establishing effective climate policy at the national and international levels has been the focus on avoiding climate change risks. Climate policy appears to require short-term sacrifices from particular economic actors and changes in the costs of services and human activities. Benefits accrue decades later in the form of avoided climate change impacts. Even if the benefits in monetary terms outweigh the costs measured over a long period of time, such propositions are not very attractive or understandable for many people. Those that could be worse off in the short term will lobby against a proposed policy. The focus on avoiding climate change risks does not appeal to immediate self-interest, at least not directly. A lot rests on solidarity with future generations.

What could be highlighted more both at the international and national levels is the fact that many interventions to stimulate development, wellbeing and economic growth, if well targeted, can contribute to a low emissions and climate resilient economy. Energy efficiency in industry, transport and buildings is good economic policy, leading to lower energy bills and lower greenhouse gas emissions. Renewable energy can provide much needed modern energy in rural areas, improve air quality and health, reduce dependency on imported energy, create new jobs and contribute to emissions reduction. Building new infrastructure, development of coastal areas, increasing food production — all good investments in development — can be done in such a way that they are more resilient against future floods and drought that result from climate change, and maximise the preservation of carbon stocks.

So if climate change is integrated into the agenda of development and economic growth, it aligns the benefits for the stakeholders interested in positive economic activities with the benefit of avoiding climate change damage. Climate change can be more mainstreamed into core economic decisionmaking, making it more likely that the necessary action will be taken. Rather than looking at positive economic and social effects as a co-benefit of reducing climate change risk, climate change risk reduction becomes a co-benefit of development and economic growth.

There is now a trend emerging to consider climate change as an integral element of socio-economic decisionmaking. New paradigms of 'low carbon growth' or 'low emissions development', 'climate compatible development' or in a broader sense 'green growth' are being adopted in many countries. The European Commission's statement in October 2011 is a good illustration:

> 'Just two weeks ago, the European Commission announced proposals on resource efficiency. Together with our proposals on a low carbon economy, they set out what is needed to transform Europe's economy to be sustainable by 2050. This package is our approach to green growth, and it builds on the efficient and sustainable management of our resources.' (EC, 2011b).

More and more countries see low-carbon growth, low emissions development or green growth as a promising way of integrating climate change action into core socio-economic decision-making. The green economy was one of the key issues for the Rio+20 meeting in 2012. UNDP, UNEP, the Organisation for Economic Co-operation and Development (OECD) and the World Bank, among others, have set up strong programmes to promote this development (OECD, 2011; UNDP, 2011; UNEP, 2011a; World Bank, 2009 and 2010a).

As a result, the main question for policy becomes 'how can we achieve the socio-economic goals of growth and development, while addressing climate change risks?' This question in turn demands answers to scientific questions: 'how can dependence on energy imports be reduced by developing domestic renewable energy resources?', 'how can air quality be improved to eliminate health hazards by shifting from fossil fuel-based energy production and transport systems to clean energy and electric cars?' and 'how can agriculture be made more productive and less vulnerable to climate change by sequestering more carbon in agricultural soils?' These questions require a more integrated analysis and assessment than earlier questions that regarded climate change mitigation as largely separate from other policy areas.

Such questions are also critical for determining the different technological pathways to the 2050 goal of a green economy that is not dependent on fossil fuels — pathways that must be determined, in part, by means of greater public engagement.

Table 14.1 Early warnings and actions

1896	Svante Arrhenius (Sweden) calculated that a doubling of CO_2 in the atmosphere from coal burning could lead to an increase in average global temperature of 3–5 °C. (In 2007 IPCC estimated that this would be 2.4–4.5 °C).
1938	Guy Stewart Callendar (United Kingdom) concluded that 'the principle result of increasing CO_2 … would be a gradual increase in the mean temperature of the colder regions'.
1958–1970	David Keeling (US) established two long term monitoring stations in 1958 in Mauna Loa on Hawaii and at the South pole to measure the background concentration of CO_2 without the influence of nearby anthropogenic (human) sources. By 1970 the Mauna Loa monitoring station showed clear rising trend in global CO_2 of 0.4 % per year.
1970s	Schneider, Twomey and Grassl identified critical interactions of clouds and air pollution that amplified or dampened the human induced greenhouse effect.
1980	The World Climate Research Programme organised and co-financed by the World Meteorological Organization and the International Council for Scientific Unions became the first global change research programme.
1980s	Models of atmospheric changes showed that both greenhouse effects and measures to avert them would take decades to be clearly seen because of inertia in the systems caused principally by the oceans.
1985	Neftel et al. (Switzerland) and Jouzel et al. (France) were the first to determine the CO_2 concentration in air bubbles of ice cores with enough precision to reconstruct the long-term history (160 000 years) of greenhouse gases.
1987/1988	Groisman and Hansen publish the first trend analyses of global mean air temperature covering a full century.

Table 14.1 Early warnings and actions (cont.)

1980 and 1985	At two scientific conferences at Villach (Austria) climate change scientists concluded that 'the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century'.
1987	The global Montreal Protocol on protecting the ozone layer sets targets for phasing out ozone-depleting substances, many of which are also powerful greenhouse gases
1988	The Intergovernmental Panel on Climate Change (IPCC) was formed focusing on climate change science, the vulnerability of society and nature to climate change and means of adaptation, and on mitigation measures for limiting or preventing greenhouse gases and their effects.
1988	SCOPE scientists warn that human induced climate change could cause increases in climate variability and of extreme weather events.
1988/1989	Scientific conferences in Toronto and Nordwijk call for a global action plan, a Framework Convention from 1988 levels and for a reduction of 20 % in global CO_2 by 2003.
1990	The IPCC published its first assessment report concluding that: 'there is a natural greenhouse effect of the atmosphere which already keeps the Earth warmer than it would otherwise be'; 'there is a strong increase of concentrations of all three long-lived naturally occurring greenhouse gases (CO_2, CH_4, N_2O), which is due to anthropogenic activities, global mean near-surface air temperature had risen by 0.3 to 0.6 °C during the 20th century, there was evidence of a rise in mean sea level, of retreats in mountain glaciers and changes in regional precipitation'.
1990/1992	The UN 2nd World Climate Conference called for a Framework Convention on Climate Change (UNFCCC) which was later signed by 153 countries and the European Communities in Rio in 1992.
1995	The IPCC published its second assessment report stating that 'The balance of evidence suggests a discernible human influence on global climate.' This was the first time that scientific evidence enabled the human-induced change signal to be perceived against the background of natural climate variability. It also stated climate change impacts were happening and could pose serious risks in the future; and that policy measures were available to reduce GHG emissions.
1995	At the first session of the Conference of the Parties to the UNFCCC (COP1) the Berlin Mandate was adopted, which recognised the need for a legally binding intergovernmental agreement to reduce greenhouse gas emissions by industrialised countries, to be ready in time for COP3 in 1997.
1996	The Council of Environment Ministers of the European Union decided that global average temperatures should not be allowed to rise more than 2 °C above the pre-industrial level.
1997	The Kyoto Protocol to the UNFCCC was adopted by more than 150 countries. Industrialised countries agreed to reduce their GHG emissions, using a basket of six GHGs, to about 5 % below their 1990 level by the 2008–2012 period.
2001	IPCC's third assessment report in 2001 concluded that 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.' Projections of climate change impacts in the future were much more serious than in the past. The potential for strong reductions in global GHG emissions was clearly demonstrated and the costs of these reductions were shown to be modest compared to the projected increase in wealth.
2001	The USA withdrew from the Kyoto Protocol.
2005	The Russian Federation ratified the Kyoto Protocol which then became binding having required ratification by 55 countries representing more than 55 % of the total emissions in 1990 from countries with reduction commitments.
2007	IPCC fourth assessment report concluded that 'the understanding of anthropogenic warming and cooling influences on climate has improved ... leading to very high confidence that the global net effect of human activities since 1750 has been one of warming'.
2007	The UK Stern Review of the Economics of Climate Change stated that the costs of aggressive mitigation action are substantially lower than the costs of climate impacts and adaptation measures.
2008	Australia signs the Kyoto Protocol.
2010/2011	Some minor errors, and deficiencies in the handling of scientific uncertainty, in the 3 000-page 2007 IPPC report were identified but these did not affect its main conclusions. Recommendations were made to make all climate change data freely available so that research findings can be further verified. IPCC improves its communications and its guidance on handling scientific uncertainties.
2011	COP17 in Durban in 2011 agreed to start negotiations for a new legally binding agreement for after 2020 and to complete negotiations by 2015; acknowledged that businesses require long-term agreements extending beyond 2020 to inform their investment decisions and recognised the need for more ambitious action by 2020 if the 2 °C limit is to be taken seriously.
2011	Canada withdraws from the Kyoto Protocol.

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15 Floods: lessons about early warning systems

Zbigniew W. Kundzewicz [1] [2]

Floods are an increasingly acute problem. Intense precipitation has become more frequent and more intense, growing manmade pressure has increased the magnitude of floods that result from any level of precipitation, and flawed decisions about the location of human infrastructure have increased the flood loss potential.

Unlike most other case studies presented in this report, this chapter focuses on flooding as a phenomenon and the requirements for effective early warning systems, rather than addressing a particular event and the lessons that can be learned.

Flooding cannot be wholly prevented. The occurrence of a flood need not be considered a 'failure' and, conversely, minimisation of losses may constitute a 'success'. There are lessons to be learned from every flood and it is important to use them in preparing for the next flood. Once we accept that no flood protection measures can guarantee complete safety, a general change of paradigm is needed to reduce human vulnerability to floods. The attitude of 'living with floods' and accommodating them in planning seems more sustainable than hopelessly striving to eradicate them.

Flood forecasting and warning systems fail because links in the chain perform poorly or fail completely. A single weak point in a system that otherwise contains excellent components may render the overall system performance unsatisfactory. A successful system requires sufficient integration of components and collaboration and coordination between multiple institutions.

The chapter deals primarily with the challenges of fluvial (river) floods. It is complemented by three short supplementary texts. The first highlights the complex, dynamic and diverse ecosystems of river floodplains, which are often degraded during construction of flood defences. Despite their huge economic value, near-natural floodplains are among the most threatened ecosystems globally.

The second discusses uncertainties in anticipating rainfall patterns and intensity, and their relationship to flood levels during extreme flows. Such uncertainties present challenges for scientists and decision-makers alike.

The third addresses the increasing risks of coastal flooding due to factors such as climate change and sea-level rise, and reviews European experience with precautionary action.

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'And the rain was upon the earth forty days and forty nights … And the waters prevailed exceedingly upon the earth; and all the high hills that were under the whole heaven were covered' (Genesis 7:12, 19).

'We have first raised the dust and then complain we cannot see' (George Berkeley).

15.1 River floods and early warnings

The term 'flooding' denotes a potentially destructive abundance of water in a normally dry location. Various categories of flood exist. They include, for example, situations where intense precipitation overwhelms urban sewer and drainage systems. In contrast, groundwater flooding occurs when the water table reaches the ground surface in a location where it does not normally do so. And coastal and estuary flooding occurs when high sea levels (due to high tides, storm surges or tsunamis) cause the coastal line to recede.

This chapter addresses river (fluvial) floods, although Panel 15.3 contains information on coastal flooding. River floods occur when water inundates areas outside the river channel, where there is potential to cause damage. They can be caused by several mechanisms, such as rain (intense or long-lasting), snowmelt (possibly with rain), glacier melt, glacial lake outbursts, dam breaks (breach) and tidal surges. Unexpected flow obstructions such as landslides, ice jams, beaver dams or debris can also cause flooding upstream.

Floods differ considerably from some of the other hazards addressed in this report. Floods are intermittent events. They usually recur rarely in a given location, although they can be commonplace at some sites, for example occurring every spring when snow cover melts. This contrasts with hazards that affect the environment continuously and can impose cumulative 'pressures'.

River floods are natural phenomena, manifesting the natural spatial and temporal variability of the river water level and discharge, which can take on extremely high values from time to time. River floods, jeopardising settlements located in floodplains, have been a continued hazard for humanity and can be identified in old myths and narratives. For millennia, people have settled in river valleys to till fertile soils, benefit from flat terrain, access water supplies easily and use water for transport. Riparian people have historically lived in harmony with nature, benefiting from benign floods and the valuable services they provide to fisheries, wetlands, wildlife and agriculture.

The notion of 'early warning of floods' can be interpreted in at least two ways that are relevant to this chapter. The first refers to a short-term flood preparedness system, where a 'flood warning' is a technical term, denoting a means of reducing flood damage to people and property. In this sense, a flood warning contains specific timely information, based on a reliable forecast, that a high water level is expected at a particular location and time. It aims to ensure that emergency actions, such as strengthening dikes or evacuation, can be undertaken.

A 'flood alert', usually issued before a 'flood warning', is less specific and has the broader aim of raising vigilance. A warning should be issued sufficiently early prior to the potential inundation to allow adequate preparation. The appropriate timeframe is affected by the catchment size relative to the vulnerable zones. The warning should also be expressed in a way that persuades people to take appropriate action to reduce damage and costs of the flood.

The other interpretation of 'early warning' in the context of floods is a statement that a high water level or discharge is likely to occur more frequently in the future. Technically, this constitutes a 'prediction' of a change in flood frequency compared to a reference period, such as the 30-year climate normals 1961–1990. An early warning of this type could, for example, predict that at a site of concern the current 100-year flood (river flow exceeded once in 100 years on average) may become a 50-year flood within some defined future time horizon. Such an early warning, over a longer time scale, is (or should be) an important signal for decision-makers that the required level of protection is unlikely to be maintained in the future unless flood preparedness is improved.

Floods continue to be a problem and we clearly do not cope with them satisfactorily. In fact, they are an increasingly serious problem. Flood risk has been greatly intensified by humans, who — to use the language of mechanics — have increased the load and decreased the resistance of the system. In many places, humans have increased the flood magnitude for any level of precipitation and have amplified the flood damage potential. Severe floods cause rising material damage worldwide and continue to cause a considerable death toll. Annual global economic losses from extreme weather events, including floods, increased ten-fold between the 1950s and

Panel 15.1 Managing river flood plains as ecosystems of global strategic importance

Klement Tockner

River floodplains (including deltas) extend from the edge of permanent water bodies to the edge of uplands. Because of their unique position at the deepest location in the landscape, floodplains integrate and accumulate upstream and catchment processes.

In their natural state, floodplains are disturbance-dominated ecosystems tightly linked to fluvial and geomorphic processes, thereby creating some of the most complex, dynamic and diverse ecosystems globally — landscapes that were once comparable in diversity with tropical rain forests or coral reefs (Junk et al., 1989; Naiman et al., 2005; Tockner et al., 2002 and 2008). This diversity has, and continues to be, deeply degraded, a fact that has so far captured remarkably little attention at the policy level. Paradoxically, a good deal of this damage is done by hydrological engineering for flood defences that reduces the ecological integrity of floodplains, while other actions (in the floodplains and elsewhere in the catchments) simultaneously remove natural flood-mitigation features.

Worldwide, floodplains cover only about 2 % of the land surface (although an accurate estimation of their extent remains difficult). Nevertheless, they are calculated to provide about 25 % of all continental ecosystem services, which is more than any other continental ecosystem type (Costanza et al., 1997; Oppermann et al., 2008; Tockner et al., 2008). Major services include flood regulation, drinking water supply (including recharging groundwater) and waste treatment. Daily nitrogen removal ranges from 0.5 to 2.6 kg N per ha (although wasting nutrients is undesirable, current systems would otherwise require considerable expenditure to remove them, e.g. from drinking water). Floodplains also provide opportunities for recreation and, in areas such as the Danube Delta Biosphere Reserve, fishing. In Europe and elsewhere, benefits also include natural fertilisation, providing grazing land and firewood.

The multiple services provided by floodplains have favoured the development of civilisations along the Nile, Euphrates, Indus, Amazon, Yangtze, and Mississippi Rivers; and many indigenous human societies are well adapted to the conditions of flooding. Floodplains continue to be preferred sites for human occupation. For example, about half of the human population in Europe and Japan lives on (former) floodplains (Nakamura et al., 2006, Tockner et al., 2009). Bangladesh, the most densely populated country worldwide, is almost entirely covered by a vast deltaic floodplain (accounting for about 80 % of the country's area).

As described in the present chapter, floods are among the most costly natural disasters worldwide (see also Tockner et al., 2008). To reduce these costs, Switzerland has declared the remarkable intention (probably unique in Europe) to restore the ecological integrity of its river floodplains and their natural flood mitigation properties. This commitment was made because flood-related costs in Switzerland have been increasing since 1970, resulting in an accumulated cost of more than CHF 15 billion over the past 35 years (BUWAL and BWG, 2003). At the same time, Switzerland had the highest global expenditure per capita on traditional hydraulic engineered flood control measures (CHF 45 billion between 1970 and 2005). This was unaffordable.

In response, the Swiss government fundamentally altered its river management strategy. Future flood control measures are now required by law to be linked to a concurrent improvement of the integrity of river floodplain ecosystems. It has been estimated that about 22 000 ha of cultivated land need to be converted back to dynamic floodplains; about 11 000 km of streams and rivers need to be restored. The current restoration rate ranges between 15 and 28 km per year; and 50 000 barriers must be removed (Armin Peter, personal communication; EAWAG, 2006). At present, more than 95 % of former floodplains have been converted to industrial, agricultural, and urban areas.

Despite their huge economic value for flood mitigation and other services and benefits, near-natural floodplains are among the most threatened ecosystems globally. In Europe, North America, and Japan, more than 90 % of former floodplains are functionally extinct or have been converted into cropland and urban areas. Conserving the remaining unimpaired floodplains as strategic global resources and restoring degraded floodplains are of the highest priority for future ecosystem management. There are major limitations, however, in implementing successful conservation and restoration strategies. Today, many river floodplains have been altered to such an extent that they must be considered as novel or emerging ecosystems where a mixture of native and non-native species, assemblages lacking a joint evolutionary

Panel 15.1 Managing river flood plains as ecosystems of global strategic importance (cont.)

history, dominate. For example, up to 80 % of the benthic invertebrates collected along the Upper Danube, the Rhine or the Elbe Rivers are already of non-native origin (Sommerwerk et al., 2010).

The rapid biotic turnover observed along regulated river corridors results from a combination of species decrease, species spread, and climate-induced species distribution shifts, although the relative contribution of these three components to the total turnover rate remains largely unknown. In central Europe, 28 000 km of navigation canals and navigable rivers connect 24 countries, creating a biological 'super-catchment' covering an area of 2.45 million km^2. This dense navigation network artificially facilitates the exchange of organisms across biogeographic barriers, thereby contributing to the increasing homogenisation of the European freshwater fauna and flora.

There is an urgent need to develop a comprehensive overview of river floodplains, their environmental state and anticipated pressures. Such an overview is a prerequisite for prioritising conservation and management. Further research should focus on:

- understanding the formation and dynamics of novel, emerging ecosystems and associated biotic communities;
- quantifying the ecological and evolutionary consequences of novel communities;
- quantifying the ecosystem services provided by novel ecosystems;
- measuring and predicting the resilience of ecosystems and species assemblages along human impact gradients;
- assessing the evolutionary potential of an ecosystem, i.e. its genetic diversity and genetic connectivity, as a complementary tool in biodiversity conservation planning;
- developing and testing new indicators of biodiversity change and impacts.

One of the best documented examples of a long-term and fundamental modification of a river floodplain is the Upper Rhine valley between Basel (Switzerland) and Worms (Germany). More than 150 years ago, Tulla's regulation of the Upper Rhine was a technical masterpiece and one of the largest construction projects worldwide during the nineteenth century. The river was shortened from 345 to 273 km, 2 200 islands were removed — an area of more than 100 000 ha between Basel and Strasbourg alone — and 240 km major dikes were constructed (Blackbourn, 2006). As a consequence, the Rhine floodplain has been converted from a fishery and waterfowl paradise to a productive agricultural area. Reconstruction of the native biodiversity is difficult because a first systematic inventory of the benthic invertebrate community was compiled at the beginning of the twentieth century, decades after the end of the 'rectification' of the Upper Rhine valley (Lauterborn, 1905). The rich biodiversity that still exists in the remnant floodplain channels and riparian forests along the Upper Rhine is most likely a legacy of past hydrogeomorphic processes. At the same time, however, the reduction in natural retention areas has led to an increase in flood peaks in the downstream sections of the Rhine valley.

A lack of adequate reference conditions restricts the development of guiding images for conservation and restoration, and limits implementation of the Water Framework Directive (EU, 2000), which strongly depends on defined reference standards for assessing alterations. Even the best protected floodplains in Europe such as the Alluvial Zone National Park (Danube, A), the Odra National Park (Odra, D) or the Danube Delta Biosphere Reserve, have been irreversibly modified. Traditional conservation and restoration strategies will simply not maintain their rich biodiversity and ecosystem processes and services in a sustainable way. Adaptive management strategies must manage these floodplains actively as coupled ecological-social-technological systems for the benefit of humans and nature. Active manipulation to deliver multiple ecosystem services is also needed to create the environmental conditions for rich (albeit largely non-native) floodplain communities (Dufour and Piegay, 2009).

At the European level, it is crucial to establish synergies among the partly contradictory requirements of the Water Framework Directive, the Habitats Directive (EU, 1992) and the Floods Directive (EU, 2007). Furthermore, we urgently need a European competence network that focuses on large rivers, including their role as long-distance migration and dispersal corridors linking various biomes; as key storage and transformation areas for carbon and nutrients; as centres for evolutionary processes; and as coupled social-ecological ecosystems.

1990s in constant prices (IPCC, 2001b). Data compiled by Munich Re (Kron, 2005) indicate that the number of great flood disasters (requiring international or interregional assistance) has grown significantly in recent decades, as have the economic impacts and the insured damage.

Several recent river flood events have caused material losses exceeding USD 10 billion. The death toll has been considerable, with individual events in less developed countries causing more than 1 000 fatalities (Kundzewicz et al., 2010a). The highest material losses, in the order of USD 30 billion, were recorded in China in the 1998 floods. Destructive floods are commonplace in many developing countries, in particular in the Asian continent (especially Bangladesh, China and India) and South America, yet numerous deluges have hit virtually all parts of the world, including Europe. As reported by Barredo (2007), a rising number of flood disasters have been observed in Europe in recent years and high-impact floods are occurring more frequently. The material flood damage recorded in Europe in 2002 (above EUR 20 billion) was higher than in any previous year.

Recognising that flood damage has increased worldwide, it is interesting to understand the reasons for this growth. Several factors may be responsible, including changes in socio-economic, terrestrial and climate systems:

- **Socio-economic changes** include increasing exposure and potential damage due to population growth and economic development in flood-prone areas; land-use change (such as urbanisation and deforestation) and changing perceptions of risk.

- **Changes in terrestrial systems** include changes in hydrological systems and ecosystems, driven by land-cover change, the regulation of river flow through such measures as channel straightening and shortening, and the construction of embankments. Conditions that determine the transformation of precipitation into runoff in the river basin also change. Draining wetlands and eliminating natural vegetation, alongside expanding impermeable areas, lead to reduced water storage capacity and consequently a higher flood peak and a shorter time to peak.

- Finally, **climate changes** are important, even if they may not always be detectable in the historical record. They include increased water-holding capacity and water content of the atmosphere in a warmer climate, increases in the frequency of heavy precipitation, changes in snow cover, and changes in seasonality and in atmospheric circulation patterns.

Human encroachment into floodplains has increased exposure to floods. Encroachment may increase as people become wealthier and technology or economic imperatives help populate more flood-prone areas. Many flawed decisions have increased the flood loss potential. The assets at risk from flooding can be enormous. For instance more than 10 million people live in areas at risk of extreme floods along the Rhine and the potential damage from floods there has been estimated at EUR 165 billion (EU, 2007). In some less developed countries, the portion of the population living in flood-prone areas is very much higher. The hope of overcoming poverty drives poor people to migrate to informal settlements in endangered, flood-prone zones around mega-cities in developing countries, which have previously been left uninhabited on purpose because effective flood protection cannot be assured.

Future changes in flood risks may be complex. In many places, flood risk is likely to grow due to a combination of anthropogenic and climatic factors. Quantifying flood statistics is difficult, however, and subject to high uncertainty. As stated in IPCC (2001a), 'the analysis of extreme events in both observations and coupled models is underdeveloped'. Recent modelling studies show that plausible climate change scenarios project future increases of both amplitude and frequency of rain-caused flooding events. Yet no conclusive and ubiquitous climate change trend in the flood behaviour has been found, based on the global data on high river flows observed so far (Kundzewicz et al., 2005; Svensson et al., 2005).

Detecting climate change at global or regional scales (let alone within catchments) is inherently difficult because of the low signal-to-noise ratio. The relatively weak climate change signal (if any) is superimposed on a strong natural variability of rainfall and river discharge, which is further confounded by land-use change. Hence, Wilby et al. (2008) speculate that statistically robust trends are unlikely to be apparent for several decades.

Although land use management and land cover change have an important effect on flood risk, it is less significant in the case of very high-intensity rainfall, which causes high flood runoff in both urban and forested basins.

There is always potential for floods that are higher than those recorded in the past, even under stationary conditions — i.e. without climate change. This is simply a sampling effect and its significance depends on the length of the historic record; as records get longer, the probability of record high precipitation occurring in an area with high damage potential increases. Flood defences are typically designed to withstand an event with a return period of 100 years, perhaps with some additional safety margin. However, the discharge for this return period is generally estimated from records gathered over an inadequately short interval and is therefore uncertain.

The highest point precipitation amounts ever recorded for different time intervals are 1 340 mm in 12 hours, 1 825 mm in one day and 3 847 mm in eight days (WMO, 1986). If precipitation of a similar scale occurred over (or directly upstream from) a large city, the result could be expected to be utter destruction.

It is important not to forget that, in addition to negative effects, floods can generate benefits. For example, the fertile Nile floods were crucial to the development of ancient Egypt. In some areas, floods are an important means of recharging groundwater aquifers. Floods may strengthen community solidarity and can enhance economic activity (related to flood preparedness and recovery). Any benefits that could be lost also need to be taken into account when considering flood prevention measures and options.

15.2 Flood forecasting and warning

Flood alerts, forecasts, warnings and responses are very important components of modern flood preparedness systems. They fall into the category of non-structural flood protection measures, which can save lives and reduce material losses and human suffering. An effective system should embrace detection of the risk of a flood-triggering situation, quantitative flood forecasting (with adequate lead time), development of a reliable warning message, issuing and disseminating the warning to communities at risk, adequate actions by communities to reduce losses and, finally, post-hoc audits to learn lessons and improve the system for the future.

Flood warning has existed for thousands of years. The Old Testament mentions the oldest 'early warning', received by Noah from God; archaeologists have revealed other, even earlier, accounts of a similar story. For centuries, floods were believed to be a divine punishment for the sins of mankind. In 1523, a forecast anticipating a flood in February 1524 was published in Augsburg, based on a quasi-scientific speculation: a peculiar conjunction of planets in the constellation Pisces. The forecast turned out to be false (Brázdil et al., 2005).

15.2.1 Flood forecasts

A flood forecast should ideally deliver reliable and accurate information on the future development of an event, enabling an alert and warning to be issued. A forecast expresses when a flood is expected to occur (ranging from minutes to days or even weeks ahead), its location and its intensity. Flood magnitude is determined by the stage, discharge, inundated area and duration of flooding. A forecast also conveys how a flood will travel downstream and evolve and what secondary effects it may cause.

In order to detect the risk of a flood-triggering situation occurring, a meteorological and hydrological monitoring system should be in place. Forecasting, based on mathematical modelling, allows experts to convert the information on rainfall, hydrological status of soil moisture and snow cover into a forecast of river discharge, water level and inundated area for a future time horizon.

For small or urban catchments and for flash floods in steep and rapid mountain streams, the time lag between an intense precipitation and the resulting river flood peak is very short (minutes to hours). In these circumstances, observations of rising river water levels may come too late for a useful flood forecast. Weather radar data (which brings its own issues) or quantitative precipitation forecasts are therefore required to estimate future river flows with sufficient lead time to provide a useful warning.

At the other extreme, the formation of a flood wave in a large river may take several weeks, allowing ample time for response to a flood forecast. A hydrodynamic flood-routing model can be used, allowing visualisation (via GIS) of the forthcoming inundation in downstream cross-sections of the river. Many activities are under way to improve forecast accuracy and to extend the forecast lead time. In this context, two important factors are data assimilation and adaptive forecasting, which makes use of current measurements to reduce forecast errors (Young, 2002).

15.2.2 Flood warnings

Flood warnings should contain more information than flood forecasts. This includes recommendations or orders for affected populations to take actions, such as evacuation or emergency flood-proofing, specifically designed to safeguard life and property (Smith and Ward, 1998). According to Nigg (1995), warning systems must fulfil two basic functions:

- assessment (from the moment that a specific hazard is detected to the point when a risk message is developed for the threatened locality);
- dissemination (issuing and transmitting the warning message to a target audience).

A warning, converting scientific forecasts into lay language, is a communication that a hazard will produce specific risks for a specific population (Nigg, 1995). Affected communities should not just be told about the hazard but also informed in such a way that they are persuaded to take specific remedial action in time. Such warnings should be 'populist' in tone and communication but their design is actually a skilled task requiring careful forethought and design.

There is an important difference between flood alerts and flood warnings. The latter have much shorter lead times that must be accurate to maintain public confidence. In Vaison-la-Romaine in 1992, Meteo-France issued two (accurate) flood alerts based on heavy rainfall predictions 12 and 24 hours ahead but because the local authorities did not know which catchment would be affected no warning was issued and many people died. The European Flood Alert System (EFAS) at the European Commission's Joint Research Centre (JRC) now produces flood alerts for the whole of Europe (JRC, 2011).

It is often noted that forecasts have advanced markedly, while progress in warnings has lagged behind despite recent advances in some countries, such as automatic telephone and text-messaging services and the provision of detailed forecasting services on the internet.

Nigg (1995) argues that to formulate warning messages:

- the basis of the warning must be credible;
- the warning message must explain the degree to which a specific area is at risk;
- people must be told what they can do to reduce their exposure to danger.

Speed of reaction to warnings is essential because there may be a short time to implement emergency pre-flood actions, such as strengthening or deploying

Photo: © istockphoto/Mitja Mladkovic defences and evacuation, before the risk becomes high. Other useful criteria or indicators of warning quality are the penetration of the warning (the proportion of those who need information that receive it) and degree of satisfaction.

15.2.3 Flood warning errors

Two types of warning errors occur:

- first, when a warning is issued but the risk does not materialise;
- second, when no warning is issued but a risk and the ensuing disaster occur.

The first does not include situations where the risk has materialised but the disaster has not. For instance, flood warning in the Netherlands in January 1995 resulted in massive evacuation. A disaster did not arrive, as the levees withstood the high water load but the warning and the evacuation were justified and perceived by the population as the right decision. The risk of dike failure was high. Similarly, during the summer 1997 flood on the Odra (see Box 15.1), the Polish town Słubice was evacuated due to high risk of inundation. As a result of major dike-strengthening action, however, and dike breaches upstream in Germany, which reduced the load, Słubice was not inundated.

As noted by Nigg (1995), officials often hesitate to issue warnings due to fear of error, especially when warning systems are just developing or when there is still a great deal of uncertainty about the occurrence of the future event.

15.2.4 Credibility and efficiency of flood warnings

The more personal the manner in which a message is delivered, the greater its credibility. In principle, person-specific warnings may trigger more urgent responses than communication directed at the general public. There can be challenges, however, in establishing more focused communication mechanisms. In the United Kingdom people in flood risk zones can sign up to receive warnings by telephone, text message or email but the take-up has not been high. This is partly because many people do not want to recognise that they are in a flood risk zone because of a fear of reduced house prices or the inability to acquire insurance.

Factors influencing the efficiency of message dissemination include the credibility of the source (which may vary according to the recipient of the message); the accessibility of the chosen communication channel; the usefulness or redundancy of the information; and the communication of a system's resistance to floods. Essentially, the information should be conveyed in wording that the public can understand and empathise with and via channels that the public finds credible.

15.2.5 Long-term early warnings

In addition to short-term (real-time) warnings related to a specific, forthcoming flood event, recent work has also emphasised the need to issue another type of early warning if the projections (predictions) of flood hazards in the more distant future indicate considerable changes in the anticipated risk (Hall et al., 2003, 2005; Hirabayashi et al., 2008; Dankers and Feyen, 2008; Kundzewicz et al., 2010a, 2010b). Early warnings of increasing flood risk in the decades ahead are necessary to upgrade defence strategies, for example by undertaking the time-consuming and resource-intensive task of strengthening levees.

Climatic and non-climatic factors affect future flood risk and adaptation needs. For example, land-cover changes and urbanisation can increase flood risk regardless of any change in climate. Observations and climate projections show widespread increases in the contribution of very wet days to total annual precipitation in the warming atmosphere (Trenberth et al., 2007). Increasing flood magnitudes are projected in areas where floods result from heavy rainfall; decreasing flood magnitudes are anticipated where they result from spring snowmelt. Winter (rain-caused) flood hazard is likely to rise for many catchments under several climate scenarios. However, global warming may not necessarily reduce snowmelt flooding everywhere. Since an increase in winter precipitation is expected, snow cover may actually increase in cold areas where the temperature remains below 0 °C.

Floods corresponding to a 100-year return in the control period may become more or less frequent in the future climate. Where they increase, upgraded flood prevention measures will be needed to ensure the required protection level. Projections by Hirabayashi et al. (2008) and by Dankers and Feyen (2008) indicate that in much of Poland, France, the United Kingdom, southern Sweden and northern Italy, today's 100-year floods will occur more frequently in 2071–2100. They are projected to occur less frequently over most of Finland and the European part of the Russian Federation. These two studies show that, in aggregate terms, the control 100-year flood is projected to become more frequent over more than 40 % of Europe, and that over 30 % of Europe the mean recurrence interval of such floods is projected to decrease from 100 years to below 50 years by 2071–2100 (Kundzewicz et al., 2010b).

Systems continue to be designed and operated assuming stationarity (the past is the key to the future). Since this assumption is clearly incorrect due to both non-climatic and climatic changes (Milly et al., 2008), existing design procedures need to be revised, accounting for land-cover change, climate change and other changes of relevance. Otherwise, systems will be under- or over-designed and either not serve their purpose adequately or be overly costly (with excessive safety margins).

Difficulties in isolating the greenhouse signal in river flow observation records, coupled with the large uncertainty in projections of future precipitation and related variables, mean that no precise quantitative information can be delivered for long-term flood preparedness planning. Nevertheless, water managers in some countries, including Germany, the Netherlands and the United Kingdom, have begun to take account of these early climate change warnings explicitly in flood protection design codes.

In Bavaria, for example, flood design values now take into account projections of a 40–50 % increase in small and medium flood discharges by 2050, and an increase of around 15 % in 100-year floods. In the United Kingdom, the precautionary allowance of the Department for Environment, Food and Rural Affairs (Defra, 2006) includes projections of increased peak river flow volumes (10 % up to 2025 and 20 % after 2085), to reflect the possible effects of climate change, based on early impact assessments. A 'climate change factor' is to be reflected in any new plans for flood control measures in the Netherlands. Measures are planned to manage the Rhine's increased discharge in the Netherlands resulting from climate change. By 2015, the measures implemented should increase the design discharge from 15 000 to 16 000 m^3/s and this should increase further to 18 000 m^3/s in the longer term (Kundzewicz et al., 2007).

15.3 Flood preparedness systems — the science and its use

Complete flood safety is impossible in low-lying areas adjacent to rivers. Flood risk can be considerably restricted, however, if an adequate preparedness system is built, consisting of a site-specific mix of measures. Flood-related research, financed by regional, national and international funding institutions, administrative authorities, water agencies, and the insurance and reinsurance industry, is indispensable to optimise preparedness systems.

In Europe, important research initiatives have been undertaken at the international and national levels. A prominent example of integrated international action is the interdisciplinary FLOODsite project (Klijn, 2009) within the Sixth Framework Programme of the European Union. FLOODsite developed integrated flood risk analysis and management methods, covering the physical, environmental and socio-economic aspects of floods from rivers, estuaries and the sea. It integrated different scientific disciplines, spatial planning and management and considered flood risk as a combination of hazard sources, pathways and consequences for people, property and the environment.

The EU Floods Directive (EU, 2007; Box 15.2) explicitly refers to FLOODsite as the largest ever EU flood research project. The FLOODsite project dealt with detection and forecasting of hydro-meteorological conditions and timely warning of the relevant authorities and the public. The research aimed to enhance the performance and shorten the lead time of flash-flood forecasting by linking rainfall-runoff models to real-time remotely sensed (radar and satellite) data. A system for detecting and estimating extreme storm rainfall was developed and tested and the uncertainty of the radar rainfall estimates was assessed.

15.3.1 Protect, adapt, retreat

An example of national flood-related research initiatives is the UK's Foresight Project (Evans et al., 2004; Hall et al., 2005), dealing with flood and coastal defence. The project's aim was to forecast changes in flood risks in the United Kingdom over the next 100 years and to identify the best options for responding to future challenges. The key finding was that if existing policies are continued the flood risks in 2080 could increase substantially. Projected changes range from little increases above current expected annual damage in an optimistic scenario to a 20-fold increase under another scenario. The projections suggest that it will be necessary to choose between investing more in sustainable approaches to flood management or learning to live with increased flooding. An integrated portfolio of responses can reduce future risk by an order of magnitude, although the relative effectiveness of response measures depends very much on the scenario considered.

The current strategy for flood preparedness in Europe can be summarised as 'protect as far as technically possible and affordable' and otherwise 'adapt and accommodate'. This has also been expressed as 'living with floods' (Germany, Netherlands) and 'making space for water' (Netherlands, the United Kingdom). If a necessary level of protection cannot be achieved and accommodation (living with floods) is not possible, then another option is retreat.

Decisions have to be made about how to design protection systems and how to control the damage potential, for example by enforcing zoning, banning floodplain development and moving out of the harm's way. Flood protection measures may either modify flood waters or modify the system susceptibility. They depend on the rate of recurrence of floods: natural measures (such as enhancing wetlands and floodplains) are appropriate for frequent floods; engineering measures are suitable for rare floods; residual risk management is essential for very rare floods (Kron, 2005). This latter category contains extreme but possible floods, and those beyond the limits of past experience.

15.3.2 *Structural and non-structural flood protection measures*

A range of flood protection and management measures exist, falling into structural ('hard') or non-structural ('soft') approaches. The former refer to large-scale defences, such as dikes, dams and flood control reservoirs, diversions and floodways, and improving drainage channel capacity. Structural defences have a very long tradition, with dams and dikes having been built for millennia. Constructing reservoirs where excess water can be stored allows a regulated temporal distribution of streamflow, reducing the natural peak flow.

The physical dimensions of structural flood protection measures, such as levees, are based on probability theory to withstand a predicted 'design flood' of a certain magnitude, e.g. a 100-year flood (although this is difficult to determine in practice), in a given location. The longer the assumed return period of the design flood, the better the level of protection and the greater the costs. This raises various value judgements, such as whether to design dikes to withstand a 100-year flood or perhaps a 1 000-year flood. The latter solution would give better protection but be far more costly. Moreover, it is misleading to expect complete flood protection or total certainty of outcomes.

Dikes protect well against small- and medium-size floods but when a deluge is of disastrous size and dikes break, losses in a levee-protected landscape can be higher than in the absence of a levee due to the false feeling of security that levees can generate among the riparian population and the high damage potential in apparently (but not completely) safe areas. No matter how high a design flood is, there is always a possibility of a greater flood occurring, inducing losses. A dike designed for a 100-year flood is likely to fail if a 1 000-year flood occurs.

In the United Kingdom, the 2005 Carlisle flood occurred when the plans for the new Carlisle flood defences were out for public consultation. The planned defences would have met the UK standard of the 100-year return period and if built they would have been breached because the 2005 event had a return period in excess of 150 years. After the event, the defences were therefore redesigned to address a 200-year return period.

Several developed countries have costly structural protection facilities to withstand a high, rare flood. Reinforced dikes or super-dikes of 300–500 meters width play an important part in flood protection of major cities in Japan, where a very high level of safety must be assured (Kundzewicz and Takeuchi, 1999). Even higher protection levels are achieved in the low-lying Netherlands. The Flood Defence Act of 1996 set high safety standards with the return period of design flood set at 1 250 years for middle to upper rivers in the Netherlands and 2 000 years for lower river reaches (Pilarczyk, 2007).

'Soft' non-structural flood protection measures include source control (watershed management), laws and regulations, zoning, economic instruments, efficient flood forecast warning systems, flood risk assessment systems, awareness-raising information and flood-related databases. Source control modifies the formation of floodwater by catching water where it falls, enhancing infiltration, reducing impermeable areas and increasing storage in the watershed. These measures counteract the adverse effects of urbanisation, such as reduced storage potential, growth in the runoff coefficient and flood peak, and acceleration of a flood wave. Restoring, retaining or enhancing water storage capacity in the river system (floodplains, polders and washlands) is also important.

Appropriate schemes of insurance, which distribute risks and losses over many people and over a longer time, coupled with aid that can compensate

Panel 15.2 Uncertainty in predicting floods (and other environmental variables)

Keith Beven

In its report on the causes of the Mississippi floods in 1993, the US Interagency Floodplain Management Review Committee's major conclusion was that the rainfalls were 'without precedent' (Galloway, 1995). Similarly, in the United Kingdom the Pitt Report described the summer 2007 rainfalls and floods as 'exceptional' and noted widespread demand for better warnings to provide the public more time to prepare and protect their property (Pitt, 2007).

The demand for better warnings appears to pose a relatively simple problem for hydrological science. With some knowledge of the pattern of heavy rainfalls, it should be possible to predict river flows and, during extremes, the likely extent of flooding. Of course, there are also organisational and social problems in conveying flood warnings to the public but here we will concentrate on the scientific problem. It is an example of the type of predictions about environmental variables that are increasingly demanded and extend all the way up to predictions about the future climate based on global atmosphere and ocean circulation models.

In fact, many of these apparently simple science problems turn out to be complex and fraught with uncertainties that are difficult to evaluate. In the case of floods, measurement technique limitations mean that there is uncertainty about the pattern and intensity of rainfall and the relationship between discharge and flood levels during extreme flows. There is uncertainty about how much rainfall will reach a river and when — in part because there is a highly non-linear relationship between the wetness of a catchment before an event and runoff generation processes. Many major floods (examples from the United Kingdom include the summer 2007 floods, the Lynmouth flood in 1952, the Boscastle flood in 2004, the Carlisle flood in 2005 and the Cumbria floods in 2009) were preceded by prior wetting, which increased subsequent runoff. Hydrological models can simulate and predict runoff generation but they can only approximate, thereby introducing further uncertainty.

There are also important modelling uncertainties in predicting the frequency with which a flood of a given magnitude will occur, how that might change in the future as a result of climate variability or change, and the impacts of land management changes on runoff generation. It is therefore unsurprising that uncertainty estimation has been an important research topic in hydrological modelling in the last two decades. This has included analysis of how the nature and magnitude of predictive uncertainties should be communicated to decision-makers and stakeholders (e.g. Faulkner et al., 2007; Beven, 2009).

This research has determined that there is still significant debate about how the effects of relevant uncertainties should be estimated, with the literature revealing a range of strongly held opinions and some interesting debates. The failure to reach more general consensus over this period may appear surprising but there are some fundamental issues involved, which apply much more generally in environmental modelling (see Beven, 2002, 2006a and 2006b).

Disagreement centres on the types of uncertainties involved. Aleatory uncertainties, arising from natural variability, can be distinguished from epistemic uncertainties, which result from the limitations of our knowledge about the system under study. Inherent unpredictability of nature and unrecognised uncertainties ('unknown unknowns') may also influence the errors in model predictions but cannot be treated explicitly because, by definition, they are not accessible for analysis (Sivakumar, 2008).

It is commonly assumed that most sources of uncertainty can be treated as aleatory, which is advantageous because such uncertainties can be treated in terms of probabilities and the full panoply of statistical theory can be used in analysis and prediction. Beven (2006b) argues, however, that this only applies in 'ideal cases'. Most of the uncertainties involved in hydrological and other environmental models have an epistemic as well as an aleatory component. Treating the sources of uncertainty as if they were aleatory in non-ideal cases will produce over-confidence in the model predictions because of the time-variable nature of epistemic uncertainties.

There is no general theory of how to handle epistemic uncertainties and some debate has focused on whether it is always appropriate to estimate uncertainties based on probabilities. Other frameworks, such as the possibilities of fuzzy set theory, allow more flexibility but introduce more subjectivity into the

Panel 15.2 Uncertainty in predicting floods (and other environmental variables) (cont.)

associated assumptions. Probability theory has the attraction of being logically consistent and objective — but if and only if the assumptions about the nature of the errors can be shown to be consistently valid and this is rarely the case. Even in models it can be shown that small departures from the ideal can lead to overconfidence in predictions (e.g. Beven et al., 2008).

In real applications, most sources of uncertainty have both aleatory and epistemic components, but it will often be the epistemic component that dominates. In predicting floods, rain gauges, radar and numerical weather prediction can be used to measure or forecast rainfall over a catchment area and provide inputs to hydrological models of runoff generation. All will be subject to epistemic errors. Numerical weather prediction is useful for identifying potential flood events but does not (yet) give generally reliable rainfall forecasts. Such forecasts are essential for flood warning, especially for flash floods in small basins with short response times, since there is no other way to provide warnings to the public with sufficient lead time. They will, however, be uncertain and not just in aleatory ways.

In larger basins, measurements of rainfall will be sufficient as an input to warning models. However, a rain gauge network may not always provide a good estimate of that input, particularly for localised convective cells or orographic effects, because the spatial pattern of the gauges may not properly represent the spatial pattern of the rainfall. Radar gives relatively good spatial coverage but does not measure rainfall directly and there may be epistemic uncertainties in the corrections and reflectivity-rainfall intensity relationship used, which will vary from event to event.

Similar arguments apply to other types of uncertainties in flood forecasting and frequency estimation.

There is no question that it is better to estimate some form of uncertainty for these predictions than to ignore the uncertainties. But this creates certain challenges. For the scientist, the problem is how best to deal with epistemic uncertainties. For the decision-maker, who depends on model predictions, the problem is how to understand and interpret the uncertainty estimates associated with a prediction — and under what circumstances not to rely on model predictions when making a decision.

Flood forecasting poses additional difficulties. One is the issue of conveying the meaning of flood warnings when the uncertainties in the forecasting process might result in one or a succession of false alarms. Furthermore, as Kundzewicz notes in the present chapter, there is also a need to explain to the public (and even to some decision-makers) that there is a finite possibility that even a new flood defence scheme may be breached by the next flood event (or, as in Carlisle in January 2005, before the new design has been built).

Estimating uncertainty associated with these types of predictions can have important consequences if it alters the resulting decision. Understanding such estimates is easier for users with a clear theoretical foundation in probability (Hall et al., 2007; Todini and Mantovan, 2007; Montanari, 2007) but, as already noted, estimates can be misleading if they lead to overconfidence in the outcomes.

Essentially, science lacks a theory of the true information content of data that is subject to epistemic uncertainties (Beven, 2008). That will take time to develop but in the meantime there are some practical ways of proceeding. One is to involve potential users of model predictions earlier in the prediction process so that decisions can be taken about how to evaluate model performance and handle different sources of uncertainty. The Environment Agency of England and Wales is starting to implement this approach within the framework of 'guidelines for good practice' for incorporating risk and uncertainty into different areas of flood risk management.

This type of stakeholder involvement in the prediction process has been advocated for some time (e.g. Stirling, 1999; EEA, 2001). The guidelines concept provides a framework for agreeing on reasonable assumptions about both aleatory and epistemic uncertainties. It should provide a good basis for assessing the value of different types of model prediction in the decision-making process.

for uninsurable losses, are additional important components of flood preparedness. Flood-risk maps developed for the insurance industry are used to help estimate insurance premiums for properties in the United Kingdom. Post-flood disaster aid, based on voluntary solidarity contributions, national assistance and international help, is essential to restore the livelihoods of survivors.

Despite some encouraging examples, such as in the US after the 1993 flood, the permanent evacuation of floodplains is virtually unthinkable in most countries. This is definitely true for Bangladesh, a densely populated and low-lying country, which ranks as the most flood-prone country on earth. The people of Bangladesh, growing rapidly in number, have to live with regular floods. Most of the country is made up of floodplains and soil fertility depends on regular flood inundation. In 1998, more than two thirds of the country were inundated. New flood embankments, even if affordable, would occupy scarce and highly demanded land. Thus, the options include reinforcing the existing structural defences and enhancing and optimising non-structural measures, including the forecast-warning system. As this example makes clear, optimum strategies for flood protection must be site-specific.

15.3.3 Uncertainty in flood risk assessment

Notwithstanding major research efforts, there is much uncertainty in the hydrological studies that underpin flood risk assessment and management (e.g. in determining a 100-year flood). Various studies (e.g. Beven, 2006a; Hall et al., 2007; Sivakumar, 2008) have judged the uncertainty analysis in hydrological studies to be highly unsatisfactory. Although disagreeing in significant respects, all called for the promotion of uncertainty analysis of measurements and modelled results in hydrological studies; uncertainty analysis should not be an add-on element — an afterthought of little importance. This is easier said than done, however, as there is considerable uncertainty regarding uncertainty estimation.

A good start would be greater rigour and consistency in analysing and reporting uncertainties. One weakness arises from the deficiencies of hydrological models and available observation records for model validation. There is an overwhelming scarcity of homogeneous long-term observation records. The inherent uncertainty in analysing any set of flood flows also stems from the fact that directly measuring the range of extreme flows can be challenging because, for example, rating curves are not available for the high flow range, gauges are destroyed by flood waves or observers are evacuated. Recourse to indirect determination is therefore necessary (Kundzewicz et al., 2010b).

Uncertainty in future projections of river flooding is very high (see Kundzewicz et al., 2010b), and grows the further we look into the future. In the near-term (e.g. the 2020s), climate model uncertainties play the dominant role, while over longer time horizons uncertainties due to greenhouse gas emission scenarios become increasingly significant. Uncertainty in practical flood-related projections is also due to a spatial and temporal scale mismatch between coarse-resolution climate models and the finer scale of a drainage basin. Scale mismatch renders downscaling (disaggregation) necessary. In fact, much more refined data are necessary for the 'point' scale of a locality (e.g. a small riparian town), which is the level at which costly adaptation is undertaken.

15.4 Lessons from floods

Flooding cannot be totally prevented. The occurrence of a flood need not be considered a 'failure' and, conversely, minimisation of losses may constitute a 'success'. The first lesson is that there are always lessons to be learned, from every flood. An example of lessons learned from a single, destructive, flood on the Odra in 1997 is presented in Box 15.1.

Learning a lesson means building awareness and understanding of the reasons for a system's failure or inadequate performance, and identifying weak points using an holistic perspective. Flood forecasting and warning systems fail because links in the chain perform poorly or not at all. The observation system may fail, the forecast may be grossly in error, the warning message may be wrong, the communication of a warning may be deficient and the response may be inadequate. A single weak point in a system, which otherwise contains many excellent components, may render the overall system performance unsatisfactory.

The components in flood forecasting and warning systems must be adequately integrated but responsibility for them may reside with different agencies. This necessitates adequate collaboration and coordination between multiple institutions, which can be challenging. In emergency situations, it may become evident that distribution of roles of

Box 15.1 Lessons learned from the 1997 Odra flood

The dramatic Odra flood in July 1997 occurred after a long flood-free period and revealed the weaknesses of the existing flood preparedness system in Poland, in particular the deficiencies of relevant legislation (Kundzewicz et al., 1999).

The flood occurred during a period of legal transition, as the previous regime's laws were essentially abandoned and many new acts were passed during a short time. The distribution of responsibilities was ambiguous and conflictual, with complicated links between different participants in flood defence activities. The law at the time provided that low-level authorities were not entitled to announce a flood alert or the alarm status. Such decisions had to be issued by the provincial anti-flood committees and were delayed as a result. Local authorities typically resorted to common-sense decisions, without waiting for instructions from above.

The information flow was similarly deficient. Hydrometeorological stations reported to the regional branches of the hydrometeorological service, although also making information available, on request, to local authorities. Some forecasts proved to be of low accuracy.

Responsibilities and cost coverage for the army, police and fire brigades were also not clearly defined. Polish civil defence was geared to act in the event of a war, rather than to deal with a peacetime emergency. In addition, telecommunication support proved vulnerable as some 189 000 telecommunication links were disconnected. Mobile phones provided more reliable communication, but network limitations were also revealed.

Advance warning on the Odra was available for the medium and lower course when the flood occurred in headwaters in Czech Republic and Poland. In principle, the State of Brandenburg in Germany had ten days before the arrival of the floodwater. Even so, detailed forecasts were difficult to obtain due to problems such as the interruption of observations in several gauges and flooding of the flood information office in Wrocław.

Consequently, the need for numerous improvements was recognised, such as building the network of weather radars; automating observations and data transmission; technical upgrading of flood warning centres, including telecommunication facilities (enabling phone, radio and fax to work without mains electricity supply); upgrading and modernising the warning system; enhanced regional, interregional and international flows of flood-related information; and building more suitable forecast models.

Considerable investments were made to improve many of these systems. The nation and the relevant services learned a lesson. When a second flood wave occurred in July 1997 the preparedness and flood management were far better than during the first crest when the nation had largely been taken by surprise.

agencies is unclear and possibly redundant. The institutional framework is a key socio-economic determinant of a nation's vulnerability against natural disasters (Raschky, 2008).

People's experience of flooding may reduce damage in the next flood. Where large floods occur in the same location twice in a short time period (e.g. on the Rhine in Cologne in December 1993 and January 1995), losses during the second flood are typically far lower than those during the first (Munich Re, 1997; Kundzewicz and Takeuchi, 1999). The first flood will provide lessons for diverse groups: riparian homeowners; farmers with fields on the floodplain; professionals in the affected water district; legislators; spatial planning (zoning) officers; and public administrators at the country, province, town and community levels.

Although flood events and human failures provide valuable lessons, memories can fade quickly after a flood. Typically, a destructive flood generates enthusiasm for strengthening flood preparedness systems and heavy expenditure follows. Following a deluge, the relevant authorities elaborate ambitious plans and launch works but lessons are soon forgotten. After some time without flooding, willingness to pay for flood preparedness decreases sharply and projects are downscaled or suspended. When the next deluge comes, it acts as a reminder and starts a new cycle. This vicious turn of events, known as the 'hydro-illogical cycle' (a concept introduced in the drought context by Donald Wilhite in the mid-1980s) is a general principle, valid across different political and economic systems. The return period of a destructive flood is usually much greater than the political horizon of decision-makers and the electorate, which is determined by terms of office and electoral cycles. Of course, the hydro-illogical cycle is also at odds with the precautionary principle.

In some countries, codifying preparedness in legislation helps overcome the hydro-illogical cycle. A prominent example is the European Union's Floods Directive (Box 15.2).

Interestingly, an important turning point in the development of flood protection strategy can be traced back to the mid-19th century in the US (Williams, 1994) when Congress looked into the problem of the Mississippi floods. The two options considered were:

- using large areas of the Mississippi floodplains as flood storage and overflow areas;
- attempting to control floods by embanking the River Mississippi in a single channel isolated from its floodplain.

Congress selected the latter option and the decision has remained influential on flood protection policy in the US and elsewhere, leading to the transformation of rivers and reduction of wetlands worldwide. In 1936, the US Federal Government assumed primary responsibility for flood damage reduction across the nation and, over the next half a century, embarked on a multibillion dollar programme of structural defences (Galloway, 1999).

Another paradigm shift resulted from the great 1993 US mid-west flood, which proved that structural 'hard' defences cannot guarantee absolute protection. As a result, the US Interagency Floodplain Management Review Committee recommended that the administration should fund acquisition of land and structures at risk from willing sellers in the floodplains, and many vulnerable families have been relocated from risky areas (Galloway, 1999). However, this response is not universal. In most countries, people who suffer in a

Box 15.2 EU Floods Directive

Between 1998 and 2004, Europe suffered over 100 major destructive floods, including the record-breaking August 2002 flood on the Danube, the Elbe and their tributaries. In response to these floods and projections of growing flood risks in Europe, in April 2007 the European Union adopted Directive 2007/60/EC on the assessment and management of flood risks (EU, 2007), commonly known as the Floods Directive. The directive embraces river floods, flash floods, urban floods, sewer floods and coastal floods; its objective is to reduce and manage the risks of floods to human health, the environment, infrastructure and property. It provides that EU Member States shall undertake, for each river basin or other management unit:

- a preliminary flood risk assessment, including a map of the river basin; a description of past floods; a description of flooding processes and their sensitivity to change; a description of development plans; an assessment of the likelihood of future floods based on hydrological data, types of floods and the projected impact of climate change and of land use trends; and a forecast of the estimated consequences of future floods;
- flood hazard maps and flood risk maps (damage maps), for high risk areas, i.e. those that could be flooded with a high probability (a 10-year return period), with a medium probability (a 100-year return period) and with a low probability (extreme events);
- preparation and implementation of flood risk management plans, aimed at achieving the required levels of protection.

Noting the diversity across the EU, the Floods Directive affords Member States flexibility to determine the level of protection required, the measures needed to achieve that level of protection (taking into account the work already done at national and local levels) and the timetables for implementing flood risk management plans.

The directive is probably the most advanced flood protection and preparedness legislation worldwide and implementation should considerably reduce flood risk throughout the 27 EU Member States. Mandatory activities, including assessing, mapping and managing flood risk in the river districts are expected to result in an unprecedented multinational upgrading of preparedness systems. The directive foresees that 'the potential future damage to be expected if no action is taken distinctly outweighs the costs' of implementation.

flood rebuild their houses (possibly more robustly) and their livelihoods in the place devastated by the flood, rather than moving elsewhere. The hazard may not have decreased, however, and floods could recur in that location.

People also take lessons from the failures of past policies. For example, some flood protection infrastructure has been criticised from a sustainable development perspective because it limits options for future generations and introduces disturbances in ecosystems. According to the Environment Agency of England and Wales (1998), sustainable flood defence schemes should protect the present generation from destructive floods but also 'avoid as far as possible committing future generations to inappropriate options for defence'. Renaturalising rivers and flood plains and reconstructing wetlands have been discussed for many years and is now actually likely to come about. Similarly, some large reservoirs, whose construction required the inundation of large areas or the displacement of many people, certainly did not match the principles of sustainable development (Kundzewicz, 1999). Studies on decommissioning reservoirs are now under way and in some cases decommissioning has already taken place, for example in France (Kernansquillec, Maisons-Rouges and St Etienne du Vigan).

Looking back at past developments often reveals that major decisions, such as regarding the construction of a large dam, are based on one-sided arguments with important aspects neglected. This bias can result from a lack of knowledge and understanding at the time that the decision was taken, as well as the evolution of value judgements over time.

15.5 Conclusions: living with floods

Floods are natural events that cannot be avoided. We should protect ourselves against floods up to an agreed safety level, this being a compromise between the desired level of safety and the accepted willingness to pay for protection. Once we accept that no flood protection measures can guarantee complete safety, a general change of paradigm is needed to reduce human vulnerability to floods. The attitude of 'living with floods' and accommodating them in planning seems more sustainable than hopelessly striving to eradicate them (Kundzewicz and Takeuchi, 1999). There must be action plans for events exceeding the design flood (i.e. when defences are bound to fail) and in this context early warning can save lives.

Misconceptions and myths about floods and flood protection are deeply rooted in society — among the general public, politicians and decision-makers. Some people naively believe that floods occur at large and regular time intervals — that terms such as 'return period' and 'recurrence interval' can be taken literally (rather than understood as averages) — and that embankments offer perfect safety.

Each tick of the clock marks the passage of time since the last flood and the countdown to the next. It is therefore important to prepare using a variety of different means, notably:

- rigorous implementation of zoning — using regulations to develop flood hazard areas and leaving floodplains with low-value infrastructure;
- strengthening existing defences;
- building or enhancing flood mitigation monitoring systems;
- forecasting;
- issuing and disseminating warnings;
- evacuation;
- relief and post-flood recovery;
- flood insurance;
- capacity-building (improving flood awareness, understanding and preparedness);
- enhancing a participatory approach, including consultation on the preparedness strategy and the level of flood protection, and household-level flood-proofing and mitigation measurements for both newly built and existing properties.

Only informed stakeholders can make rational decisions and agree on an acceptable flood protection strategy, being aware of both costs and benefits. There may be conflicting interests between those living in floodplains and demanding efficient and very costly protection, and the rest of the nation.

Efficient actions aimed at awareness-raising can reduce flood losses. Many past fatalities could have been avoided with greater awareness. In some developed countries such as the US, most flood fatalities involve vehicles whose drivers underestimate the danger.

Panel 15.3 Dealing with the risk of coastal flooding — experiences from European countries

Pier Vellinga and Jeroen Aerts

Coastal storm surges and floods are the most frequent and costly extreme weather events occurring in Europe, representing 69 % of the overall natural catastrophic losses (CEA, 2007). In 2010, for example, France was the European country hit hardest by the winter storm Xynthia, with 51 casualties and damages of more than EUR 1.5 billion. Many of the country's sea walls, including those around the Isle de Re off the country's west coast, were damaged or washed away (AIR, 2010).

Other low-lying coastal regions in Europe have endured similar experiences. In 1953 the winter storm that hit coastal stretches around the North Sea, especially in the United Kingdom and the Netherlands, killed more than 2 000 people. Areas around Hamburg and Bremen and parts of the Baltic coast are frequently hit by coastal storm surges. And although the shores of the Mediterranean and the Black Sea are generally steep, the river deltas of the Rhone, the Po, the Danube and many other smaller deltas experience floods from time to time. The 'Aqua Alta' in Venice Lagoon is a well known phenomenon.

The risk from coastal flooding is expected to increase in the future. First, climate change and sea-level rise is expected to increase the frequency and severity of flood events. Sea levels on average have already risen by about 10 cm per century over the last two to three centuries and are expected to rise at even higher rates in coming centuries (IPCC, 2007). This trend is exacerbated by land subsidence, which is determined by soil quality and the degree of water extraction in some low-lying coastal areas in Europe. The economic impact of natural catastrophes is also increasing due to the growing number of people living in areas with high risk levels, and increased economic activity in these regions (Bouwer et al., 2007).

History suggests that the human population is usually taken by surprise by coastal floods due to their 'low probability and high impact' character. Vulnerability to such events increases very gradually through slow sea-level rise and socio-economic developments. There is never an acute reason for strengthening the coastal protection system or for elevating settlements until the area and its population are hit by a major flood with significant loss of lives and economic damage.

The records of major coastal flooding episodes in the Netherlands, for example, illustrate that people have been taken by surprise about once every hundred years for the last 1 000 years. Apparently after some 50 years the flood disaster tends to disappear from the collective memory and flood protection measures are insufficiently maintained as a consequence. While the sea level keeps on rising and settlements keep expanding, a new high water event starts a new cycle of disaster and renovation of coastal protection works. The Netherlands and the United Kingdom only began investing in large-scale storm surge barriers after the devastating storm in 1953. The challenge for low-lying countries now is to anticipate climate change and accelerated sea-level rise.

The concept of measures to reduce the risk of flooding varies over time and by region. It ranges from local small-scale embankments to large-scale reclamation works and tidal barriers to lower the probability of coastal flooding. For example, London, large parts of the Netherlands, St. Petersburg in Russia and more recently Venice either have developed or are developing large-scale tidal storm surge barriers. These large engineering projects are expensive but protect population and capital investments up to a certain standard, usually in the order of withstanding the most extreme conditions statistically expected to occur once in a thousand or so years.

On the other hand, the closure of environmentally rich coastal areas such as estuaries through dams and barriers can harm biodiversity and water quality. Hence, flood protection through 'building with nature' has recently gained interest. Examples are periodic beach nourishment and coastal marshland development as ways to protect land and create buffer zones to lower wave impact (Day et al., 2007). Furthermore, coastal zone management strategies in, for example, the United Kingdom and France also aim to reduce the impact of coastal flooding by developing stringent building codes (flood proofing buildings) and zoning regulations (limiting urban expansion).

In France, a system of community-based prevention plans for natural risks addresses floodreducing measures. The possibility of gaining more favourable flood insurance terms provides an incentive for implementing such plans (Letermy, 2009). Innovative examples are found in the cities of Hamburg and

Panel 15.3 Dealing with the risk of coastal flooding — experiences from European countries (cont.)

Rotterdam. These cities have chosen to develop new residential areas on old port facilities located outside the main flood defences and hence prone to flooding but are elevating the buildings to safe levels. In Hamburg even public roads and bridges will be elevated to the height of 7.5 m above sea level to ensure unrestricted access for the fire and emergency services in the event of an extreme storm tide (Aerts et al., 2009).

Future projections of sea-level rise and human exposure to flood risk are inherently uncertain, necessitating new flood management methods and strategies. The 'climate proofing' concept has been developed to deal with sea-level rise and greater uncertainty about extreme weather events (Kabat et al., 2005). For example, levees and storm surge barriers are currently designed according to deterministic principles, using relatively short historic records and extrapolation methods to determine maximum surge heights. Extreme events are rare, however, and data on these events are sparse. Hence, new probabilistic methods are needed that provide engineers with a range of possible scenarios and may support a more robust protection designs.

Other 'climate proofing' measures include broadening levees to form 'superlevees', which can be used as ground for urban development (Vellinga et al., 2009). Such unbreachable dikes were developed in Japan near Tokyo, to protect against the potentially very high seas caused by tsunamis. They are now being considered by many water boards in the Netherlands as a way to deal with higher flood levels. For sandy beaches, the existing practice of beach nourishment (with sand) has become more sophisticated, such that the sand can be placed on the foreshore, creating a buffer against continuously rising seas. Finally, spatial planners, developers and insurers are actively engaged in reconsidering current regulations in order to ensure more flood- and climate-proof development of vulnerable coastal areas (Burby, 2001).

Despite their shortcomings, hard structural flood protection measures, such as dams and levees, will be needed to safeguard existing developments, in particular in urban areas. An effective flood protection system is generally a mix of structural and non-structural measures, with the latter approaches normally conforming better to the spirit of sustainable development.

Mitigating flood risks requires a change from reaction to anticipation. An immediate challenge is to improve flood forecasting at a range of time horizons of concern, from short-term weather forecasting and quantitative precipitation forecasts (useful for flash floods) to longer-term forecasting, useful for large basins. In this we should be encouraged that, thanks to improvements in the advance time and accuracy of forecasts, it has already been possible to reduce the number of flood fatalities in many countries.

Smith and Ward (1998) identify the development of infrastructure on floodplains as the major factor increasing flood risk (in terms of both hazard and vulnerability). Floods constitute a danger to life and property only when humans encroach into flood-prone areas and become vulnerable. This has already happened in many locations in Europe. If endangered locations have already been developed, a remedy is that humans, and infrastructure, move out of harm's way. In many countries the strategy of retreat is unpalatable, however, favoured by neither the broader population nor decision-makers. In some countries, such as Bangladesh, it is simply not an option.

Modern flood risk management comprises pre-flood prevention, risk mitigation measures and preparedness, followed by pre-planned flood management actions during and after an event. The risk-based approach to flood management is based on analysing the probability and consequences of flooding across the full range of severity, and implementing mechanisms to manage all possible events. Modern flood management also looks to the future and flood risk managers should continuously acquire and update evidence about long-term changes in flood risk.

Table 15.1 Early warnings and actions

C. 2000 BC	Levees and dams in China and the Middle-East provide flood protection
1854	Regular flood forecasting in France, following the advance of the telegraph. Italy developed such systems in 1866 and the US did so in 1871
1861	Adoption of a flood protection policy based on levee construction in the US, following a report by the US Army Corps of Engineers (Smith and Ward, 1998). This led to the transformation of seasonal wetlands to productive agricultural land
1931	Destructive summer floods in China cause a huge number of fatalities (although sources vary significantly on the numbers — ranging from 145 000 to 3 700 000)
1944	The Pick-Sloan Flood Control Act, enacted in the second session of the 78th US Congress, authorised a programme of structural defences, dams and levees across the US. It led to the establishment of the Pick-Sloan Missouri Basin Program
1970s	Early use of radar and satellite in flood forecasting
1994	After the 1993 mid-west flood in the US, the Interagency Floodplain Management Review Committee suggested relocating people off the floodplains and reclaiming wetlands (IFMRC, 1994)
1997	Large floods in central Europe affecting the basins of the Odra/Oder (Czech Republic, Poland, Germany) and the Vistula cause 110 fatalities and material damage in the range of billions of dollars — a substantial portion of the GDP of the countries in economic transition
1998	Floods in China cause material damage of USD 30 billion and over 3 600 fatalities
1998	Major flooding occurs in Bangladesh, inundating nearly 70 % of the country
2002	Dramatic floods in Europe (Austria, Bulgaria, Czech Republic, Germany, Hungary, Moldova, Romania, Slovakia, Ukraine) in August 2002 cause total damage in excess of EUR 20 billion
2007	Adoption of the EU Floods Directive

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16 Seed-dressing systemic insecticides and honeybees

Laura Maxim and Jeroen van der Sluijs

In 1994 French beekeepers began to report alarming signs. During summer, many honeybees did not return to the hives. Honeybees gathered close together in small groups on the ground or hovered, disoriented, in front of the hive and displayed abnormal foraging behaviour. These signs were accompanied by winter losses.

Evidence pointed to Bayer's seed-dressing systemic insecticide Gaucho®, which contains the active substance imidacloprid. This chapter presents the historical evolution of evidence on the risks of Gaucho® to honeybees in sunflower and maize seed-dressing in France, and analyses the actions in response to the accumulating evidence regarding these risks.

The social processes that ultimately lead to application of the precautionary principle for the ban of Gaucho® in sunflower and maize seed-dressing are described, with a focus on the ways in which scientific findings were used by stakeholders and decision-makers to influence policy during the controversy.

Public scientists were in a difficult position in this case. The results of their work were central to a social debate with high economic and political stakes. In certain cases their work was not judged according to its scientific merit but based on whether or not it supported the positions of some stakeholders. This situation tested the ability and courage of researchers to withstand pressure and continue working on imidacloprid.

Other European countries also suspended neonicotinoid seed-dressing insecticides. Evidence of the toxicity of neonicotinoids present in the dust emitted during sowing of coated seeds supported such decisions. Most important, the French case highlighted the major weaknesses of regulatory risk assessment and marketing authorisation of pesticides, and particularly neonicotinoids. These insights were recently confirmed by work by the European Food Safety Authority.

From this case study eight lessons are drawn about governance of controversies related to chemical risks. The study is followed by two additional texts. A first panel presents Bayer Crop Science's comments on the analysis in this chapter. A second contains the authors' response to the Bayer comments.

16.1 Introduction

Insecticides come in various forms. Many coat the surface of plants but systemic insecticides work differently, entering a treated plant's sap via the leaves or roots and coming into contact with insects when they feed on the plant. Seed-dressings and soil treatments operate in precisely this way. The active ingredient enters the roots and disperses to the aerial parts of the plant during growth, offering long-lasting protection from aerial and soil pests.

Some systemic insecticides are neonicotinoids, which have been widely used in seed-dressing and soil treatment since the early 1990s but can also be applied by spraying crops. Over the past decade they have become the most widely used class of insecticides worldwide, with total sales of EUR 1.5 billion in 2008 (24 % of the global insecticide market). By 2010, the first neonicotinoid, imidacloprid, was registered in more than 120 countries for foliar and seed treatment (Jeschke and Nauen, 2008; Jeschke et al., 2010).

In some situations, authorised doses of systemic insecticides can affect beneficial insects like honeybees, bumblebees, biological control agents (Smith and Krischik, 1999; Kunkel et al., 2001; Desneux et al., 2007; Rogers et al., 2007; Katsarou et al., 2009; Mommaerts et al., 2009), birds (Berny et al., 1999) and earthworms (Luo et al., 1999; Kreutzweiser et al., 2008; Capowiez et al., 2009). More than 25 000 species of bees exist and are crucial for the survival and evolution of about 80 % of the flowering plant species that depend on animal pollination (FAO, 2011).

The widespread use of systemic insecticides raises serious concerns about their threat to wild pollinators (EPA, 2003; Greatti et al., 2006; Bortolotti et al., 2002; Desneux et al., 2007). Declines in wild pollinators are reported worldwide (Allen-Wardell et al., 1998; Steffan-Dewenter et al., 2005; Biesmeijer et al., 2006), which is particularly worrying since they are essential for 35 % of global crop output (by weight) (Klein et al., 2006). This has lead to growing concern about agriculture's dependence on pollinators and fears of a global pollination crisis (Ghazoul, 2005a and 2005b; Klein, 2008; Aizen and Harder, 2009).

Many factors influence the state of honeybees and pollinators more generally. Land use practices and agrochemicals are regarded as particularly important (Kuldna et al., 2009). This chapter focuses on the risk to honeybees resulting from the seed-dressing systemic insecticide Gaucho®, whose active substance is imidacloprid. Specifically, it examines the vehement controversy in France over the use of Gaucho® and the justifications that ultimately lead to banning its use on sunflower and maize seed-dressing in that country. Another

Box 16.1 Honeybees, wild bees and other pollinators

In Europe, pollination (i.e. the transport of pollen from producing anthers to receiving stigma) is mainly achieved by three means:

- *passive self-pollination* (direct contact between anthers and stigma or transfer through gravity), which is rarely the dominant pollination route;
- *transport by the wind*, which is the dominant pollination route for about 10 % of flowering plants;
- *pollination by animals, particularly insects*, which is the dominant pollination route for the other flowering plant species — 87 of the leading global food crops depend on animal pollination, compared to 28 crops that do not (Klein, 2007).

Worldwide, honeybees have a major role in pollinating:

- *vegetable crops*, such as watermelon, cantaloupe, melon, cucumber, gherkin, pumpkin, squash, gourd, marrow and zucchini;
- *fruit crops,* such as apple, peach, nectarine, kiwi fruit, mango, avocado, plum, pear, sweet cherry, sour cherry, apricot, mirabelle, raspberry, blackberry, cloudberry, dewberry, rowanberry, cranberry, greengage, sloe, carambola, starfruit, durian, loquat, Japanese plum, Japanese medlar, rose hips and dogroses;
- *nut crops*, such as almond, cashew nut, cashew apple and macadamia;
- *edible oil and proteinaceous crops*, such as canola and turnip rape;
- *spices and condiments*, such as coriander, cardamom and fennel (Klein et al., 2007).

Box 16.2 The life of a honeybee

An adult summer worker honeybee lives about four or five weeks. Three days after being laid, the egg becomes a **larva**, which in turn becomes a **nymph** after about six more days. During the following 12 days, the nymph transforms into an adult honeybee.

During its **adult life**, the honeybee fulfils several roles. At first it stays in the hive as a **nurse**, cleaning the hive and nourishing the larvae. After 10–14 days it stores the collected nectar and pollen, ventilates the hive, covers the cells, secretes beeswax and builds new cells. At the end of the period spent inside the hive, it can be a **guard**. After about three weeks inside the hive and until death, the honeybee is a **forager**, and works outside the hive, collecting pollen, nectar, water and propolis. The division of tasks and the age for going from one task to another can vary, depending on the needs of the colony.

Honeybees feed exclusively on pollen, nectar and honey. It is estimated that most of the foraging activity is undertaken within 6 km of the hive, although honeybees can forage up to 12 km from the hive (von Frisch, 1967; Seeley, 1985; Winston, 1987).

Pollen foragers collect pollen on flowers and carry it to the hive on their posterior legs. Nectar foragers transport nectar in their crop and bring it to the colony. It can be consumed immediately or transformed into honey by water evaporation and changes in sugar composition. Pollen and honey are stored in the hive and can be consumed later.

Nectar and pollen are consumed differently by honeybees of different ages:

- Larvae essentially consume jelly, which is secreted from the glands in nurses' heads and also some pollen, depending on their age.
- Nurses consume pollen, essentially to develop their hypopharyngeal and mandibular glands and to produce jelly.
- Adult honeybees consume different quantities of nectar/honey, depending on the tasks they perform. Large amounts of nectar/honey are consumed for wax production, heat production in the hive (brood-attending bees and winter bees) and for foraging (Rortais et al., 2005; Benjamin and McCallum, 2008).

seed-dressing insecticide, Régent TS® (which contains the active substance fipronil) is also addressed, although not extensively as telling its story would require a chapter of its own.

In this chapter we describe and analyse the social processes that lead to the application of the precautionary principle in France. Scientific data played an important role in these processes. We describe the ways in which stakeholders have used scientific findings to influence policy during the controversy. The scientific data considered in this chapter are thus not exhaustive but selected to reflect the French debate.

The French ban on Gaucho® is significant because insecticides containing imidacloprid are among the most used globally (Jeschke et al., 2010) and have a wide range of uses. At its launch, Gaucho® was marketed as a means of reducing aerial pollution because it was supposedly confined to the soil and very small amounts are applied to seeds. For sunflower the application was 0.7 mg/seed, which amounts to 56–70 g of imidacloprid per hectare (Belzunces and Tasei, 1997). For maize the application was 0.98 mg/seed.

Despite these claimed advantages, France banned the insecticide's use in sunflower and maize seed-dressing due to concerns about its risks to honeybees. In this chapter, we present the historical evolution of the evidence regarding the risks of Gaucho® to honeybees in sunflower and maize seed-dressing and analyse the actions taken in response to the accumulating evidence regarding these risks.

Knowledge can vary in its relevance for supporting an action such as banning imidacloprid. Different stakeholders may perceive the relevance differently, with three factors playing a key role:

1. The scientific quality of the knowledge (**substantive quality**), which includes technical aspects (is the measurement accurate?), methodological aspects (is a particular method appropriate for the intended use?) and epistemological aspects (is enough knowledge available?).

Box 16.3 Uses of imidacloprid in France

In July 2010, imidacloprid was authorised in France to treat fruit trees such as apricot, peach, pear, quince, apple and plum trees. It is also present in products for disinfecting storage facilities, shelters for domestic animals, storage and transport material, treatment facilities for waste and transport material. Other uses include insecticidal treatment of rose bushes.

In France, imidacloprid is currently banned for seed-dressing of sunflower and maize but it is still used in seed-dressing for sugar beet, wheat and barley (Ministère de l'Agriculture, 2011). Residues subsisting in the soil might potentially be taken up by the crops cultivated after the seed-treated crop, or by wild plants (Bonmatin et al., 2005).

2. The quality of the research processes that have generated the knowledge and the expert processes that are used to assess its relevance to support an action (**procedural quality**) ([1]). This relates to researchers' and experts' competence, field experience, institutional affiliation, well-being at work, financial dependencies and other kinds of relationships among themselves and with other stakeholders (for instance, whether or not local knowledge is incorporated in the research).

3. The **social quality**, associated to the value judgments influencing the communication and use of scientific information by experts themselves and by stakeholders, in political debates.

In Sections 16.2, 16.3 and 16.4, we present the development of knowledge in these three areas. The first part of this chapter (Section 16.4.3 included) describes in detail the French controversy until the ban of Gaucho® on maize in 2004. Sections 16.4.4 and 16.4.5 are less exhaustive and result essentially from reactions to the different comments made during the reviewing process.

Many scientific and grey references have been produced in the world since 2004 and we could not include them all, in order not to loose focus but also for reasons of space limits. We have included post-2004 references if: 1) they were produced in France and 2) they were produced in European countries where regulatory decisions have been taken to ban imidacloprid.

The analysis yields lessons about the quality and use of knowledge in risk assessment and management ([2]), which are presented in Section 16.5. Conclusions and prospects are presented in Section 16.6.

16.2 Development of scientific understanding of the issue

16.2.1 Technical and epistemological quality of the evidence

1994: early warnings

In France, dressing seeds with Gaucho® was authorised in 1991 for sugar beet, in 1992 for maize and in 1993 for sunflower. Gaucho® was first used in sunflower farming in 1994. After that year, beekeepers started to report alarming clinical signs. After several days of foraging during the sunflower flowering, many honeybees did not return to their hives. Bee behaviour also caused concern: honeybees gathered close together in small groups on the ground or hovered disoriented in front of the hive; foraging behaviour was abnormal; and queens produced increased amounts of brood to compensate for the loss of foragers. In certain cases, dead honeybees were also reported in front of the hives.

In affected apiaries, most hives were impacted. Those apiaries suffered a 40–70 % loss in sunflower honey yield in the years after 1994, relative to the average yield obtained in previous years. Before 1994, the annual yield variation had been ± 10 %. At the end of winter, losses were up to 30–50 % of the hives, compared with the usual 5–10 % (personal communications from 20 beekeepers; Coordination des Apiculteurs, 2001; Alétru, 2003).

([1]) For example, the expert process by which the 'acceptability' of a calculated risk is assessed in official commissions or working groups. Such an assessment determines an action, that is, the use or not of a substance in crop protection.
([2]) For more details on the case, see Maxim and Van der Sluijs, 2007.

In the following years the beekeepers reported the same clinical signs and their specific impacts on honeybees foraging in sunflowers and maize areas (e.g. Belzunces and Tasei, 1997; CNEVA Sophia-Antipolis, 1997; Pham-Delègue et Cluzeau, 1998; Coordination des Apiculteurs, 2001; Alétru, 2003). The intensity of the clinical signs in France fluctuated, both temporally (from year to year) and spatially. They seemed to depend on factors such as the proportion of the different food resources present in the honeybees' environment (CST, 2003).

Appreciable declines in sunflower honey harvest were reported, implying major economic losses. Searching for possible causes, the beekeepers found that Gaucho® had been first used as a seed-dressing in sunflower farming in 1994. They reported honeybee problems increasing concomitantly with the area of Gaucho®-dressed sunflower (Chauvency, 1997; Belzunces and Tasei, 1997; CNEVA Sophia-Antipolis, 1997; Pham-Delègue and Cluzeau, 1998). Consequently, beekeepers asked Bayer (which manufactures Gaucho®) for information about the potential toxicity of the active substance imidacloprid for honeybees (Coordination des Apiculteurs, 2000).

This request was the start of a long series of scientific studies ([3]) involving Bayer-funded scientists, the Ministry of Agriculture, the French Food Safety Agency (AFSSA), beekeepers, and researchers working in public institutes ([4]) (henceforth 'public scientists').

Evolution of knowledge over time

When Gaucho® was launched commercially, the manufacturer considered that it posed no risk to honeybees, provided it was applied as seed-dressing (Bayer, 1992).

Bayer's reaction to the beekeepers demand was to conduct field and semi-field (under-tunnel ([5])) research. According to Bayer these studies showed that Gaucho® posed no risk to honeybees (Belzunces and Tasei, 1997).

However, the clinical signs continued. Bayer's experiments were presented at the Fourth International Conference on Pests in Agriculture, held in Montpellier on 6–8 January 1997, and also during a meeting organised by the Association de Coordination Technique Agricole (ACTA) in October 1997. They were criticised (ACTA, 1997; Belzunces and Tasei, 1997), so public scientists were also asked to research the issue.

Honeybee exposure to imidacloprid: 1993–1999

One of the main issues in assessing exposure to Gaucho® was the precision of measuring very low concentrations of imidacloprid in pollen and nectar. In 1993, the detection limit established by Bayer-funded scientists for measuring the presence of imidacloprid in plants was 10 ppb ([6]) (Placke and Weber, 1993). However, it was later found that much lower detection limits (DL) were needed to identify imidacloprid's presence in pollen and nectar.

The studies undertaken by Bayer during this period either could not detect imidacloprid in pollen and nectar, or detected it but could not quantify it (CST, 2003). In 1999, a study quantified the substance in sunflowers treated with Gaucho® to be 3.3 ppb in pollen and 1.9 ppb in nectar (Stork, 1999).

When public research started (1997–1998), the General Directorate for Food of the Ministry of Agriculture (DGAL) demanded analyses using 'the lowest detection limit possible', but 'without going below 0.01 mg/kg' (10 ppb) ([7]). For the 1998 programme DGAL noted that 'it is not useful to try to work with the lowest detection limits' ([8]). This DL corresponded to the characteristics of the Bayer method (Pflanzenschutz Nachrichten Bayer, 46.1993.2 inverse chromatography in liquid phase and UV detection). Bayer representatives also participated in the committee charged with developing the research protocol.

At the time that the DGAL demanded the analysis, CETIOM (the Technical Center for Oilseed Crops ([9])) had already estimated that detection limits much

([3]) In the following, we have selected the data that played an important role in the debate, rather than uselessly trying to inventory all the data available. The complete list of the results available before 2003 is available in CST (2003).

([4]) In France, scientists working in national research institutes (e.g. INRA, CNRS) and universities are public servants. Their entire salaries and a part of their functioning (sometimes equipment) expenses are funded by the public institution.

([5]) A tunnel is a tent of several meters, which allows air to pass through and isolates the honeybee colony being used for testing from the exterior. The purpose of a tunnel is to ensure that honeybees only feed on the source chosen for the experiment (e.g. plants contaminated with imidacloprid), while simulating field conditions.

([6]) The unit 'ppb' (parts per billion) is used for very low mass concentrations, more precisely 10^{-9} (e.g. 1 ppb = 1 µg/kg).

([7]) In the original French: 'sans toutefois descendre à une valeur inférieure à 0.01 mg/kg'.

([8]) In the original French: 'il n'est pas utile de chercher à travailler avec la limite de détermination la plus basse possible'.

([9]) Centre Technique Interprofessionnel des Oléagineux Métropolitains.

lower than 10 ppb — about 1.4 ppb — were necessary to find imidacloprid in nectar.

Print media learned of the DGAL's recommendation and of Bayers implications in drafting the protocol, raising doubts about the DGAL's impartiality with respect to Bayer and about its willingness to find relevant results (Libération, 1999a).

These first studies of public researchers reported the presence (< 10 ppb) of imidacloprid in sunflower leafs and pollen but did not quantify it (Pham-Delègue and Cluzeau, 1998).

The findings from research 'raised suspicions about the effects of the product, without formally proving its responsibility' ([10]) (Ministère de l'Agriculture, 2001b). Doubts about the harmlessness of Gaucho® led to the application of the precautionary principle. In January 1999 the Minister of Agriculture, Jean Glavany, decided to ban the use of Gaucho® in sunflower seed-dressing (Libération, 1999b).

This ban was renewed in 2001 for two years, again in 2004 for three years and at present, February 2012, it is still in force.

Honeybee exposure to imidacloprid: 2000–2002
Beekeepers continued to report clinical signs of intoxication after Gaucho® use in sunflowers was suspended in 1999. Three explanatory hypotheses were proposed:

- honeybees were still being exposed to the pollen of maize treated with Gaucho® (sunflower and maize are in flower in the same time);
- imidacloprid persists in soil after treatments of other crops (such as sugar beet, wheat and barley) and was taken up by untreated sunflowers grown one or more years after a seed-dressed crop;
- honeybees were affected by the dressing of sunflower seeds with RégentTS®, which had been provisionally authorised in December 1995.

Following the extension of the ban on using Gaucho® on sunflower and the refusal to ban it on maize, in 2001 (Ministère de l'Agriculture, 2001a; Conseil d'Etat, 2002), the Ministry of Agriculture established a Scientific and Technical Committee for the Multifactor Study of the Honeybee Colonies Decline (henceforth the 'CST' ([11])).

Between 2000 and 2002, using different methods and lower detection limits, public scientists identified 2–4 ppb of imidacloprid in seed-dressed sunflower and maize pollen (Bonmatin et al., 2001 and 2002; Bonmatin and Charvet, 2002), 13.3 ppb of imidacloprid in seed-dressed sunflower pollen (Laurent and Scalla, 2001) and 1.6 ppb in seed-dressed sunflower nectar (Lagarde, 2000).

During these years, it was understood that honeybees could collect imidacloprid-contaminated nectar and pollen for up to a month of sunflower and maize flowering. Bees could show the effects of repeated consumption of contaminated pollen and nectar almost immediately or some days or weeks later because pollen and nectar are stored in the hive. Furthermore, different categories of bees could be exposed in different ways and to varying extents. For example, pollen foragers (which differ from nectar foragers) do not consume pollen, merely bringing it to the hive. The pollen is consumed by nurse bees and to a lesser extent by larvae (Rortais et al., 2005).

The exposure of nectar foragers to imidacloprid contained in the nectar they gather can vary depending on the resources available in the hive environment. In addition, foragers take some nectar or honey already stocked in the hive before they leave for foraging. Depending on the distance from the hive where they forage, the honeybees are obliged to consume more or less of the nectar/honey taken from the hive and/or of the nectar collected, for energy for flying and foraging. They can therefore ingest more or less imidacloprid.

In 2002, Bayer publicly declared that the levels of exposure of honeybees to imidacloprid present in pollen and nectar ranged between 0 and 5 ppb (AFSSA, 2002).

Honeybee exposure to imidacloprid: 2003–2006
Based on exposure assessments and using scientific quality criteria to select among the available measurements, CST validated the findings of 3.3 ppb of imidacloprid in the pollen of Gaucho®-treated sunflowers, 3.5 ppb in pollen of Gaucho®-treated maize, and 1.9 ppb in the nectar of Gaucho®-treated sunflowers (CST, 2003).

([10]) In the original French: 'Les résultats ont généré des suspicions sur l'effet du produit, sans pour autant prouver formellement sa responsabilité.'
([11]) Comité Scientifique et Technique de l'Etude Multifactorielle des Troubles des Abeilles.

After seed treatment, imidacloprid transforms in the plant (metabolised) into many derivatives (metabolites), more or less completely. The main metabolites are 5-hydroxy-imidacloprid, 4-hydroxy-imidacloprid, 4-5 hydroxy-imidacloprid, olefin, imidacloprid-guanidine, imidacloprid-urea and 6-chloronicotinic acid.

Although two ([12]) of these metabolites show acute toxicity for honeybees (olefin and 5-hydroxy-imidacloprid), no study measuring metabolites in sunflower nectar or in sunflower and maize pollen, could be validated by the CST. For this reason, this committee recommended the development of detection and quantification limits low enough for their identification and quantification in pollen and nectar.

Lethal and sublethal effects
Pesticides can produce four types of effects on honeybees: acute or chronic lethal effects and acute or chronic sublethal effects.

- **Acute lethal effects** are expressed as the lethal dose (LD) at which 50 % of the exposed honeybees die within 48 hours: abbreviated to 'LD_{50} (48 hours)'.

- **Chronic lethal effects** refer to honeybee mortality that occurs after prolonged exposure (e.g. about 10 days).

In contrast to acute lethal effects, there were no standardised protocols for chronic lethal effects. Therefore, for imidacloprid, they were expressed in three ways:

- LD_{50}: the dose at which 50 % of the exposed honeybees die within 10 days;

- NOEC (No Observed Effect Concentration): the highest concentration of imidacloprid producing no observed effect;

- LOEC (Lowest Observed Effect Concentration): the lowest concentration of imidacloprid producing an observed effect.

Sublethal effects are modifications of factors such as honeybee behaviour, physiology and immune system. They do not directly cause the death of the individual or the collapse of the colony but may become lethal in time and/or may make the colony more sensitive (for example, more prone to diseases), which may lead to its collapse. For instance, an individual with memory, orientation or physiological impairments might fail to return to its hive, dying from hunger or cold. This would not be detected in standard pesticide tests, which focus on acute mortality. In addition, a key aspect in honeybee biology is that the colony behaves as a 'superorganism' ([13]). Hence, sublethal effects affecting individuals performing specific functions can influence the functioning of the whole colony. As was the case for chronic lethal effects, standardised protocols for sublethal effects were lacking.

- **Acute sublethal effects** of imidacloprid and its metabolites were assessed by exposing honeybees only once to the substance (by ingestion or by contact), and observing them for some time (variable from one laboratory to another, from several minutes to four days).

- **Chronic sublethal effects** were assessed by exposing honeybees more than once to the substance during a certain period of time (for example, each 24 hours, for 10 days).

Both acute and chronic sublethal effects are expressed as NOEC and/or LOEC.

Studies of lethal and sublethal effects: 1997–2000
Whereas intoxication by sprayed pesticides is usually confirmed by the numerous dead and moribund honeybees in front of the hives, beekeepers reported disappearance of most foragers in many hives. This lead them to hypothesise that imidacloprid was affecting the general mobility and/or orientation of the honeybees.

From 1999 onwards, **Bayer-funded scientists** also conducted studies on chronic lethal and sublethal effects. They found much lower values of LOEC for imidacloprid than previously reported. Whereas three Bayer scientists (Ambolet, Crevat and Schmidt)

([12]) The other four metabolites do not show any particular toxicity for honeybees.
([13]) Moritz and Southwick (1992) define superorganisms as 'superorganismic units with organisms arranged in at least two non-uniform types and differentiated into sterile and reproductive organisms with different functions' (p. 4). They highlight that superorganisms should not be confounded with social groups because, among other things, 'superorganisms need a sufficient membership so that the number of organisms involved in a task rather than the individual quality of how a task is performed becomes important' (p. 5). These numerous colony members function as a cooperative unit. Superorganisms maintain intraorganismic homeostasis (food storage, nest hygienic) and they are either well armed or highly cryptic. Superorganisms only originate from other superorganisms. For example in the case of bees a large part of a colony with a fertile queen undergoes 'fission' from the initial population and forms a swarm. 'In the end, however, only one feature really counts. It makes absolutely no sense invoking such a definition if natural selection does not act upon the superorganism itself. As long as natural selection is only working on individuals we have no need for such an additional perspective' (p. 6).

had reported a LOEC value of 5 000 ppb at the Fourth International Conference on Pests in Agriculture (6–8 January 1997), the new estimates were just 20 ppb, equivalent to 0.5–1.4 ng per honeybee (Kirchner, 1998, 1999 and 2000).

Other values found in 1999 and 2000 by **Bayer-funded scientists**, for the **highest concentrations which do not produce** sublethal effects (**NOEC**) ranged from 0.25–0.7 ng/honeybee (10 ppb) (Kirchner, 1999, 2000) to 0.94 ng/honeybee, 1.25–3.5 ng/honeybee, 1.5 ng/honeybee, 8.2 ng/honeybee, and 9 ng/honeybee (Schmitzer, 1999; Schmuck and Schöning, 1999; Thomson, 2000; Wilhelmy, 2000; Barth, 2000).

Among the **lowest concentrations at which imidacloprid produces** sublethal effects (**LOEC**), **public researchers** reported: 0.075–0.21 ng/honeybee (3 ppb); 0.15–0.42 ng/honeybee (6 ppb); 0.25–0.7 ng/honeybee (10 ppb), and 0.31–0.87 ng/ honeybee (12.5 ppb) (ACTA, 1998; Pham-Delègue, 1998; Pham-Delègue and Cluzeau, 1998; Colin, 2000; Colin and Bonmatin, 2000; Colin et al., 2002).

To enable comparison between the data obtained by Bayer and those obtained by public scientists, we note that, by definition, NOEC is the test concentration **immediately below** the LOEC. The NOEC values corresponding to data produced by public scientists were, by definition, below the LOEC values that they generated and which are presented here.

Having said this, one might find strange that among the values above, the **NOECs** from Bayer are **larger** than most of the **LOEC** obtained by public scientists. However, this strange result can be partially explained by the fact that the values of NOEC of Bayer come from sublethal **acute** intoxication, whereas the two values cited from public scientists are sublethal **chronic** values.

Indeed, the differences between the values above might arise from different sources. For example, as no standard tests existed, the laboratories used differing testing protocols. In addition, various sublethal effects were studied (knockdown effect, locomotion coordination, quantity of syrup ingested, pollen consumption, wax production, parent recognition, memory, visits to the food source, odour recognition, etc.). Of course, the results depend on what, and how, one measures.

Studies of lethal and sublethal effects: 2001–2004

In 2001, **public scientists** identified chronic lethal effects at LD_{50} = 12 pg/honeybee after 10 days of feeding with imidacloprid-containing syrup (0.1 ppb) (Suchail, 2001).

In 2002, **Bayer** declared that 'Bayer's studies established that below 20 ppb, no negative effect can be observed on honeybee colonies' ([14]) (AFSSA, 2002).

Properties of imidacloprid: persistence in soils and presence in untreated crops

In its dossier submitted to the Ministry of Agriculture (Bayer, 1999), **Bayer** quoted half-lives for Gaucho® (DT50) ([15]) of 188 ± 25 days and 249 ± 40 days for two soil types. It should be noted that this exceeds the threshold of three months established in EU Directive 91/414/EEC (Annex VI, Part C, point 2.5.1.1) for conducting detailed ecotoxicological studies:

> 'No authorization shall be granted if the active substance and, where they are of significance from the toxicological, ecotoxicological or environmental point of view, metabolites and breakdown or reaction products, after use of the plant protection product under the proposed conditions of use during tests in the field, persist in soil for more than one year (i.e. DT90 > 1 year and DT50 > 3 months) […] unless it is scientifically demonstrated that under field conditions there is no accumulation in soil at such levels that unacceptable residues in succeeding crops occur and/or that unacceptable phytotoxic effects on succeeding crops occur and/or that there is an unacceptable impact on the environment...'

Gaucho® was authorised in France on the basis of this EU Directive and a French regulation ([16]).

The average levels of imidacloprid found in the soil by **public scientists** were 10.25 ppb during the year that the crop was treated with Gaucho® and 4.4 ppb the following year (Bonmatin et al., 2000).

([14]) In the original French: 'Les études Bayer ont établi que jusqu'à 20 ppb, aucun effet négatif ne pouvait être observé sur des colonies d'abeilles'.

([15]) DT50 is the degradation half-life, or period required for 50 % dissipation/degradation of the initial concentration of substance. DT90 is the time needed for the dissipation/degradation of 90 % of the initial concentration of substance.

([16]) Arrêté du Ministre de l'Agriculture de 6 septembre 1994 portant application du décret no 94-359 du 5 mai 1994 relatif au contrôle des produits phytopharmaceutiques, modifié par l'arrêté du 27 mai 1998.

16.2.2 *Methodological quality of the evidence*

Method of risk assessment

The risk of sprayed ('classic') pesticides to honeybees were assessed using mortality studies in laboratory conditions, followed by semi-field studies and finally field studies (Halm et al., 2006). The first step in such studies is to calculate a hazard quotient (HQ = the field application rate/oral or contact LD_{50}) (OEPP/EPPO, 2003). Further studies are demanded if the HQ exceeds a certain threshold (Halm et al., 2006).

Bayer used the LD_{50} methodology in its dossier applying for marketing authorisation for Gaucho® (Bayer, 1999). However, the methodology based on LD_{50} is designed to assess the risk of sprayed pesticides and has been shown to be inappropriate for seed-dressing systemic insecticides for several reasons:

- Seed-dressing systemic insecticides are applied on seeds and disperse in the plant during growth. The field application rate of active substance as an exposure parameter is therefore a highly inadequate measure for the true exposure of honeybees (Halm et al., 2006). What is important for the effects of seed-dressing insecticides on honeybees is not the amount applied per hectare, but the amount of imidacloprid (and metabolites) in the pollen and nectar.

- Both acute and chronic effects are important for the colony (given the clinical signs observed), whereas LD_{50} only considers the acute effects on adult honeybees.

- Seed-dressing systemic insecticides can have sublethal effects affecting the performance of the whole colony, not just individuals, because foragers can bring the pesticide inside the hive via pollen and nectar.

- The risks of seed-dressing systemic insecticides vary, depending on the age and role of the honeybees in the colony (Rortais et al., 2005).

Consequently, the risk assessment procedure that the **CST** chose for imidacloprid was based on evaluating the ratio PEC:PNEC. This approach, which is used to assess the environmental risk of industrial chemicals, allows comparisons between the levels of exposure (Predicted Exposure Concentration — PEC) and toxicity (Predicted No Effect Concentration — PNEC), and considers both lethal and various sublethal effects in the short and longer term, for different age groups and casts of honeybees and for different matrices (e.g. honey and pollen) (Halm et al., 2006). Thus, the PEC:PNEC approach results in a probability (risk) that effects found in controlled studies of specific items of toxicity are found in real conditions.

Field and laboratory studies

The **Bayer-funded scientists** and **public scientists** disagreed about the relative relevance of laboratory and field studies ([17]). Bayer held that the results of field experiments would either prove or disprove the risk of the active substance, regardless of whether they conformed to the results of laboratory studies. The public scientists argued that field studies cannot be decisive for deciding on the risk of a pesticide to honeybees.

The principle of an experiment is to vary one factor, keeping all the others constant. This cannot be done in current field experiments with bees, because the combination of abiotic and — especially — biotic factors is never identical in control fields (where the insecticide has not been used) and test fields. Bee

Photo: © istockphoto/Youra Pechkin

([17]) A distinction is made between 'field experiments' and 'monitoring', which measures clinical signs in real conditions.

colonies themselves are not identical, and the food sources available in the environment for honeybees are always diverse.

Furthermore, in field tests, it is impossible to prevent honeybees visiting fields not in the experiment. For example, the distance separating control and test areas is often too small to prevent bees foraging in other fields ([18]). Many differences have been reported in honeybees' mortality, both by beekeepers and during open field experiments (CST, 2003). Therefore, it is probable that observations made in a particular field experiment are not representative of the range of effects that could occur in real conditions. Due to the large variability of factors that cannot be controlled (e.g. soil structure, climate, combination of plants attractive for bees etc.), current field experiments only give information about the particular situation in which they were done.

In the end, it was not a scientific institution but the highest judicial administrative institution in France, the **State Council**, that decided (29 December 1999) that the results of both field experiments and laboratory studies may be legitimately used in risk assessment (Fau, 2000). This is common practice in risk assessment of chemicals, which is based on the PEC:PNEC ratio.

16.3 Processes of generating knowledge and assessing risk

16.3.1 Knowledge producers: public scientists

Public scientists were in a very difficult position in this case. The results of their work were central to a social debate with high economic and political stakes. In certain cases their work was not judged based on scientific merits but whether or not it supported the positions of certain stakeholders. This situation challenged the ability and courage of researchers to continue their work on imidacloprid.

One stated: 'From the beginning of the programme, in January 1998, I personally received a letter from Bayer threatening me with a lawsuit for defamation' ([19]) (AFP, 2003). The letter written by Bayer's lawyers warned of both judicial action and financial reparations (personal letter).

Bayer also wrote a letter to the researcher's hierarchical superior, asking him to use his position to influence the researcher's interventions in the press (personal letter). The superior refused the demand of Bayer but advised his researcher to take extreme care with the press.

Another researcher said: 'I worked for three years on the topic and the management… my managers […], asked me to change topic' ([20]) (Elie and Garaud, 2003).

In 2000, one public scientist acquired European funds to analyse the risk of imidacloprid to honeybees. However, the researcher's hierarchical superior suddenly stopped the programme, even though the researcher had already produced some first results in previous studies on imidacloprid, the funding was confirmed and the work had both social and scientific relevance (personal communication).

We lack information about the experiences of Bayer-funded scientists. During the process of reviewing this chapter a Bayer researcher was directly asked for such information but none was provided.

16.3.2 Official evaluators of evidence of the risk of Gaucho® to honeybees

Commission for Toxic Products (CTP)
In 1993, in the light of Bayer's claims that honeybees were not exposed to imidacloprid applied in seed-dressing, the Commission for Toxic Products (CTP) ([21]) issued an assessment in favour of

([18]) Semi-field (tunnel) studies are also unable to provide a decisive indication of a pesticide's risk to honeybees for several reasons. First, the quantity of food and the time of exposure to the contaminated source are much less important in semi-field experiments than in real conditions. Second, one cannot know if the honeybees really consume the collected pollen and nectar (contaminated for the purpose of the test) or if they continue to consume the reserves already present in the hive at the beginning of the experiment. Third, the foraging distance is very small, and therefore some distance-dependent behavioural effects (for instance, orientation troubles) may not be seen under semi-field experiments but could appear in real conditions, when honeybees have to forage far from the hive.

([19]) In the original French: 'Dès le début du programme, en janvier 1998 j'ai reçu personnellement une lettre de Bayer me menaçant d'un procès en diffamation.'

([20]) In the original French: 'J'ai travaillé trois ans sur le sujet et la direction… ma direction […], m'a demandé de changer de sujet.'

([21]) La Commission d'étude de la toxicité des produits anti-parasitaires à usage agricole et des produits assimilés, des matières fertilisantes et des supports de culture, known as Commission for Toxic Products, was under the aegis of the Ministry of Agriculture. It was composed of experts in toxicology and eco-toxicology. Its remit was to analyse authorisation dossiers from toxicological and eco-toxicological points of view. In 2006, the Commission was replaced by expert groups headed by the French Food Safety Agency AFSSA (called DIVE).

authorising Gaucho®, without consulting its specialist Honeybee Working Group ([22]).

After the emergence of clinical signs in the field and the first evaluation report (Belzunces and Tasei, 1997), the assessment of the CTP (11 December 1997) was ambiguous. It found that in the light of the information available, it was impossible to confirm or deny a causal link between the use of Gaucho® and honey yield losses. The CTP continued to issue ambivalent assessments until December 2002.

From 1997 to 2001, the CTP considered that there was not enough knowledge to pronounce clear conclusions and repeatedly recommended further studies. For example, in 1997: 'The demonstration, made by Bayer that Gaucho® is not involved, is not made in a rigorous and complete manner. On the other hand, the declarations coming from beekeepers are not rigorous and stable enough for saying that Gaucho® is the **only** ([23]) cause of honeybee colonies problems' ([24]) (CTP, 1997).

In 1998 the CTP stated that, 'the data examined do not allow us to conclude to an **unquestionable effect** of imidacloprid and/or of its metabolites on honeybees and honey production. Conversely, it is also not possible **to completely exclude** the effect of imidacloprid and/or its metabolites, given the toxic effect at low doses, which have to do with the concentrations potentially present in the plants at the foraging time' ([25]) (CTP, 1998).

In 2002, the conclusion of the CTP was expressed in unclear language and referred vaguely to all honeybee losses in France instead of focusing on the clinical signs observed in areas of intensive agriculture: 'The risk assessment does not allow us to demonstrate that maize seed-dressing with Gaucho® can be **solely** responsible, at national level, for **all** colony losses, behavioural troubles, honeybee mortalities or general decline in the honey production' ([26]) (CTP, 2002, p. 22).

In all these cases, the CTP conclusions were answering a question that had never been asked, that is, is Gaucho® responsible for all honeybee losses, **everywhere in France**? They thus avoided a clear answer to the question really asked: is Gaucho® responsible for honeybee losses **in intensive sunflower and maize seed-dressed cultures**?

The CPT lacked clear operating procedures and the assessment of the dossiers submitted by companies during the authorisation processes was based on unstructured expert judgement. It did not involve a systematic reflection on the quality of the results presented in these dossiers, based on clear assessment criteria. During their meetings, the workload was such that members of the CTP were often dealing with several dossiers simultaneously and therefore could not have in depth discussions on each of them.

While the CTP issued advice to the Ministry several times during 1997–2002, only one member of the CTP was a bee specialist. The CTP had a Honeybee Working Group but this was not consulted until late in the debate (in 2000). A former member of the CTP argued that they were not consulted earlier because two members were beekeepers and were considered to have an interest in banning Gaucho® (personal communication). Even in the Honeybee Working Group, honeybee scientists were under-represented. Overall, the divergent data coming from different sources, the lack of sufficient expertise on honeybee biology and the absence of enough time and rigorous criteria for evaluating the dossiers, all contributed to producing ambiguous advice.

State Council

In the case of Gaucho®, different stakeholders, persons, and evaluation and decision bodies used varying criteria to judge the quality of the scientific evidence available. Thus, in contrast to the CTP, which was formally charged with assessing the

([22]) The Honeybee Group was a CTP working group set up to report the risks to honeybees of plant protection products (PPP) submitted for authorisation for marketing. It advised on awarding a product the 'honeybee label' indicating that it poses no risk to honeybees when used on flowering plants.

([23]) The underlining in this quote and all subsequent quotes has been added by the authors of the present paper.

([24]) In the original French: 'La démonstration par Bayer que le Gaucho est hors de cause n'est pas établie de façon suffisamment rigoureuse et complète. D'autre part, il n'y a pas assez de rigueur et de stabilité dans les rapports de terrain provenant des apiculteurs pour affirmer que le Gaucho est la seule cause de troubles dont les colonies d'abeilles sont victimes.'

([25]) In the original French: 'Les données examinées ne permettent pas de conclure à un effet indiscutable de l'imidacloprid ou de ses métabolites sur les abeilles et la production de miel. Inversement, il n'est pas possible d'exclure totalement l'effet de l'imidacloprid et de ses métabolites, compte tenu de l'effet toxique à faible doses, doses en rapport avec des concentrations potentiellement présentes dans les plantes à l'époque du butinage.'

([26]) In the original French: 'L'évaluation du risqué réalisée ne permet donc pas de démontrer que le traitement de semences de maïs par la préparation Gaucho puisse être le seul responsable au niveau national de l'ensemble des dépopulations de ruches, des troubles comportementaux, des mortalités d'abeilles et plus globalement de la baisse de production apicole.'

conformity of the existing evidence with the regulatory demands for pesticides risk assessment, the State Council employed legal criteria, assessing conformity with the law.

The first intervention of the State Council was in 1999, immediately after the ban on using Gaucho® on sunflower seeds, when Bayer mounted a legal challenge to the ministerial decision. About that time, several international consortia of seed producers (Monsanto, Novartis, Rhône-Poulenc, Pionneer, Maisadour and Limagrain) rallied behind Bayer and formulated a similar case against the Minister's decision. The beekeepers syndicate UNAF ([27]) co-defended the Minister's decision in court. The State Council decided in favour of the beekeepers and the Minister, judging that the Minister's precautionary decision was based on an appropriate evaluation of the results from the 1998 scientific programme and the conclusions of the CTP, which expressed doubts about the harmlessness of Gaucho® for honeybees.

The State Council was involved again in 2002 and 2004, calling on the Minister to reconsider his decisions refusing to ban Gaucho® in maize seed-dressing (see Section 16.4.2), on the grounds that the Ministry had not rightly evaluated its harmlessness in the way demanded by French legislation ([28]). In its conclusion in 2002, the State Council pointed out that, given the reasons for concern about Gaucho®, the Ministry should have examined all the necessary data to evaluate its effects on honeybees in maize seed-dressing. That is, the Ministry should have asked for quantification of the use of maize pollen by honeybees, as well as of the nature and intensity of the effects on honeybees of maize pollen containing imidacloprid. In 2004, the State Council again stated that the CTP's risk assessment of Gaucho®-treated maize for the Ministry failed to comply with the law as the effects on larvae had not been assessed.

Other cases in court

In 2001, Bayer took three representatives of beekeepers' syndicates to court in their home towns (Châteauroux, Mende and Troyes), accusing them of discrediting Gaucho® (GVA, 2001). In all cases, the courts decided in favour of beekeepers, based on the freedom of the syndicates to play their role in society and to express their opinions publicly. One of the courts explicitly criticised the attempt of Bayer CropScience to intimidate a syndicate leader who was defending the interests of his profession (UNAF, 2004).

An investigation into Gaucho® was launched in a court in Paris, following a charge brought by UNAF in 2001. The investigation continues to stagnate. Since its beginning, two judges have been replaced for different reasons. The judge currently dealing with the case has proceeded with new interrogation of experts and parties involved. In March 2011, the judge was still investigating the available evidence, in order to decide if there will be a trial or not.

16.3.3 Scientific and Technical Committee

Based on the analysis of 338 bibliographical references, the CST concluded that seed-dressing sunflower and maize posed serious risks to honeybee colonies via larvae feeding, pollen consumption by nurses, nectar ingestion by foragers, and honey consumption by honeybees living inside the hive:

> 'Based on our current state of knowledge and on the scenarios we developed to evaluate exposure, and based on the uncertainty factors chosen to evaluate the dangers, the PEC:PNEC ratios determined are of concern. They are in agreement with the field observations reported by numerous beekeepers' areas of intensive corn and sunflower growing, relating to the mortality of foragers (scenario 4), their disappearance, behavioural disturbances and certain winter mortalities (scenario 5). Consequently, the dressing of sunflower seeds with Gaucho® poses significant risks for bees of different ages, with the exception of the pollen ingestion by foragers during the making of pollen balls (scenario 3).
>
> 'Regarding corn seed dressed with Gaucho®, the PEC:PNEC ratio turns out to be, as for the sunflower, of concern in the case of pollen consumption by nurse bees, which would lead to an accrued mortality of these and be one of the explanatory elements for the weakening of bee populations observed

([27]) UNAF (Union Nationale de l'Apiculture Française) is one of the three French beekeeping syndicates, representing about 22 000 beekeepers.
([28]) Arrêté du 6 septembre 1994.

despite the ban on Gaucho® on sunflowers. Finally, given that other factors can contribute to the weakening of bee colonies, research should be continued on the frequency, mechanism and causes of these clinical signs' ([29]) (CST, 2003, p. 11).

Although the interim CST report on the risks of Gaucho® to honeybees was completed in 2002, DGAL (the General Directorate for Food, within the Ministry of Agriculture) did not submit it then to the Management Committee ([30]) of the CST. Just before publication in 2003, the Ministry of Agriculture withdrew its logo. One interpretation of this was that it emphasised the independence of the CST, alternatively it could be seen as demonstrating that the Ministry of Agriculture did not want to show any support for the results. This last interpretation is reinforced by a post-publication letter from the DGAL, in which the Directorate considered that the findings of CST were too precise and asked for more studies.

16.4 Societal debate and the policy responses

16.4.1 Stakeholder strategies

Beekeepers systematically presented and compared the results of studies conducted by Bayer, the Ministry of Agriculture, public research and their own field observations. Their objective was to make the results public in order to show the congruity of their own observations with the scientific results and to mobilise civil society for support. The beekeeping sector was supported by civil society, as the issues were of major concern to the French public. The sector's arguments received good coverage in the national press.

DGAL's public statements were ambiguous. Its lack of transparency undermined trust: for example, when beekeepers' requested the authorisation dossier for Gaucho®, DGAL only released limited information (Clément, 2000). DGAL communicated all the documents requested by beekeepers only after intervention from both the Minister of Agriculture himself and the Commission for Access to Administrative Documents.

There was variance in the public positions of different ministries of the French government and different services within the Ministry of Agriculture. The decisions of the Ministers of Agriculture to suspend the use of Gaucho® in seed-dressings for sunflower (1999, 2001, 2003) and maize (2004) contrasted with DGAL's procrastination.

Bayer had an inappropriate communication strategy on scientific figures, which contributed to increasing mistrust from the other stakeholders. For example, in 2002, Bayer publicly acknowledged exposure 'between 0 and 5 ppb, which is the quantification limit' ([31]) (AFSSA, 2002, p. 32). This statement represented a major step forward in Bayer's communication of scientific figures but was still vague about the information available on imidacloprid. However, Bayer-funded scientists had already obtained precise figures for sunflower, i.e. 3.3 ppb in pollen and 1.9 ppb in nectar (Stork, 1999) ([32]). In addition, between 2000 and 2001 public scientists had also reported quantification limits well below 5 ppb, i.e. 1 ppb for quantifying imidacloprid in pollen and nectar (Lagarde, 2000, Bonmatin et al., 2001) and detection limits of 0.3 ppb for pollen (Bonmatin et al., 2001) and 0.8 for nectar (Lagarde, 2000). These quantification and identification limits, as well as the precise measures of imidacloprid in pollen and nectar, available from public scientists, were ignored by Bayer in its statements on Gaucho® despite being publicly available ([33]).

([29]) In the original French: 'Dans l'état actuel de nos connaissances, selon les scénarios développés pour évaluer l'exposition et selon les facteurs d'incertitude choisis pour évaluer les dangers, les rapports PEC/PNEC obtenus sont préoccupants. Ils sont en accord avec les observations de terrain rapportées par de nombreux apiculteurs en zones de grande culture (maïs, tournesol), concernant la mortalité des butineuses (scénario 4), leur disparition, leurs troubles comportementaux et certaines mortalités d'hiver (scénario 5). En conséquence, l'enrobage de semences de tournesol Gaucho® conduit à un risque significatif pour les abeilles de différents âges, à l'exception de l'ingestion de pollen par les butineuses lors de la confection de pelotes (scénario 3).
'En ce qui concerne l'enrobage Gaucho® de semences de maïs, le rapport PEC/PNEC s'avère, comme pour le tournesol, préoccupant dans le cadre de la consommation de pollen par les nourrices, ce qui pourrait entraîner une mortalité accrue de celles–ci et être un des éléments de l'explication de l'affaiblissement des populations d'abeilles encore observé malgré l'interdiction du Gaucho® sur tournesol. Enfin, étant donné que d'autres facteurs peuvent contribuer à l'affaiblissement des colonies d'abeilles, il convient que les recherches soient poursuivies sur la fréquence, les mécanismes et les causes de ces symptômes.'

([30]) The Management Committee's remit was to supervise the scientific, economic and regulatory aspects of the CST's work and to ensure communication with the Minister of Agriculture, stakeholders and the public.

([31]) In the original French: 'comprise entre 0 et 5 ppb, qui est la limite de quantification'.

([32]) The data obtained by Bayer using radiolabelled imidacloprid have been published in 2001 (Schmuck et al., 2001).

([33]) For instance, Apiservices (2001) presents a synthesis of the available data and was published online on 16 February 2001.

Bayer steadfastly maintained that using Gaucho® in sunflower seed-dressing had no effect on honeybees (Bayer CropScience, 2006). In 2006, the case dossier on the company's website did not mention the CST's conclusion that 'in the actual state of our knowledge […] the PEC:PNEC ratios obtained are worrisome' ([34]), or the findings from French public scientists regarding the risks of Gaucho® for honeybees ([35]).

16.4.2 Policy response to scientific evidence on risk

A dossier prepared by the Ministry of Agriculture (2001c) frames the 1999 decision of the Minister to ban Gaucho® on sunflower in the following terms:

> 'The Ministry of Agriculture has conducted a first series of laboratory studies, as well as field studies in three test departments: Vendée, Indre and Deux-Sèvres. The results yielded suspicions about the effects of the product, without, however, formally proving its responsibility. **Applying the precautionary principle**, the Minister of Agriculture has decided, in January 1999, to temporarily ban the product in sunflower seed-dressing' ([36]).

The Minister of Agriculture's ban on Gaucho® as maize seed-dressing was introduced later. The stakes were higher for Bayer (only 10 % of Gaucho® revenue came from use on sunflower, the area under maize in France being 2.5 times that under sunflower ([37])), for farmers, for beekeepers, for the general public (as articulated by the media) and probably for the Minister himself as a politician. In addition to the economic importance of maize, it is frequently cultivated without rotation. Therefore the pressure from pests (and maize growers) can be higher than for sunflower. Justifying his decision not to ban Gaucho® in maize seed-dressing, the Minister of Agriculture stated to the State Council that maize does not produce nectar and therefore honeybees do not visit this plant for producing honey, apparently unaware that honeybees do, however, visit maize to collect its pollen, which they consume (Conseil d'Etat, 2002).

Although a procedure for the reversal of this authorisation was under way at the State Council, on 21 January 2002 the Ministry of Agriculture renewed the authorisation of Gaucho® on maize for ten more years. Subsequently, the judicial inquiry on Gaucho® was extended to challenge this renewed authorisation (Saunier, 2005). In October 2002 the State Council concluded its re-examination of the scientific evidence and advised the Minister to reconsider his decision. In 2003, the Minister of Agriculture refused again to ban the use of Gaucho® in maize seed-dressing. In September 2003 the CST concluded that imidacloprid in maize seed-dressing posed a serious risk to honeybees (specifically the nurses consuming pollen). Again, in March 2004, the State Council advised the Minister to reconsider their decision but it was not until July 2004 that this use of Gaucho® on maize was banned. The press release communicating the Ministry's decision refers to the CST report, and states that 'the risk for honeybees seems less important than in case of sunflower seed-dressing because exposure occurs only via pollen but is, however, of concern' ([38]) (Ministère de l'Agriculture, 2004).

Prior to this, in a letter published on 21 November 2003, the head of the Bureau for the Regulation of Pesticide Products of the DGAL had revealed various shortcomings of the official risk assessment and management procedure: there were only three public servants to deal with 20 000 applications for authorisation per year; risk assessments were performed jointly with the industry; there was lack of transparency in the procedures; and insufficient attention was paid to the issue of pesticide residues in food during the risk assessment. In consequence,

([34]) In the original French: 'Dans l'état actuel de nos connaissances [...] les rapports PEC/PNEC obtenus sont préoccupants.'

([35]) On the Bayer CropScience France website (www.bayercropscience.fr) in 2006, there was a file entitled 'Honeybees'. In November 2009, on this website, if one searches for 'honeybee' ('abeille'), no document can be found. On the website of Bayer Cropscience World, searching 'honeybees' gives no specific reference to Gaucho®, but searching 'Gaucho' results in some documents on the French case. Among them, the document referring to the ban of Gaucho® on maize still does not mention the conclusions of the CST or of French scientists. In January 2011, seaching for honey + bee + gaucho gives 1 result, referring to the judgement of the court of Chateauroux, whereas searching bee + gaucho gives 14 results, among which 4 refer to honeybees.

([36]) In the original French: 'Le ministère de l'Agriculture et de la Pêche a conduit une première série d'études en laboratoire, comme sur le terrain dans trois départements tests: la Vendée, l'Indre et les Deux-Sèvres. Les résultats ont généré des suspicions sur l'effet du produit, sans pour autant prouver formellement sa responsabilité. En application du principe de précaution, le ministre de l'Agriculture et de la Pêche a décidé en janvier 1999 le retrait provisoire de l'autorisation de mise sur le marché du produit sur traitement de semences de tournesol.'

([37]) Official figures from the website of the Ministry of Agriculture (Agreste, 2011) for the year 2000 put the area used for maize at 1 764 767 ha and for sunflower 728 555 ha.

([38]) In the original French: 'le risque pour les abeilles, s'il apparaît moins important que dans le cas de l'usage pour l'enrobage des graines de tournesol du fait de la seule exposition au pollen, reste préoccupant.'

the Bureau chief concluded, 'it is impossible for the Bureau to accomplish its mission' ([39]).

16.4.3 *Costs and benefits of the policy responses*

In the last 20 years, the **chemical industry** has been increasingly regulated. Directive 91/414/EEC required the reassessment of active substances contained in plant-protection products already on the EU market. Many active substances have since been withdrawn. Furthermore, some pests have developed resistance to formerly used pesticides.

European manufacturers of agricultural chemicals face higher research and development costs. On average, it costs some USD 50 million to develop a new product. Nevertheless, systemic insecticides represent a highly profitable investment. For example, imidacloprid-based insecticides ([40]) brought Bayer DM 800 million of global sales in 1998 (approximately EUR 409 million) (Bayer, 1998) and EUR 556 million in 2007 (Bayer CropScience, 2008). Furthermore, focusing on these products also represents a networking investment for the industry because partnerships are made with seed producers and distribution chains. We do not have information about the economic consequences for the chemical industry of banning Gaucho® or RégentTS® in France.

The economic situation of the **French beekeeping sector** worsened significantly between 1994 and 2004. In 1994, there were 1 370 220 beehives and 84 800 beekeepers. By 2004, there were 1 360 973 beehives and 68 800 beekeepers (GEM-ONIFLHOR, 2005). Many small producers abandoned beekeeping in the interim. The apparent stability of the number of hives between 1994 and 2004 belies the higher turn-over of colonies to replace those lost. The decrease in the sunflower average honey yield (Belzunces and Tasei, 1997; CNEVA Sophia-Antipolis, 1997; Pham-Delègue et Cluzeau, 1998; Coordination des Apiculteurs, 2001; Alétru, 2003), and the increase in colony mortality forced professional beekeepers to increase the number of hives to compensate for their losses.

The relative contribution of insecticides and other factors (e.g. the international market for honey and honeybee diseases) to the decline of French beekeeping is unclear. France's honey imports per annum rose from 6 000 tonnes in 1993 to 17 000 tonnes in 2004, whereas domestic honey consumption stayed constant at about 40 000 tonnes per annum (GEM-ONIFLHOR, 2005). A study of the cooperative France Miel ([41]) for western France showed that severe losses in the sunflower honey yield started in 1995 and continued over the following years (Figure 16.1).

Data similar to those obtained for western France exist for the cooperative Poitou-Charentes (Figure 16.2) and for the department of Deux-Sèvres, produced by the Agricultural Chamber (Chambre d'Agriculture). In 2005, the important decrease in the production of sunflower honey is also referred to in a national audit report of the beekeeping branch (GEM-ONIFLHOR, 2005).

These data are not exhaustive but they show that the losses of sunflower honey yield were significant, started around 1994 and continued in the following years.

Among the beekeeping sector's expenses, there was also additional outlay on research (funding research to assess the risk of Gaucho® and RégentTS® through European funds for beekeeping) and legal fees (for the different judicial interventions). The financial burden was double because the funds had been intended to support the development of beekeeping. Having been spent on defending beekeepers' stakes in the debate, some could not be used to achieve the development goals.

The beekeepers have not been compensated for their economic losses but after 2003, France was granted financial support from the European Commission to restore honeybee colonies, as general support for beekeeping in a time of economic hardship.

In the **agricultural sector**, the economic repercussions are unclear. A large proportion of French crops (such as sunflower, maize and cereals) were rapidly given seed-dressing protection, even when pest control was rarely needed (for example for sunflowers). The Technical Center for Oilseed Crops (CETIOM) website specifies ([42]) that 'sunflower has a low attractiveness for [click beetle]

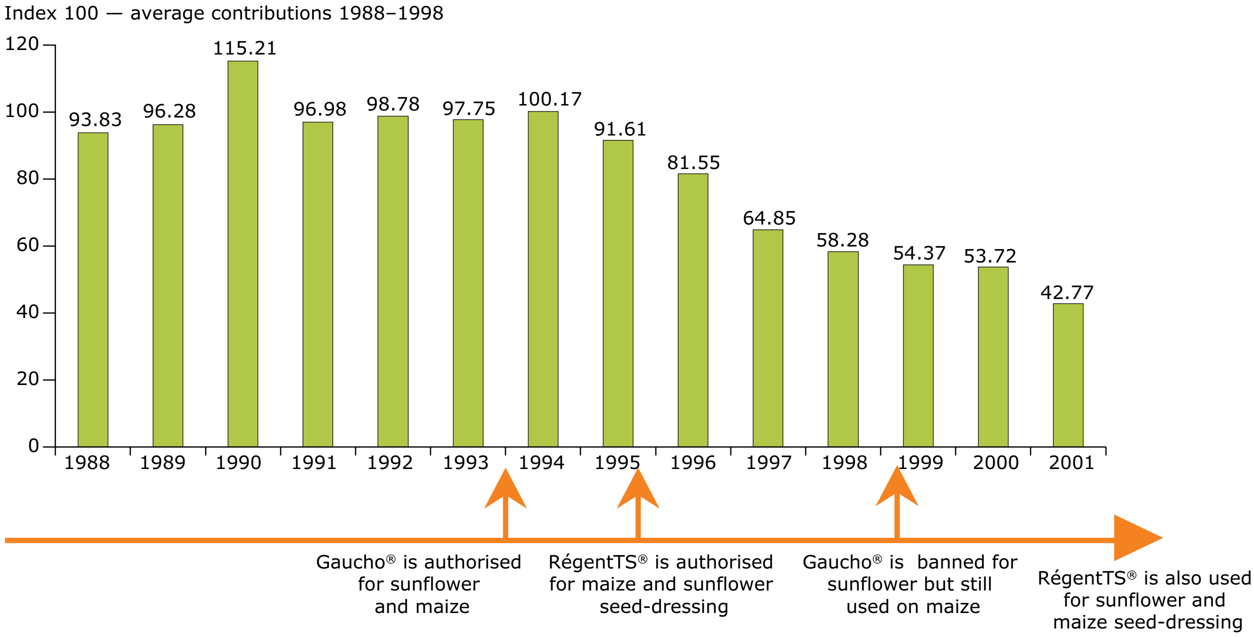
([39]) 'Trois fonctionnaires pour traiter 20 000 demandes d'autorisation par an, 'une cogestion de l'évaluation des risques avec les industriels', 'une absence de transparence dans les procédures'. 'En matière d'évaluation des risques, le domaine des résidus de pesticides dans les aliments est insuffisamment couvert.' Enfin, 'Le bureau est dans l'impossibilité de remplir ses missions.' (Le Point, 21 November 2003).

([40]) Gaucho®, Confidor®, Admire® and Provado® in 1998 and Confidor®, Admire®, Gaucho® and Merit® in 2007.

([41]) Additional figures for the evolution of sunflower honey are available in France Miel (2000).

([42]) This information has been already present on this website in 2003.

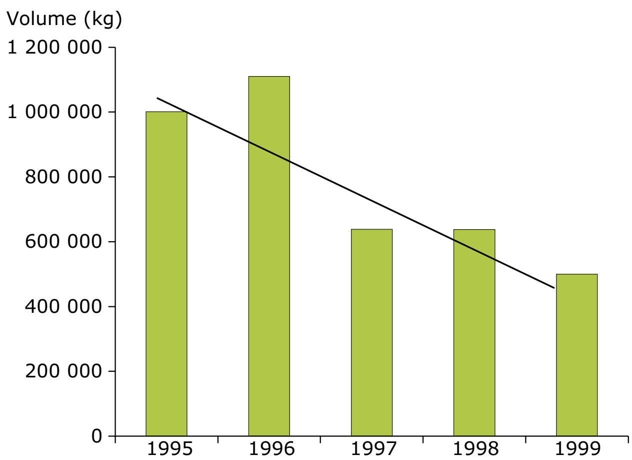
Figure 16.1 Sunflower honey harvest in western France (*)



Note: * The method for obtaining these data was communicated to Laura Maxim by France Miel. The quantities of sunflower honey comprise all the quantities brought to France Miel between 1988 and 1998 by a representative sample of professional beekeepers providing honey to France Miel, from the departments 72 (Sarthe), 49 (Maine-et-Loire), 85 (Vendée), 17 (Charente-Maritime), 33 (Gironde) and 32 (Gers). The vertical axis represents an index 100 — which is the average of the quantities of sunflower honey provided to France Miel between 1988 and 1994. Beekeepers are committed to supply all of their annual harvests to the cooperative. A laboratory further checks the floral origin of the supplied honey. It was not possible to calculate the evolution of the quantity of sunflower honey beyond 2001 because some beekeepers from the sample abandoned beekeeping, left the cooperative, developed other activities in addition to beekeeping or retired. Note that sunflower seeds were also dressed with another insecticide after 1995, RégentTS®.

Source: Laura Maxim.

Figure 16.2 Sunflower honey yearly harvest totals since 1995, for the Cooperative Poitou-Charentes



Source: Coordination des Apiculteurs, 2000.

larvae and the time lag during which the plant is sensitive to these larvae is relatively short' ([43]). Furthermore, for 'most of the areas where sunflower is cultivated in France', the risk is 'low or zero' ([44]) (CETIOM, 2011).

Contrary to the use of curative treatments usually recommended to farmers when pest density was above an economic threshold, the new control method was preventive regardless of the presence and abundance of pests.

Seed-dressing reduces the work needed for crop protection, so it could be economically attractive to farmers. But some farmers said that their productivity was unchanged or diminished, and reported more empty seeds in the flowerheads, suggesting a possible link with the poor pollination associated with Gaucho® (Elie and Garaud, 2003).

([43]) In the original French: 'le tournesol est faiblement attractif pour les larves et la période de sensibilité aux attaques est relativement brève.'

([44]) In the original French: 'Population de taupins nulle à faible, dégâts très peu probables sur tournesol: Majorité des situations où le tournesol est cultivé aujourd'hui en France.'

Mainstream (intensive) farmers' organisations such as the General Association of Maize Producers (AGPM) ([45]) argued that banning seed-dressing insecticides increased pressure from pests, particularly on maize (Beulin et al., 2005; AGPM, 2008).

In 2002 the rapporteur on 'insecticides' in the Committee for Pesticides Authorisation ([46]) stated that, at that time, the two 'really effective' plant protection products that served as alternatives to Gaucho® and were available for certain maize pests were terbufos (which was due to be withdrawn from the EU market in 2003) and RégentTS® (Comité d'homologation, 2002).

In 2005, farmers reported losses of 500 000 tonnes of maize-grain in France (worth EUR 50 million) and some of them linked this figure to the ban on seed-dressing insecticides (Dossier de la protection des sémences, 2005). However, others blamed the productivity drop on the exceptionally hot and dry summer that year. AGPM itself has pointed towards the decrease in maize yield from 2003 due to increasingly drier summers.

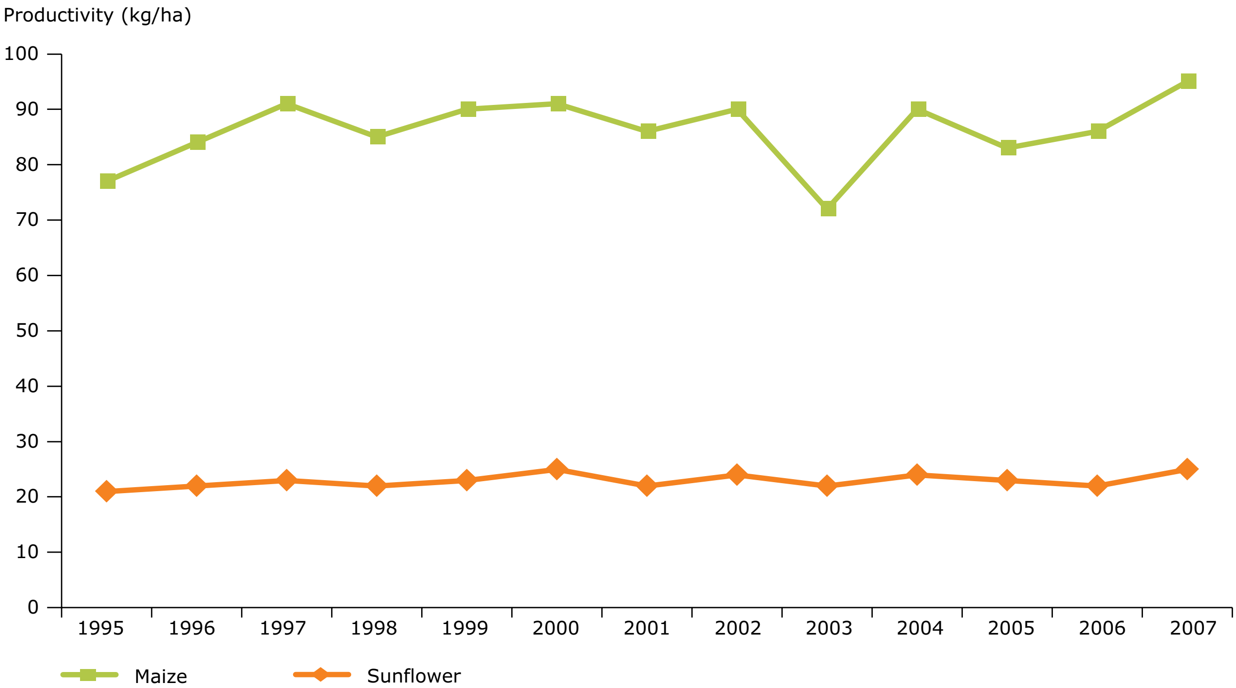
Figure 16.3 shows that the seed-dressing ban is not directly correlated with productivity: 2007 was the best year in over a decade. For maize, production was worst not after 2004, when Gaucho® was banned on this crop and RégentTS® on all uses, but in 2003, when a major heatwave hit Europe.

Beekeepers contended that, because not all maize crops in France were seed dressed, maize could be cultivated without seed-dressing insecticides. Contrastingly, the website of the General Association of Maize Producers (Dossier de la protection des secmences, 2005) reports that there is no authorised alternative treatment to control wireworms.

The losses for agriculture associated to the potential decline in pollination during this period (1994–2004) have not been assessed.

Finally, resistance to insecticides is more likely with the long persistent molecules of seed-dressings (such as imidacloprid, fipronil and thiametoxam) which exert a constant pressure on natural selection, compared to sprays.

Figure 16.3 Trends in maize and sunflower yields in France from 1995 to 2007



Source: Data from AGRESTE, Statistiques agricoles annuelles.

([45]) L'Association Générale des Producteurs de Maïs — also a defender of industrial agriculture, for example through cultivating GMOs and intensive biofuel crops.

([46]) Comité d'homologation — one of the two authorities previously involved in evaluating applications for authorisation of pesticides in France. The other instance was the CTP.

16.4.4 Debate in France: 2004–2011

The figures for bee mortality in France are very diverse and heterogeneous among sources. According to UNAF, since 2003 honeybee colonies have partially recovered in France. UNAF reported that high **summer** mortality has stopped in intensive agriculture areas and the general state of the French hives improved (Clément, 2005; UNAF, 2007 and 2008).

An AFSSA study between 2002 and 2005 on 120 hives reported normal activity of honeybees, and usual winter mortalities (5–10 %) (Aubert et al., 2008).

AFSSA (Faucon and Chauzat, 2008) and some beekeepers (Schiro, 2007) reported high mortality for the **winter** 2005–2006. However, according to EFSA (2008), only 1.2 % of French beekeepers made declarations regarding mortality in 2006 and 0.6 % did so in 2007.

Following the 2006–2007 **winter**, apiaries were reported to be in good condition in early spring 2007 (Clément, 2007).

For the 2007–2008 winter, an inquiry by the National Center for Apicultural Development (CNDA), based on 168 professional beekeepers' answers (representing about 5 % of French hives and 10 % of French professional beekeepers), found an average **winter** loss of colonies for France of around 30 %. That was some 12 % higher than CNDA figures for the two previous winters (De Boyer des Roches et al., 2009).

The reality is that no system exists in France for the accurate and extensive monitoring of honeybees. The national statistics of the French Ministry of Agriculture are recognised to support neither accurate quantification of bee mortality, nor identification of causes. Furthermore, official statistics focus on the survey of bee contagious diseases. The Ministry of Agriculture's data on the influence of diseases on French hives differ markedly from those collected by the AFSSA (2009).

AFSSA has produced several reports after 2004, presenting results from its eco-epidemiological studies, suggesting that honeybee problems had multiple causes, with diseases being important in winter mortalities. They showed that varroa is currently a pressure in French hives, as few drugs against this mite are available (AFSSA, 2009).

The reports AFSSA (2009) and CST (2003) differ in terms of their objectives and, therefore, in their methods. These differences are apparent in their respective bibliographies. Of the 338 bibliographic references considered in the CST report, only five were included in AFSSA (2009). Similarly, 173 of the references available before 2003 and included in AFSSA (2009) report were not included in the CST report.

The majority of the references considered by the CST concern imidacloprid. Contrastingly, 43 % of the documents considered in the AFSSA report concern diseases and viruses and only about 15 % concern ecotoxicological issues, with only 3 % focusing on imidacloprid.

Nevertheless, the AFSSA report describes its analysis as '**An almost exhaustive study** of French and European investigations carried out on the issue of bee morbidity and mortality' (p. 12). It also asserts that 'This information has allowed an almost exhaustive inventory of the causes of bee diseases and particularly bee colony mortality to be drawn up' (p. 101). However, the statistics regarding references demonstrate that almost none of the documents reviewed during the CST were considered by AFSSA. The AFSSA analysis only refers to some of the references available on honeybee losses in France — mainly those referring to diseases. Therefore the AFSSA inventory of sources cannot be considered as being 'almost exhaustive'.

AFSSA (2009) does not assess the influence of Gaucho® and Régent® on honeybees in sunflower and maize areas (e.g. the word Gaucho® is present four times in the main text of the document, twice in naming the precautionary decision of the Ministry and twice in naming the corresponding CST report).

Regarding, generally, the influence of pesticides on honeybees, AFSSA (2009) states that 'The group's deliberations do not confirm the hypothesis of a predominant role attributed to pesticides by beekeeping professionals in French bee colony mortality'. This statement takes an important place, because it is found in the conclusions section. However, this general conclusion lacks precision in several respects that are relevant to the present chapter:

- It is not clear to which 'pesticides' the text refers. Do the authors refer to all pesticides?
- It is not clear to which 'beekeeping professionals' the text refers. Is it beekeepers in maize and sunflower areas or beekeepers in other areas (for example mountain regions)?

- It is not clear which 'French bee mortality' this statement refers to because the time period is not specified. Is it before 2004 (before the ban on imidacloprid in maize seed-dressing and on fipronil in all agricultural uses?) or is it after 2004?

- The method used to draw this conclusion is not clear either. How were the 'group deliberations' organised in order to produce this conclusion? On which bibliographic basis were these conclusions drawn, given that less than 15 % of the documents considered refer directly to pesticides? How were these documents chosen, among all the references available on the effects of pesticides on honeybees, and used to reach this conclusion?

Suchail et al. (2001) investigated the oral acute and chronic toxicity of imidacloprid and its main metabolites (5-hydroxyimidacloprid, 4,5-dihydroxyimidacloprid, desnitroimidacloprid, 6-chloronicotinic acid, olefin, and urea derivative) in *Apis mellifera*. Regarding two metabolites (urea and 6-chloronicotinic acid), their results were contested in a study published by a Bayer-funded scientist (Schmuck, 2004). This study could not find any increased treatment-related mortality or behavioural abnormalities following chronic exposure of honeybees to these two metabolites, at 0.0001, 0.001, and 0.010 mg/L 50 % sucrose solution.

Schmuck (2004) did not address the parent molecule, imidacloprid, in an experimental way but through a literature analysis. The author argued that comparison with other studies should be considered sufficient to reject the results found by Suchail (2001), based on the argument that Suchail's results are lower than others. This comparative literature survey neither analysed the sources of the differences between the results, nor examined comparatively the protocols used by the various researchers to understand the sources of these differences.

Post-2003 studies also found that exposure to imidacloprid is also possible through aerial pollution, through foraging on wild flowers coated with imidacloprid-containing dust as a result of sowing-related activities (Greatti et al., 2006) and through consumption by honeybees of leaf guttation drops of corn plants germinated from imidacloprid-coated seeds (Girolami et al., 2009).

Public scientists in France found that the persistence of imidacloprid resulted in its presence in untreated crops cultivated after seed-treated crops. Bonmatin et al. (2005) found 1–2 ppb imidacloprid in flowerheads of untreated sunflowers grown a year after seed-dressed sunflowers. Imidacloprid was still detectable two years after treatment (detection limit = 0.1 ppb). In pollen, imidacloprid was detected one year after treatment (detection limit = 0.3 ppb).

Immunodepression caused by sublethal exposure to insecticides may favour lethal diseases (Glinski and Kauko, 2000; ISIS, 2011). Indeed, beekeepers formulated this hypothesis and launched a call for research (Alétru, 2003). Results of a survey initiated in France showed that the most frequently found pesticide residue in pollen samples was imidacloprid (in 49.4 % of the samples), followed by one of its metabolites, 6-chloronicotinic acid (in 44.4 % of the samples). At least one of these two molecules was present in 69 % of the samples (Chauzat et al., 2006).

Alaux et al. (2009) found that honeybees that were both infected with the pathogen Nosema and exposed to imidacloprid at concentrations encountered in the environment showed the highest mortality rate comparing to honeybees infected with Nosema alone or treated with imidacloprid alone. Although imidacloprid contamination in the hive is usually found at sublethal doses, infection with Nosema increases the energy demands of bees and therefore their food intake. By this means bees could be exposed to lethal doses. Alaux et al. (2009) found that in the long term the synergy between Nosema and imidacloprid induced the immunosupression of an enzyme essential in sterilising larval food, leading to higher susceptibility of the colony to pathogens.

Authorisation has been requested since 2004 for two other seed-dressing insecticides in France. Poncho® (with the active substance clothianidin), produced by Bayer, has not been authorised for maize. Cruiser® (with the active substance thiametoxam), produced by Syngenta, has been authorised and honeybees were monitored in three regions in 2008 and six in 2009. In June 2009, the Minister of Agriculture decided not to renew the marketing authorisation of Cruiser® until autumn 2009. In December 2009, Cruiser® was reauthorised for use on maize for 2010.

Relationships between beekeepers and the Ministry of Agriculture seem to have improved. The decisions of the Ministers of Agriculture to ban Gaucho® on sunflower and maize significantly calmed the controversy and a Technical Beekeeping Institute has been created.

16.4.5 Assessment of Gaucho® at the European level

In the framework of Directive 91/414/EEC, imidacloprid has been assessed at European level for inclusion on the list of active substances allowed for marketing in the European Union. The rapporteur Member State for imidacloprid was Germany, which submitted a Draft Assessment Report (DAR) to the EFSA in 2005 (Rapporteur Member State, Germany, 2006). In 2008, imidacloprid was included on the list of active substances allowed for marketing in the EU ([47]).

Several studies produced in France, relating to the risk of Gaucho® to honeybees were not considered in the DAR. Notably missing were relevant studies on the exposure of honeybees to contaminated pollen and nectar (e.g. none of Jean-Marc Bonmatin's studies was included). In addition, the DAR report accorded only limited importance to sublethal effects, although there were at the core of the investigations in France because of their potential to create lethal effects in field conditions. Finally, the risk assessment methodology was not adapted to seed-dressing formulations.

Several NGOs (Stichting Natuur en Milieu, PAN-Europe, Inter Environment Wallonie, Nature et Progres and Mouvement pour le Droit et le Respect des Générations Futures (MDRGF)), analysed the DAR in a letter sent to the European Commissioner for Health. They articulated several criticisms of the DAR: the absence of necessary tests for each bee category (e.g. larval tests); underestimation of the nectar consumption per bee, meaning that the non-effect concentration was set too high; validation of studies without any validation criteria; discrediting of reports non-favourable to imidacloprid but thorough validation of reports favourable to the thesis that there were no risks to honeybees; flawed consumption tests and colony sizes too small to test egg-laying; insufficient measurement of sowing dust effects; and no consideration of synergic effects between the active substance and bee pathogens (Kindemba, 2009).

16.5 Lessons on the governance of controversies

The lessons developed in the present chapter are based on the case study of Gaucho® but may be relevant for governance of the controversy about systemic insecticide risks in general, in France and in Europe.

The most important factor fuelling the debate in France was increasing mutual mistrust between the parties involved, arising, in part, from a failure to generate and ensure access to information. This reinforces one of the lessons from the first volume of *Late lessons from early warnings* (EEA, 2001), namely the need to 'Provide adequate long-term environmental and health monitoring and research into early warnings'.

Initially, various local/regional government services confirmed the clinical signs described by beekeepers (CNEVA, 1997; AFSSA, 2001; Chambre d'Agriculture de la Vendée, FDSEA de la Vendée and FDSEA des Deux-Sèvres in Alétru, 2003). However, beekeepers have stated that on several occasions they could not access raw field data held centrally by the Ministry of Agriculture. Thereafter, beekeepers viewed further initiatives of the DGAL with suspicion, criticised the 'paralysis by analysis', the diversion of the 'official' research towards too 'complex' subjects and their exclusion from creating the research protocols. The Ministry of Agriculture did, however, finance two post-doctoral projects for two years, which made an important contribution to the work of the CST.

Another important lesson from the first volume of *Late lessons from early warnings* is the need to 'Ensure the use of "lay" and local knowledge, as well as relevant specialist expertise in the appraisal' (EEA, 2001) to ensure a correct understanding of the problem and to deal with conflicting social processes.

The first volume highlighted the importance of rigorous monitoring to identify early warnings and the need to provide sufficient funding to achieve that goal. We could add that the experience of honeybee colony decline in France shows that **bodies performing monitoring studies should have the trust and acceptance of the field actors directly concerned** (in our case, beekeepers and farmers). From the first alert, particular attention should have been given to the professional beekeepers, who have daily experience and good knowledge of the land and of the insects they breed. Where key actors are not properly engaged, the monitoring process becomes discredited and ineffective. For example, the actors directly concerned may cease to participate or the monitoring protocols may be poorly designed, leading to a focus on non-essential features of the

([47]) France maintains its ban on sunflower and maize seed-dressing.

problem. Furthermore, extensive local observations from such actors can help understand variability in clinical signs and the reasons that different circumstances produce varying exposures and effects.

Ensuring that relevant specialist expertise is involved is also of key importance to increase trust and the quality of information. As the current case exemplifies (see Section 16.3.2 above), there is a need to ensure that specialists involved in risk assessments are selected based on competence and transparent procedures. Furthermore, the risk assessment process should involve the relevant disciplines and the experts should have the relevant research experience (i.e. articles on the topic, published in peer-reviewed journals). For example, members of the official commissions assessing the evidence in risk assessment of honeybees must include more honeybee specialists than, for example, plant specialists. Where a causal pattern is being researched, balance should be ensured among the different fields of specialisation (such as honeybee diseases, toxicology and climate) because specialists in, for example, diseases are more prone to produce conclusions on diseases than on ecotoxicological aspects.

Governance of controversies about chemical risks must therefore be guided by a continuous focus on promoting mutual trust between the stakeholders, including scientists and policymakers.

With that goal in mind, **eight new lessons can be drawn from the present case study**.

First, governance must focus on identifying potential properties of new chemicals and anticipating surprises that may arise from them. It is unwise to assume that methods used to assess the risks of existing technologies are also appropriate for assessing risks from new technologies ([48]). In the present case, even though the nature of the risk posed by systemic pesticides was different from the one associated with sprayed insecticides, the same assessment tools (LD_{50} and HQ) were used for authorisation, without any assessment of their adequacy for new patterns of exposure and effects. The lesson learned is: **when dealing with new technologies, verify whether the methods already in use for risk assessment are relevant, given the specific new properties and characteristics of new risks**.

A second lesson deals with the adequacy of the present standardised tests regarding the assessment of pesticide risks to honeybees. The lesson is: **develop new tests to assess sublethal effects of pesticides, their chronic effects and their effects on the colony**.

The laboratory studies measuring imidacloprid's sublethal effects or chronic lethal effects showed a range of different results. One important reason for this diversity is the lack of standardised protocols for such studies, resulting in each laboratory using different approaches. From one study to another, several factors can be a source of variability (the subspecies of honeybees used, their age, the temperature, the fasting time, etc.). Each of these parameters can induce differences in the results. For example, it has been shown that there is considerable genetic variation between colonies regarding the immune responsiveness of colony members (Evans and Pettis, 2005). Alaux et al. (2009) also found differences between the responses of colonies to their experiment, despite the fact that these colonies came from the same location and were exposed to the same environment. They suggested that genetic background and colony history (pathogens, food sources) can produce these differences.

The differences between existing protocols are producing results that are difficult to compare. To address sublethal and chronic lethal effects of pesticides on honeybees, new official directives using standardised protocols are therefore needed.

Today, field experiments play a decisive role in determining the risks of a substance. However, the complexity of environmental factors and of bee colonies themselves means that the same conditions can never be reproduced. A particular combination of such factors arising in a field experiment cannot be considered representative of some kind of 'average' environmental conditions to which honeybees or other organisms could be exposed.

After 2004 a group of honeybee experts appointed (but not funded) by the French Ministry of Agriculture was tasked to develop new tests for honeybees for inclusion in risk assessment practice. This group had proposed several draft tests to the Commission for Biological Essays, charged with validating methods for risk assessment in France.

In Europe, until 2010, honeybee tests followed the European and Mediterranean Plant Protection Organisation (EPPO) 2001 norms (OEPP/EPPO, 2001). The International Commission on Plant-Bee

([48]) This is a very old lesson, developed in detail in the analysis of DDT by Dunlap (1978).

Relations (ICPBR) proposed a modified honeybee risk assessment scheme for systemic pesticides and changed the test guidelines for semi-field and field studies. Both have been submitted to EPPO for consideration (Thompson, 2010). The modified risk assessment scheme has been adopted as EPPO norm in 2010 (OEPP/EPPO, 2010a, b).

However, the process of revising this norm failed to significantly change the risk assessment pattern. The 2010 norm still does not consider sublethal and chronic effects properly. Furthermore, standardised laboratory tests are still missing for chronic and sublethal effects. Therefore, the European Commission has mandated the European Food Safety Authority (EFSA) to create a working group to assess the current risk assessment scheme.

The third lesson is not to underestimate the resources needed to implement policies. The case of Gaucho® revealed the French administration's difficulties managing the authorisation of new pesticides. Policymakers need to **ensure adequate personnel (in number and competence) and financial resources to design efficient regulatory procedures for risk governance and thus reinforce their ability to manage risks effectively**.

The fourth lesson is that **the independence and competence of the experts on the issue at hand must be assured, as well as complete transparency of the research process**. This lesson refers to researchers working both in private and in publicly funded structures.

Publically funded researchers can be also at risk of conflicts of interest. First, the low funding of public research can mean that some laboratories are obliged to find external sources of funding (including pesticide-producing companies). Second, some public researchers may also be consultants for the chemicals industry (e.g. addressing the effects of certain substances on honeybees or other subjects such as the development of anti-mite products against *Varroa jacobsoni* for companies which are also producing insecticides used in crops visited by honeybees).

Conflicts of interest can be financial, with the funding potentially influencing a researcher's work in favour of the funder. They can also be intellectual, where the prior commitment of a scientist to a particular world view prevents him or her seeing other perspectives. However, even if no scientist is 'completely free' of subjectivity, some strive to be as impartial as possible. All the conditions for them to be able to do so must be institutionally insured.

Furthermore, building a clear framework for their expertise, which reduces the possibility of selective use of information, of avoiding responsibility or of ambiguous statements, could reinforce the legitimacy of expertise and diminish its potential for generating controversies.

Research policies and funding should be balanced between two core goals: science explicitly targeting the development of knowledge with commercial purposes (resources for the 'knowledge economy'); and science targeting the development of socially valuable knowledge (resources for the 'knowledge society'), such as knowledge on health and environmental risks. The first kind of science can draw largely on private funding. The second type of knowledge requires publicly managed funding and a particular status for the researchers involved, ensuring the 'highest possible level' of independence from vested interests and institutional pressure. Research developed in public structures can complement the evidence on chemical risks produced by the industry pursuant to existing regulatory frameworks.

In addition, the contractual relationship between industry sponsors and public or private researchers of risk could provide for a legal guarantee that, for example, findings will be published regardless of their content.

Industry dossiers that support the authorisation of chemicals must be transparent. External parties should be allowed to scrutinise the dossiers and the original studies, contributing to content and to the overall quality of the dossier. The capacity of different stakeholders to provide comments should be balanced, thereby preventing the most powerful stakeholder from capturing the process with repeated comments. Complete information on the assessment of health and environmental risks should be easily available to both scientists and NGOs, and opportunities to comment should be created and stimulated. One option could be Substance Information Review Forums, similar to the Substance Information Exchange Forums organised in the framework of the REACH Regulation. To create real opportunities for review, the original studies on which risk assessments are based should be available through a cost-free database. Such a library could be also useful for cases where doubts arise about the risks of a substance after is has been authorised.

All researchers, private or public, publishing or involved in regulatory risk assessments should communicate their conflicts of interest. This is already the case in many situations but these declarations should also be readily available to the public (e.g. on the internet). Researchers should not be involved in evaluating the risk of pesticides produced by the company financing them or their laboratories.

The fifth lesson is: **be aware that the social quality of the scientific information you communicate in the debate determines your public trustworthiness**. The present case study showed major deficiencies in the communication of scientific information by Bayer and by certain administrative services of the French State, contributing to the distrust of other stakeholders and intensification of the debate. We have six recommendations for the social quality of information communicated in a contested policy process:

- be reliable — base your arguments on all available scientific knowledge;
- be robust — answer criticism instead of ignoring it;
- be complete — do not ignore the information produced by other stakeholders, especially those contradicting your own views;
- have a discourse relevant for the issue under debate (e.g. regarding the particular clinical signs or the geographical area evoked), instead of referring to general issues only distantly related to the problem addressed;
- be logical, do not contradict yourself except if you change your views and you explicitly recognise this;
- ensure the legitimacy of your sources (make appeal to competent researchers, who do not have conflicts of interests) (for further details, see Maxim and van der Sluijs, 2007).

The sixth lesson is that **structures responsible for assessing the scientific adequacy of applications for marketing authorisation should develop clear and standardised scientific quality criteria to enable existing studies to be evaluated and compared**.

All the existing literature, including scientific papers, should be taken into account in risk assessments and the scientific quality of the data submitted by the industry should somehow be assessed. An important issue is the balance between the burden of proof (i.e. who has the responsibility to produce evidence for decision-making on risks) and its credibility. The selection of valid studies (e.g. for obtaining marketing authorisation) should be based on uniform and clear criteria of scientific quality, not on some unjustified 'expert appreciation' of their relevance. Lack of precise criteria for evaluating the quality of a study can lead to arbitrary or subjectively justified exclusion of certain studies from the risk assessment process. This exclusion can potentially have a decisive influence on the final result.

In addition to existing practices for the quality of the laboratory work, criteria for evaluating the scientific quality of studies should be established. Good Laboratory Practice (GLP) standards ensure a framework in which laboratory studies are controllably planned, performed, monitored, recorded, reported and archived. However, the GLP certification only provides guarantees about the transparency and the traceability of the laboratory work. It does not guarantee the scientific quality of the study. For non-standardised tests, GLP does not warrant, for example, that the protocol chosen for a study adequately takes into account the biology and the behaviour of the studied organism or that the results are correctly interpreted. However, whereas new patterns of risk need to be assessed, novel tests that are not yet standardised are increasingly needed.

The seventh lesson deals with multicausality: **prioritise the potential causal factors and address them separately before assessing potential correlation or synergies among them**. Honeybee losses can be influenced by many factors but this should not become an excuse for not dealing with particular clinical signs and particular causes. Action should not be hampered because several potential causes are involved. On the contrary, potential causes have to be prioritised before being addressed. The different causes could play different roles, e.g. some might be 'primary' (i.e. influencing the expression of other causes), whereas others may be 'secondary' (e.g. immunodepression due to pesticides could favour diseases, as was shown for imidacloprid and Nosema) (see also Maxim and Van der Sluijs, 2010).

The discourse on multicausality is only apparently contradictory with the discourse on the risk of Gaucho® to honeybees. Thus, the fact that many factors influence honeybees **all over the country** does not contradict the fact that Gaucho® posed a risk to honeybees **in Gaucho®-treated extensive sunflower and maize areas**. It is obvious that some causes can mainly act in some geographical areas and other factors can be present everywhere in a country. Certain factors could act at particular moments of the year (e.g. during the summer), whereas others could act throughout the year.

In choosing which factor to focus research on first, considerations such as feasibility, potential to reduce the final effects, and co-benefits (e.g. reduction of social conflict) need to be taken into account. Investment in research, to improve understanding of synergistic effects between low doses of systemic insecticides and other factors like diseases, seems important for addressing losses of bee colonies.

The eight lesson is: **build the regulatory background needed to protect early-warning scientists**. The case of Gaucho® raises questions about science's role in democracy and about the resources scientists receive from society. There are many critics of science but how many also address society's obligations towards scientists? How much freedom of thought and responsible action are science professionals institutionally given in such conflicting cases? How does society recognise and provide legal protection to early warning scientists?

Although the impacts of pesticides are important and have high social relevance, generalised social conflict associated with this issue is likely to discourage scientists from working on the subject.

In the European 'knowledge society', democratic production of knowledge should benefit from institutional structures favouring scientific accountability (based on sound peer review and validation) and the freedom of scientists to pursue their work independently on socially sensitive issues. If science is to continue to inform decision-making, open discussion and criticism, respectfully expressed, is to be encouraged. Misuse of scientific results to support predetermined conclusions, and actions that provoke anxiety and psychological pressure are unacceptable (see also Gleick, 2007).

16.6 Conclusions and prospects

Imidacloprid seems to be a substance particularly 'fit for the precautionary principle'. The effects on living beings are highly variable, both for honeybees (the lowest oral LD_{50} is 21 times lower than the largest LD_{50}, a factor of 40 separates the lowest and largest contact LD_{50}s and a factor of 1 000 separates the LOECs for chronic toxicity) and for other organisms, for example wild bees (Tasei et al., 2000; Morandin and Winston, 2003; Desneux et al., 2007; Colla and Packer, 2008; Mommaerts et al., 2009). Calculated half-lives of imidacloprid range from 83 days to 1–2 years.

Imidacloprid's persistence in soil is affected by various factors, including temperature, soil composition and whether the field is cropped or not (Canadian Council of Ministers of the Environment, 2007). It is thus plausible to say that the risks of imidacloprid are dependent on a specific assembly of environmental factors, such as temperature, humidity and soil composition. Furthermore, more than one study failed to find a dose-effect relationship between imidacloprid and chronic effects (Suchail, 2001; Schmuck, 2004). Given this variability, it seems likely that some of the effects of Gaucho® are **uncontrollable**.

The present chapter focused on the **social** consequences of this diversity of ecotoxicological effects. It is interesting to find that a diverse ecotoxicological portfolio allows each stakeholder to identify their own 'scientific arguments' and use them for defending opposite positions in the debate.

Declining honeybee colonies have been reported in several European countries (e.g. Belgium, Italy, Portugal, Germany, the Netherlands and the United Kingdom) and have sometimes been related to seed-dressing insecticides (CARI, 2003; Panella, 2001; Ministério da Agricultura, do Desenvolvimento Rural e das Pescas, 2000; COLOSS, 2009). The European Parliament has officially acknowledged the issue since December 2001, when a resolution dealing with the production and marketing of honey was adopted (European Parliament, 2001). It states that: 'extremely serious damage has been caused to bee populations in several Member States by systemic insecticides with extremely long residual activity periods used in arable seed coatings, which have led to the mass poisoning of colonies.'

The precautionary principle has been applied in other European countries for seed-dressing insecticides. Imidacloprid, clothianidin, thiametoxam and fipronil have been temporarily banned in Italy, on oilseed rape, sunflower and maize seed-dressing. A research programme (APENET) has been started to improve understanding of relationships between these active substances and the honeybee losses found in this country. APENET found that after the ban, the number of reports of high mortality during spring decreased from 185 cases in 2008 to two cases in 2009 (Il punto coldiretti, 2009). The ministry decided on 14 September 2009 to extend the ban until 20 September 2010 (Ministero della Salute, 2009) and then until the 30 June 2011 (Ministero della Salute, 2010). Italian researchers found a clear indication that honeybees were killed by the dust emitted during sowing neonicotinoid-coated maize in conditions of high humidity (Marzaro et al., 2011).

In Slovenia, clothianidin, thiametoxam and imidacloprid in oilseed rape and corn seed treatment have been successively banned, reapproved and then banned again between 2008 and 2011.

In Germany, eight insecticidal seed treatment products with the active substances clotianidin, thiametoxam and imidacloprid were temporarily banned on maize in May 2008 and the bans were renewed for February 2009 (BVL, 2009). In January 2011, certain formulations of the three active substances were suspended, whereas others were authorised in agricultural uses (BVL, 2011). Germany lifted the suspensions except for the use of the neonicotinoid clothianidin in corn seed-treatment (EPA, 2011).

Since 2006, American apiaries have reported 'Colony Collapse Disorder', where colonies are suddenly lost (MAAREC, 2011). Because the clinical signs of disappearing adult honeybees recalled the clinical signs found by French beekeepers, the popular and scientific media — rightly or wrongly — drew parallels with honeybee colony decline in France. Clearly, before any conclusions are drawn, the specific characteristics ('fingerprints') of the clinical signs and their spatial and temporal patterns must be properly compared.

There is growing evidence in some European countries of parallel declines in pollinators and pollinated plants (Biesmeijer et al., 2006; Vaissière, 2005). In some cases, such as China's Sichuan province (Newsweek, 2008), honeybee declines have forced farmers to pollinate fruit trees by hand. Can Europe afford this?

Domestic honeybees are managed by humans and represent a source of revenues. Much less is known about other species. The role of the honeybee as a bioindicator for the state of the environment was highlighted during the debate in France. A study published in the journal *Nature* (The Honeybee Genome Sequencing Consortium, 2006) found that honeybees tend to respond faster than other insects to environmental pollution. It seems that the size of the major detoxifying gene families is smaller in the honeybee, which makes it unusually sensitive to certain pesticides; honeybee losses can be interpreted as an 'alarm bell' of harm to other entomofauna and indirectly to plants, birds and other species.

Our case study highlights the importance of ensuring scientists' independence (which is never absolute but varies significantly). Knowledge of risks can be limited by a number of factors: funding constraints, which necessitate the need for private sector resources; a dearth of research positions in toxicology and eco-toxicology; or assessing the quality of the research by institutional rather than scientific criteria.

Social concerns are essential to establishing a relevant research agenda. As pollinators, honeybees have an ecologic impact on the survival of plants in the wild. But they have important impacts on people, most notably the economic value of free pollination of many fruits and vegetables.

Table 16.1 Early warnings and actions

1991	First authorisation of Gaucho® in France, for sugar beet seed-dressing. Adoption of Council Directive 91/414/EEC
1993	Authorisation of Gaucho® for sunflower seed-dressing
1994	First use of Gaucho® in sunflower seed-dressing First clinical signs observed by beekeepers, during sunflower nectar flow. Analysing all the potential factors involved, beekeepers suspect Gaucho® of harm to their apiaries
1995–1997	Bayer conducts several studies on the risk of Gaucho® for honeybees. All report absence of harm. Greater declines in honeybee colonies are reported. At the same time, the areas growing Gaucho® seed-dressed sunflower are also rapidly increasing
1997	During an important meeting with representatives of Bayer and the Ministry of Agriculture, beekeepers publicly point to Gaucho® as cause for observed massive honeybees' losses. The first report of the Commission for Toxic Products is published. It recommends further research
1998	The first research programme involving publicly funded researchers detects imidacloprid in sunflower nectar and pollen. RégentTS® is suspected of contributing to the clinical signs in honeybees. On 17 December, more than 1 000 beekeepers demonstrate in Paris, in front of the Eiffel Tower, demanding a ban on Gaucho®. In the apiaries affected, sunflower honey yields 30–70 % below normal potential are reported
1999	In January, the Ministry of Agriculture decides to ban Gaucho® in sunflower seed-dressing for two years, applying the precautionary principle. The conflict shifts to court, as Bayer challenged the ministerial decision in the administrative court of Paris (March 1999). The UNAF defends the Minister's decision in court
2000	In response to new scientific findings detecting imidacloprid in maize pollen and confirming high persistency in soils, beekeepers demand to ban imidacloprid for all uses
2002–2003	Intoxication episodes severely affect several thousand hives; residues of fipronil are found in dead honeybees
2004	The Minister of Agriculture temporarily bans Gaucho® in maize seed-dressing and RégentTS® for all agricultural uses
2005–2007	French beekeepers report cessation of high summer mortality. Colony recovery is gradual but winter losses vary annually
2009	Scientific publication proving synergic effects between imidacloprid and Nosema
2010	UNEP publishes report on global honeybee colony disorders and other threats to insect pollinators (UNEP, 2010)
2011	French/German beekeepers ask EEA to consider bees as sentinel species for their ecosystems (EEA, 2011)

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Panel 16.1 The Bayer CropScience view on Maxim and van der Sluijs 'Seed-dressing systemic insecticides and honeybees

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The authors' efforts to analyse the challenge for democratic governance of controversies on chemical risks are commendable in their aims. There are, however, shortcomings in the focus they chose. Democratic governance is a complex matter. It requires looking at the root causes of societal and political reactions and to separate them from emotional and intellectual forces involved. Moreover, policymakers are often under pressure to take rapid decisions: thus as long as causal patterns are far from clear, all potential ones should at least be addressed.

The publication focuses on chemical governance in response to bee colony losses in France. The insecticidal seed treatment Gaucho® is taken *a priori* by the authors as THE key cause of these losses. This approach can not arrive at a balanced conclusion since it fades out numerous scientific papers that cover the multiple factors contributing to bee losses (such as bee diseases, habitat loss and with that loss of bee feeding-grounds, changing agro–ecosystems, including due to economic and trade reasons, or unfavourable climatic conditions that add stress on honey bee health). The authors also omit to consider literature (Rivière-Wekstein, 2006) that covers the sum of the socio-political, economic and other drivers that led to the suspension of Gaucho® in France. This would, however, have been an essential source when undertaking this research, especially in the context of governance.

Bee losses were first attributed to imidacloprid in France during the 1990s. They were not related to specific product incidents. Rather the product market introduction coincided with a time when bee health issues had increased. Later, an accident with another neonicotionoid insecticide occurred in Germany which was attributed to an inappropriate quality of the seed treatment process. This was very regrettable, although lessons were learned and resulted in enhanced mitigation measures to prevent reoccurrence. Due to both these situations much research — partly pioneering new testing designs was undertaken. As a consequence more is known today about bee safety of the neonicotinoids.

For some years now, the majority of researchers have highlighted the multi-factorial nature of bee colony losses. A series of long-term, large-scale monitoring programmes confirm these findings. They have been conducted in Belgium, France, Germany, the US and other countries. In these programmes, exposure to pesticides was measured as well as colony health and safety. None of them have found a correlation between colony losses and exposure to neonicotinoid seed-dressing products (Chauzat et al., 2009, 2010; Nguyen et al., 2009; Genersch et al., 2010).

Bayer CropScience is committed to finding solutions to enhance honeybee health, e.g. by providing Varroa mite management products including potential new treatments, and bee safety, e.g. by ensuring the sustainable use of its pesticides through research and promotion of 'bee-responsible' farming practices. When evaluating new pesticides (this costs about EUR 250 million per compound) prior to market release we follow legal requirements and the spirit of precaution in a way that is as practical and responsible as possible; we also acknowledge that perceptions will vary among stakeholders of what constitutes an acceptable level of precaution, depending on their knowledge, perspectives and interests. The positive tension between innovation and precaution we see, continues to drive both technological progress and the move towards enhanced pesticide regulation — to the benefit of agriculture, the consumer and the environment. This is what was generated through the Gaucho® case, especially in the context of bee safety. Suspending products may be helpful in some instances. It does however bear the risk of stopping innovation if it is not handled carefully, thus being made reversible — should new data confirm the lack of plausibility of earlier decisions.

From field observation of aphids, we were already able to deduce, before the first registration of Gaucho®, that bees would not be affected by systemic residues in treated sunflowers. Laboratory tests had shown that aphids are ten times more sensitive to Gaucho® than bees. Despite treatment of seeds with Gaucho®, aphids were observed in the field re-invading sunflower plants before blooming, so it was logical to conclude that there would no longer be effects on bees either at the time of blooming. Since its registration in the early 90s, Gaucho® has met all post-registration re-evaluation requirements and NO evidence of a causative link between Gaucho® use and bee colony losses could be found. (e.g. Faucon and Chauzat, 2008; Nguyen et al., 2009). In addition, large-scale monitoring programmes run under field conditions during the

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post-authorisation period confirmed the original findings of 1998 (no causative link to Gaucho®) of the ACTA monitoring programme (Association de Coordination Technique Agricole).

Gaucho® continues to be registered for use in sunflower crops in various countries, including Argentina, Australia, Bulgaria and Croatia. In none of these countries have bee colony losses been reported in connection with sunflower growing (Neumann and Carreck, 2010; Ivanova and Petrov, 2010; Tlak Gajger et al., 2010). During the years following the suspension of Gaucho® in France, bee colonies have continued to suffer losses (e.g. Faucon and Chauzat, 2008; AFSSA, 2009; Chauzat et al., 2010b). According to a statement made in November 2007 by the then French Minister of Agriculture, Michel Barnier to the National Assembly bee losses were also observed in regions where Gaucho® had not been applied.

We are thankful for the opportunity to share our view here with various stakeholders. Further information on the subject can be found in Bayer's 2011 publication on 'Honey bee care: Challenges and solutions' http://www.bayercropscience.com/bcsweb/cropprotection.nsf/id/EN_Bee_Health_Crop_Protection_2010/$file/Honey_bee_care.pdf.

See the full comprehensive review, including additional references:
http://www.eea.europa.eu/publications/late-lessons-2/bees-insecticides-debate.

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Panel 16.2 Response to the Bayer Cropscience (Richard Schmuck) comments on the chapter

Laura Maxim, Jeroen van der Sluijs

Mr Schmuck insists on how complex and uncertain things are and on how policymakers are taking decisions under pressure. However, the decision to ban Gaucho® was taken in France about five years after the first clinical signs in bees and two years after the public boom of the controversy — for sunflower. The corresponding delay for maize was ten, respectively seven, years. The word 'rapid' does not seem adequate to us for these time frames.

Further in the text, these same policymakers (Mr Barnier) are subsequently quoted in Mr Schmuck's text as legitimate and reliable sources. Should one understand that policymakers 'act under pressure' when they apply the precautionary principle as they did in banning Gaucho®, and that they are 'good policymakers' when they see reality as being too complex to take a decision but actually decide to maintain the status quo?

The speech of Mr Barnier is, by the way, perfectly reasonable, stating that honeybees' losses are not all due to only one factor (indeed, nobody ever claimed that one factor causes all honeybee losses!). He also says that several factors influence honeybees, and that all these factors do not act at the same time and at the same place, which are truisms. The fact that honeybee losses can be due to Gaucho® is not at all contrary to the fact that honeybee losses can also be due to diseases or lack of food, just as human beings can die of many causes, such as car accidents, diseases or cancer. This is not an argument for not trying to limit car accidents or treat cancer, just as the fact that many factors can influence honeybees is not an argument for not dealing with Gaucho®.

Multicausality cannot become an argument for avoiding dealing with specific causes, or for avoiding establishing priorities among causes and addressing them. There is clear value in prioritising those causes that are easier to control. For example, it is much more difficult to address climate change than to limit the use of a specific pesticide.

The phrase 'The insecticidal seed treatment Gaucho® is taken *a priori* by the authors as THE key cause of these losses' is a blunt misrepresentation of our text, Mr Schmuck then arguing against this misrepresentation. If read carefully, our text is precise: 'In this chapter, we present the historical evolution of the evidence regarding the risks of Gaucho® for honeybees in sunflower and maize seed-dressing, and analyse the actions in response to the accumulating evidence regarding these risks.' Our subject is not all honeybee losses, in France or in the world, in all times. We address honeybee losses 'in sunflower and maize areas', from the start of the controversy in 1994, to the political decisions to ban Gaucho® in sunflower and maize seed-dressing, in 1999 and 2004, and analyse the developments in science and society that ultimately lead to these decisions. As we have also specified in our chapter, 'many factors can play a role in the state of honeybees and pollinators more generally'.

We disagree with Mr Schmuck that the book of Gil Rivière-Wekstein can be considered an 'essential source'. Its author is the director of a firm providing consultancy for companies, who has produced papers on diverse subjects not related to honeybees such as USA Elections 2004: eleven democrat candidates facing George W. Bush and Enron, the crush of an empire.

More generally and beyond this particular reference, the length of our paper did not allow us to include extensive reference to several insightful and relevant books written in France on the subject of Gaucho® by journalists, policymakers or NGOs, including:

- Cicolella, André and Benoît-Browaeys, Dorothée, 2005. Alerts on health: experts and citizens face to private interests ([49]).
- Nicolino, Fabrice and Veillerette, François, 2007. Pesticides: revelations about a French scandal ([50]).

([49]) Alertes santé : experts et citoyens face aux intérêts privés.
([50]) Pesticides : revelations sur un scandale français.

Panel 16.2 Response to the Bayer Cropscience (Richard Schmuck) comments on the chapter (cont.)

Massive bee-poisoning events from dust emissions during sowing of maize coated with neonicotinoids such as the one in 2008 in Germany are not incidents or accidents but have continued to happen since in many countries. The Italian moratorium on seed dressing with neonicotinoids lead to a reduction of the number of such reported poisoning incidents from 185 beekeepers (6 328 hives) per year to 3 beekeepers per year, these 3 remaining cases could all be linked to illegal use of neonicotinoid seed dressing (APENET) ([51]).

The loss of 2 500 bee colonies during maize sowing in the Pomurje region in Slovenia in April 2011 demonstrates that the prescribed mitigation measures are still insufficient (Drofenik, 2011).

A series of recent field trials by Girolami's group (Marzaro et al., 2011; Girolami et al., 2012; in press) has demonstrated that even when all mitigation measures are implemented such as deflectors and improved coatings, the pneumatic maize sowing machines still produce a ellipsoidal toxic cloud of dust particles of 3 meter high and 20 meter wide that is acute lethal to honeybees that cross this cloud on their flight. A single flight though that dust cloud showed to provide an average dose of 300 ng imidacloprid per honeybee.

The use of 'Gaucho®' in sunflower crops in countries such as Argentina and Australia cannot be compared to its previous use in France. The concentration of imidacloprid presently used in the 'Gaucho®' product is much lower than it was in France in the 1990s. The two situations are therefore not comparable, since that lower doses of imidacloprid lead to lower exposure of bees, and might have more long-term than short-term effects. As well, it can be hypothesised that national characteristics such as soil, climate, relative attractiveness of the plants for honeybees etc. could significantly influence the imidacloprid uptake from soils and its availability to honeybees.

It seems that Mr Schmuck used extrapolation from aphids to honeybees for being 'able to deduce, before the first registration of Gaucho®, that bees would not be affected by systemic residues in treated sunflowers'. He does not specify if this extrapolation was based on scientific publications or on some sort of 'expert judgment'. So we have searched in the Web of Science — Current Contents database (including 8 500 major journals and 9 000 web sources) with the key words (in topic): aphid AND honeybee (variant: honey bee) (+ AND extrapolation). Only two relevant records were found (Matsuda, 2009 and Guez, 2003), which did not exist at the time when the extrapolation had apparently been done before the registration of Gaucho®. These publications rather support evidence against this extrapolation.

Moreover, several important differences between honeybees and aphids raise doubts about the relevancy of such an extrapolation:

- looking at aphids behaviour on sunflower plants only considers short-term effects but ignores the long-term effects. Indeed, honeybees store pollen and nectar in the colony and can consume them on the long run. The honeybees could repeatedly ingest the contaminant on the long term, leading to chronic effects.
- different ages of individuals in a honeybee colony vary in their sensitivity to insecticides. Even if foragers (collecting pollen and nectar in the fields) are not affected, other honeybees in the colony could be intoxicated (nurses, larvae)
- all the aspects related to the complex social organisation of honeybees are missing in aphids
- observing aphids cannot account for synergic effects of neonicotinoids on the honeybees colonies, as those highlighted by Cummins (2007), Alaux et al. (2009), Videau et al. (2011) and Pettis et al. (2012) for imidacloprid and the pathogen Nosema.

We are astonished that the effects in aphids were assumed to be similar to the effects in honeybees. Such extrapolative assumption would indicate lack of selectivity of imidacloprid on target and non-target species and should have, on the contrary, raised worries about the potential effects on honeybees.

([51]) http://www.bijensterfte.nl/sites/default/files/Piotr_Medrzycki_-_Apimondia_2009.pdf and http://pub.jki.bund.de/index.php/JKA/article/view/146/131.

Panel 16.2 Response to the Bayer Cropscience (Richard Schmuck) comments on the chapter (cont.)

Several other sources cited by Mr Schmuck merit consideration. First, it is normal that different signs and potential causes will be identified depending on the protocol used and the specific situation studied. Ivanova and Petrov (2010) and Tlak Gajger et al. (2010) employed surveys that did not address summer mortalities but winter colony losses. In both papers, the causal investigation used only beekeepers' opinions but did not undertake chemical analysis. The Bulgarian survey looked at 1.3 % of beekeepers, the Croatian one at 3.6 %. One of the two papers, Ivanova and Petrov (2010), refers to sunflower, mentioning: 'untypical behaviour of honeybees in some regions of north Bulgaria manifested by avoiding flowering sunflower was also reported'. No indication is given about how this behaviour had been measured or observed, for example whether it was apparent in diminishing sunflower honey production or behavioural signs. The paper mentions that 'the problem appeared to be more serious for areas with cultivated fields and grasslands due to crop protection activities, such as the north-central and north-eastern parts of Bulgaria….'

Neumann and Carreck (2010) is another undue reference for addressing honeybees' intoxication on sunflower crops, as sunflower is not referred to at all. The paper notes, however, that 'These interactions are particularly worrying, as sub-lethal effects of one driver could make another one more lethal; for example a combination of pesticides and pathogens' (p. 3).

Another paper by Bacandritsos et al. (2010), which was not cited in Mr Schmuck's response, refers to summer losses in Greece. This paper reports results of chemical analysis of honeybee tissues showing that 60 % of the samples analysed contained imidacloprid, in an average concentration of 27 ng/g tissue. A high level of virus and N. ceranae infection accompanied this contamination. Also, the study by Krupke et al. (2012) shows a link between clothianidin coated maize and bee mortality in spring in the same area.

Some of the authors quoted by Mr Schmuck have recently published papers on pesticide loads in France (Chauzat et al., 2010). Imidacloprid was found to be widely available to honeybees. The average levels of imidacloprid found in pollen is 0.9 ppb (with a maximum of 5.7 ppb). These results are in line with results published four years earlier by Chauzat et al. (2006), who found that the most frequently found pesticide residue was imidacloprid (identified in 49.4 % of the samples), followed by one of its metabolites, 6-chloronicotinic acid (in 44.4 % of the samples). At least one of these two molecules was present in 69 % of the samples. Statistical tests also showed no variance in concentrations between sampling locations, meaning that imidacloprid is present *everywhere* in the 5 sites considered, and that it is present in pollen loads *throughout the year*, with a maximum presence during July–August but comparable concentrations during spring and autumn.

The presence of imidacloprid in pollens all through the year, even long after the treatment moment, shows that honeybees are exposed all through the year, and not only during the agricultural season. This could also be an indication that imidacloprid is so persistent that it might be uptaken in non-treated crops or wild plants. Indeed, imidacloprid is currently banned in France for seed-dressing of sunflower and maize but it is still used in seed-dressing for sugar beet, wheat and barley. It is also authorised to treat fruit trees such as apricot, peach, pear, quince, apple and plum trees, in products for disinfecting storage facilities, shelters for domestic animals etc.

In conclusion, our chapter responds to one of the main objectives of the present report, which is to describe and analyse cases of application of the precautionary principle and reflect on what can be learned from these cases. The partial French ban of Gaucho® in sunflower and maize seed-dressing is one such explicit application of the precautionary principle.

See the full answer at: http://www.eea.europa.eu/publications/late-lessons-2/bees-insecticides-debate.

Panel 16.2 Response to the Bayer Cropscience (Richard Schmuck) comments on the chapter (cont.)

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17 Ecosystems and managing the dynamics of change

Jacqueline McGlade and Sybille van den Hove

A decade after Rachel Carson's *Silent Spring* was published, describing the toxic legacy of the twentieth century, Annie Dillard in her Pulitzer prize winning book *Pilgrim at Tinker Creek*, opened up a different way of looking at the world. It presaged a twenty first century in which the global economy would be based on a more thorough understanding of nature, its functioning and material wealth. Wholly descriptive, yet increasingly relevant, her book captured the very essence of what this chapter is about: that amongst the observations which routinely help to predict the evolution of the natural world are the seeds of surprise — surprise of the unusual and surprise as a portent of future change. Our systemic failure to anticipate such surprises forms the core of this chapter. A series of case studies from fisheries, forests, savannah and aquatic systems are used to underline how early warnings about changes in these natural systems emerged but were not used.

The chapter highlights how the division of knowledge into political, disciplinary and geographic silos has led to the 'recurring nightmares' of short-term interests outcompeting long-term vision; situations where competition replaces co-operation; fragmentation of values and interest; fragmentation of authority and responsibility; and fragmentation of information and knowledge leading to inadequate solutions or even additional problems. In addition, the lack of institutional fit has often confounded the effectiveness of the stewardship of ecosystem services, and led to unexpected surprises, excessive rent seeking and high transaction costs.

Using counterfactual thinking (i.e. the dependence of *whether*, *when* and *how* one event occurs on *whether, when* and *how* another event occurs and the possible alteration of events), built around the four interconnected concepts of *planetary boundaries, tipping points, panarchy* and *resilience*, the chapter provides an analytical lens through which to explore why many of the warning signals were not seen. The chapter concludes by suggesting why ecosystems are likely to be even more at risk in the future and why we will need to observe and interpret the dynamics of both nature and institutions ever more closely if we are to avoid sudden irreversible ecological changes.

17.1 Introduction

> 'The road we have been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lies disaster. The other fork of the road — the one 'less travelled by' — offers our last, our only chance to reach a destination that assures the preservation of our earth' (Carson, 1962).

A decade after Rachel Carson called the world's attention to the dangers of industrial chemicals in her book *Silent Spring* (Carson, 1962), another writer, Annie Dillard (1974) took her readers on a yearlong investigation into nature's beauty and complexity in her Pulitzer prize winning story *Pilgrim at Tinker Creek*. Quintessentially descriptive, the book shows how close observation of nature and its inherent surprises — both of the unusual and as a portent of things to come — is vital for achieving an understanding of the resilience of ecosystems and the resources within them. Charles Keeling, dubbed the father of climate change science, followed this same approach throughout his lifetime's work on measuring the levels of carbon dioxide in the atmosphere.

Detailed observation of past forms of nature is also vital for anticipating surprises. As R. G. Collingwood (1939) argued in his autobiography, history provides something 'altogether different from [scientific] rules, namely insight'. The historian is like a woodsman compared to an ignorant traveller who might say 'Nothing here but trees and grass' whereas the woodsman says 'Look, there is a tiger in that grass'.

Memory is also an important element in determining current ecosystem structure and function (Hendry and McGlade, 1995). For example, the history and age of an individual tree determine its susceptibility to physiological shock, native disease and parasites; this generally rises with age, leading to an increased probability of accelerated death in elderly stands. However, the history of each position within a forest also has an influences on the current stand, as the state of the soil, the height of the water table, the level of nutrients are affected by the species that have grown there over previous centuries.

By combining insights such as these with detailed observations from comparative analyses of ecosystems and heuristics from the natural and social sciences, scientists have begun to build a more general theory of the dynamics of socio-ecological change across a broad range of ecosystems (Walker et al., 2006); they include lakes and wetlands (Carpenter and Brock, 2004), rangelands (Janssen et al., 2004), forests (Bodin et al., 2006) and coral reefs (Hughes et al., 2003). These developments have also highlighted just how limited many more classical scientific approaches really are for dealing with real-world situations (i.e. developing hypotheses and testing them with simple causal models validated with controlled experiments or statistical sampling). As the case studies in this chapter show, the continued dependence of many resource managers on these more traditional approaches has contributed to the catastrophic decline of some resources.

The chapter looks at how scientific evidence and advice are generated and used in policies for managing natural resources and ecosystems. Through case studies of key events, resources, important actors and institutions and the lens of planetary dynamics and resilience of socio-ecological systems, the chapter explores the reasons why the evidence was sometimes flawed, how and why scientific advice influenced or was ignored during the process of decision-making, and looks at some prospects for the future.

17.2 Data, knowledge and counterfactual thinking

Field ecologists have traditionally adopted a diversity-oriented approach to gathering data and creating knowledge. Their assessments are often based on detailed case studies using measurements of many system-specific attributes with configurational complexity (McGlade, 2003). Conversely, resource managers, have historically adopted a variable-oriented approach based on the measurement of a small number of attributes relating to global patterns emerging from surveys of a large number of cases. The two approaches represent the ends of an inverse relationship between the number of cases and variables. They represent a fundamentally different way of developing counterfactual thinking (i.e. the dependence of whether, when and how one event occurs on whether, when and how another event occurs and the possible alteration of events) and their misapplication has contributed to the catastrophic demise of some the world's key ecosystems and resources.

This section contains two case studies (Box 17.1 and Panel 17.1): the first demonstrates how a well-structured diversity-oriented approach, using close observation at carefully selected sites and correct counterfactual thinking, produced a data series which influenced the global community's thinking about climate change. In contrast, the second shows how a variable-oriented approach based on flawed counterfactual thinking and a poorly described polythetic scheme, led to the catastrophic demise of an international fishery. This second case study shows how false inferences were used to suppress early warnings leading to an unanticipated, sudden collapse and irreversible demise and highlights how ill-suited the models and observations were in relation to the complexity of the socio-ecological system; and the consequences of separating knowledge about the resource into disciplinary, community and geographic silos.

17.2.1 *Complex causality and configurations — context matters*

The diversity-oriented approach uses information about cross-scale interconnections amongst many parts of the system to produce a detailed representation of a particular ecosystem. Causation is viewed as conjunctural, or combinatorial and heterogeneous and there is no assumption that the same causal factors operate in the same way in all contexts or in all instances. Diversity-oriented analyses tend not to provide insights into causal generalisations, but rather into the validity of specific processes. This approach builds links between the detail of specific ecosystem analyses and the broad view of ecology via an understanding of complex causality and the identification of specific necessary and sufficient conditions for a particular set of interactions to influence the overall system (Hogg et al., 1989). It works best when causation is complex, where no single condition is either necessary or sufficient or when causes are sufficient only in combination. Identification of the necessary conditions for change and their detection are extremely important steps in ecosystem assessment and can have very powerful policy implications.

Few variable-oriented studies are framed in such terms. Instead, the variable-oriented approach takes a small number of dependent variables across many instances in order to identify a parsimonious set of causal variables. Causation is dealt with through simplifying assumptions about chains of association between independent variables, reflecting the inferential framework of many resource managers. The theoretical basis is an additive linear model, which relies on the fact that it is possible to assess the independent effect of each causal variable, net of the effects of all others. The assumption is that for a particular outcome, the necessary conditions need only be presence or absence.

Typically, variable-oriented analyses focus on statistical similarities and differences and inductively derive a small number of groupings where within-group differences are minimised and between-group differences maximised. These schemes are polythetic, i.e. the cases that are grouped together can differ substantially from each other for one or more attribute as long as they are similar for the majority of attributes selected by the researcher. By contrast in diversity-oriented analyses, context matters and cases are examined as configurations in which as many as possible relevant aspects as possible are looked at in the form of combinations. Such analyses concentrate on the specific features of individual cases, identifying those that are most relevant, whilst considering how those features cohere with each other as distinct types.

Polythetic schemes, typical of the variable-oriented approach widely used in resource management, violate the core principles of the configurational or diversity-oriented approach used for studying resilience and the dynamics of socio-ecological systems. The question is whether the approach adopted can make a difference in terms of being able to better understand or anticipate surprises and change.

A good example of a configurational, diversity-oriented approach with strong counterfactual thinking is the work of the climate scientist, Charles Keeling (Box 17.1). Whilst there are some sceptics who maintain that the cause of global warming is evidenced in measurements of solar radiative output, the vast majority of policymakers and scientists now agree that the root cause, i.e. human activity, can be seen in the measurements of carbon dioxide. To a large extent, this view is the result of the Keeling's work. Having built up a picture of the causal linkages between greenhouse gas emissions and human activities, he carefully chose sites where he then took precise measurements of carbon dioxide at rapid intervals over more than four decades. What he was able to show was the inexorable increase in CO_2 over that time. The Keeling Curve (see Figure 14.1) is now one of least disputed pieces of evidence of climate change. Keeling adhered to the idea that close observation of a natural phenomenon — the 'breathing of the planet' — was an essential part of understanding the dynamics of global changing.

Box 17.1 The Keeling Curve — how close observation revealed the secret of climate change

Fifty-five years ago, the young American scientist Charles Keeling began one of the most important projects in the study of climate change, recording in immense detail the changing levels of carbon dioxide in the atmosphere. Starting out in January 1958, Keeling set up his equipment on the northern slope of world's largest volcano, Mauna Loa and started a lifelong experiment that would change our view of humans on the planet.

The real story had begun much earlier, when Keeling was only 27, and had told colleagues that all the existing measurements of carbon dioxide were wrong or misleading. Recognising that no one else was really interested in taking consistent, continuous measurements of the levels of carbon dioxide in the atmosphere, he decided to take on the task himself. He had studied chemistry, but his great love was being close to nature. So he jumped at the chance to combine these two passions in a post at the California Institute of Technology.

Keeling had by then developed his own protocols and started taking measurements of CO_2 every three hours in different areas, including the roof of Caltech. He did not mind that it was not the most exciting science; collecting samples gave him the chance to do what he loved — packing up his car and family and heading off into the wilderness, camping in forests and national parks, far away from any urban areas.

He kept meticulous records of all his measurements in a series of notebooks, and it was from these that he got his first clue as to how carbon dioxide in the atmosphere was changing — work that would later see him dubbed 'the father of climate change science'.

Scientists already knew that CO_2 levels fluctuated according to the seasons and location, but they did not know why or whether there was a global base level. Keeling wanted to use his new measuring techniques to find out if there was. He and colleagues began getting measurements from carefully selected sites all around the world, including Antarctica, with the intention of making comparisons between them.

What Keeling understood from his own counterfactual thinking was that the measurement of CO_2 in the atmosphere was vital to the development of an understanding of humanity's effects on the planet. He also realised that persistence and attention to detail were essential to the success of the experiment, so whilst other scientists might have moved on to discover new phenomena, Keeling decided that he could not give up — he had to stay with it. In this sense, the science itself forced him to behave unusually as a scientist.

By 1956 he had accepted a post at the Scripps Institute of Oceanography; realising that he needed to measure CO_2 over the course of years not months he knew he had to find the ideal spot to run the experiment. The site he chose was a former US military site on the slopes of the world's largest volcano Mauna Loa in Hawaii. In the middle of a huge ocean, it was away from contamination and any sources of CO_2 which would have interfered with the measurements. Given that Keeling had to pick an initial site to represent the whole of the world, Mauna Loa observatory was probably the best choice he could have made.

In this ideal environment Keeling started his project, taking samples of air and making CO_2 measurements for the next 40 years. Each day he would venture outside and, after holding his breath, fill a specially designed flask with the incoming ocean breeze. The air would be taken back to the lab to measure its carbon dioxide content.

The result was one of the most famous graphs in science, and would become known as the Keeling Curve. It showed a jagged edge with an amazing regularity and a steep relentless rise of carbon dioxide in the Earth's atmosphere, showing the world's inability to absorb the excess carbon dioxide that human activities were producing.

Placing a temperature curve on top of this curve gave Keeling the foreboding in the 1970s of what was to come. The clean curve of the increase in carbon dioxide spoke to the magnitude of the forces at work, and a picture of all of humanity's exhausts superimposed on the 'breathing' of the planet.

What Keeling discovered is one of the few undisputed pieces of evidence in climate science. Several times he faced cuts to his funding, but always found ways to carry on. His analyser, which was installed in March 1958, collected carbon dioxide data in its original configuration until it was decommissioned in January 2006; even the original strip chart recorder operated from 1958 until 2006. Charles Keeling died in 2004 and today his son Ralph continues the work.

17.2.2 A tale of two cods

The widespread use of variable-oriented approaches in resource management has thrown up a number of problems, especially a general lack of anticipation about sudden collapses. In fisheries, a simple equilibrium model became paradigmatic during the 1960s; it was based on determining the Maximum Sustainable Yield (MSY) under different extraction rates and constant rates of birth, growth and death. The model was related to the larger literature of optimal control techniques and the calculus of variations, which had been successfully applied in theoretical physics, aeronautics, chemistry and management (Hotelling, 1931; Pontryagin et al., 1962), and then spread to economics and resource policy (Dasgupta, 1982; Clark and Kirkwood, 1986). Concerns were raised by some about the utility of MSY models (Larkin, 1977), but these early warning signals were ignored.

It was only when the northern cod (*Gadus morhua*) off Newfoundland collapsed in 1986 (Panel 17.1) that questions began to be raised about its effectiveness. The story of what happened in Newfoundland exposed fundamental flaws in the inferences being made about why the cod population was decreasing, about the roles of the scientists and fishermen in the collection of data, the development of advice and the delays in actions taken by the government. However, the comparison with what happened in Norway is just as interesting. The immediate reaction by the Norwegian government to the collapse of the Barents Sea cod was to impose a moratorium and to invest in more research. The outcomes of the two government actions could not have been made clearer when three years later the Barents Sea cod spawning biomass was bigger than it had been in twenty-five years, whilst the potential collapse of Canadian fish stock was still being covered up.

What is also interesting from the perspective of *Late lessons from early warnings* was the reaction by Norway's Fisheries Minister, Oddrum Pettersen, who said that although the warning signs were there, the knowledge to understand them was missing. As a consequence the government took precautionary actions through the moratorium and invested in research to increase knowledge about the linkages between species of fish, especially cod and capelin, and mammals in the Barents Sea. This led Norwegian scientists to develop new counterfactual thinking about the collapse of the cod stock. They believed that the large year-classes of two and three-year old cod had eaten over a million tonnes of capelin at the same time as there was overfishing of the same capelin stock. The result was a sudden collapse of the capelin, which led to the cod eating each other; the seal population, which fed on capelin, also turned to feeding on cod. At the same time a change in ocean temperatures triggered collapses in stocks in the coastal waters of Russia, Iceland, Sweden, Finland and the Faeroes and Lofoten islands.

Meanwhile in Canada, the government scientists insisted that there was no proven connection between fishing on spawning stocks and the survival of the 0-year class. Senior officials maintained that there was no evidence that fishing on spawning grounds in any way harmed the stock. In Norway such fishing was banned on the basis that although it was difficult to find the relation between recruitment and spawning stock, the scientists were convinced that there was such a relation. The Norwegians had understood that no evidence of harm is not the same as evidence of no harm.

17.2.3 Post moratorium

What lessons can be learnt from the demise of the northern cod, especially as the majority of the world's commercial fisheries are over-exploited and many resources are managed using similar models and approaches?

Fisheries management is like a black-box; it is very difficult to see how things are calculated or how things work. In the case of the Canadian moratorium, the Minister of Fisheries, John Crosbie, blamed the collapse on three main factors:

- overestimation of the stock leading to the setting of total allowable catches that were too high;
- foreign overfishing;
- devastating ecological factors.

The effects of ecological factors became myth-like, but in fact as Finlayson and McCay (1998) point out, there were some very obvious problems with these assertions which showed that the counterfactual thinking behind the assessment was deeply flawed.

First of all the stock was treated as one unit whereas it was known to be comprised of distinct populations with different migratory behaviour and patterns; not including this variability may have contributed to the overestimation of biomass (deYoung and Rose, 1993; Finlayson, 1994).

Panel 17.1 The last hunters

Jacqueline McGlade

A view from inside

In 1980, as a newly recruited scientist in the Department of Fisheries and Oceans (DFO), in the Canadian federal government, I was given the responsibility for assessing the size of the stocks of pollock (*Pollachius virens*) off the eastern coast of Canada and determining the size of the quotas. Pollock was one of the less valuable stocks, but nevertheless thousands of tonnes were landed each year. At the time, DFO was the largest employer of biologists in the public service and the second largest of research scientists and technicians; it was heavily decentralised with more than 2 200 personnel and nearly one third of the departmental budget. When the 200 nautical mile limit was declared, the offshore area accounted for one third of Canada's territory.

My task involved estimating the size of the spawning biomass, determining the distribution of potential yield in terms of catch per unit of effort by all the fleets across all age-classes. I was given a small team, a computer, historical data sets and a model, derived from the equilibrium model of Beverton and Holt, known as a Virtual Population Model, plus a few weeks of ship-time on a research vessel in the middle of the winter to complete the annual recruitment survey, an inshore programme for tagging juveniles and a genetics laboratory to determine stock structures. Estimates of catches and effort from the dockside and fleets would arrive at the Bedford Institute of Oceanography in Nova Scotia and we would quality check the data, enter the various numbers, and eventually age-biomass tables would be calculated and graphs produced for different levels of fishing mortality: the target of choice was $F_{0.1}$. — the level of fishing mortality at which the increase in yield to be obtained by adding one unit of fishing effort is 10 % of the increase in yield to be obtained by adding one unit to a lightly exploited stock.

When we went out tagging, we would talk to the fishermen about what they were observing but this was not a common practice, nor was it a regular part of the assessment for most of the stocks. Once a year, the scientists from the department responsible for groundfish would meet under the auspices of CAFSAC (Canadian Atlantic Fisheries Scientific Advisory Committee) and go over the analyses for each stock to set annual predictions of stock abundance on which to establish the total annual allowable catches and harvesting rules. I used to say that you had to leave your ego at the door, because you would often be sent out again and again to redo the analysis using new combinations of recruitment, fishing effort and mortality rates: this was the reason why it was called 'tuning'.

My colleagues had similar experiences to me, but there was always the worry especially with some of the more valuable stocks that the models were too simple to capture the complexity of the real-life situation and the mechanics of running them on the available computers were not straightforward. There was also the issue of the quality of the data: they were often out of date and even though we had an observer programme to check what was going on at sea, there was no guarantee that the fishermen were accurately recording the locations or the size of their catches. Successive ministers would say that science was the foundation of everything, and that fisheries management required a sound knowledge of the fish stocks.

Canada's northern cod

Many official reports, articles and books have been written about the collapse of the northern cod (*Gadus morhua*) in the 1980s (see especially Finlayson, 1994; Harris, 1998, Steele et al., 1992). The question is: why, with such open support and well funded research, did DFO scientists not anticipate the problem?

From the fisherman's perspective, there were signs in the 1980s that the condition of the inshore cod was deteriorating. The industry asked Memorial University biologists to review the1986 cod assessment for Newfoundland waters. Their conclusion was that the DFO assessment had seriously overestimated the size of the stock. The authors also postulated a connection between the large offshore landings and the poor inshore catches. The surprise was that they had used the same data and come out with startlingly different conclusions.

In the 1986 CAFSAC Advisory Document there were inconsistencies between the projected increases in biomass and the fact that the total allowable catches had been at least twice as high as they should have been over the previous eight years. The document suggested that something was very wrong. When the research survey results came in, pointing to an enormous abundance of cod, scientists should have realised that there was no biological means for the stock to have increased as much when there were still

Panel 17.1 The last hunters (cont.)

so few fish inshore. There was, however, one potential explanation for the increase: in the 1960s, another biologist Wilfrid Templeman had warned that if the dense schools of cod which gathered to spawn in the deep warmer waters were overfished, they would continue to concentrate but in a smaller areas. Thus catch rates might continue to increase even as the stock was collapsing. Unfortunately, DFO accepted the data as they stood.

The next year, in 1987, another external panel of experts was commissioned to write a report on the cod; this time they were given access to the DFO data and also looked at the anecdotal evidence of fishermen. The report concluded that DFO had got its figures tragically wrong (Alverson, 1987). The Chairman, Lee Alverson said that the problem had been caused by errors in interpretation of some of the survey information, compounded by a reliance on a faulty mathematical model. He said that the error had been magnified because it had taken several years to find and admit to the problem and by then the stock was already on a downturn. When asked who was to blame he pointed to the government who owned and managed the resource on behalf of all Canadians and were reticent in making effective and timely decisions. He also pointed out how little the DFO scientists knew about the biology of the species and the ecosystem in which it lived.

It was at this point that the DFO scientists came up with the idea that the absent cod inshore were trapped in warmer water, avoiding the cold intermediate layer, rather than being fished out.

Alverson's report was the first time that the government's concerns about the health of the stock were made public, yet the politicians and senior staff in Ottawa remained convinced that the ocean would continue to provide fish and raised the allowable catch level for 1988. This was a clear indication that any concerns about the health of the stock were put far behind socio-economic considerations.

In December 1988, DFO scientists in a dramatic reversal of advice proposed a fifty per cent cut in the quota for 1989.The Federal and Newfoundland Ministers knew that this would lead to thousands being out of work and bankruptcies everywhere. They decided that the consequences would be too devastating, supporting their decision by saying that the scientists had been wrong before. Moreover, there was resistance amongst some senior DFO scientists to admit that any mistakes had been made. The assistant deputy minister later published the official line: 'It appeared that the sudden, unexpected decline in northern cod during 1991 was the result not of high fishing mortality, but rather abnormal environmental conditions … which, through mechanisms not yet understood, may have led to an abrupt increase in natural mortality in the early 1980s' (Parsons, 1993).

Despite the increasing evidence that the unthinkable was happening to the cod stock, the politicians asked for more evidence. In 1989 the Northern Cod Review Panel, led by Leslie Harris, began its work. Meanwhile the inshore fishermen took the federal government to court to stop destructive fishing practices on the spawning grounds. They lost and DFO officials maintained the line that there was no evidence that fishing on spawning grounds in any way harmed the stock. By now Ottawa was already subsidising Newfoundland to the level of 2.56 billion Canadian dollars (CAD). The release of the Harris report in 1990 showed how dire the situation had become: it concluded that the reduction in quotas in 1990 would not be enough to reverse the trend of a declining spawning stock but would rather contribute to a further decline (Harris, 1990).

On the point of how had the collapse come about, Harris pointed to the disastrous advice given to managers and politicians by the DFO scientific branch. He stated that the scientists 'lulled by false data signals and, to some extent, overconfident of the validity of their predictions, failed to recognise the statistical inadequacies in their bulk biomass model and failed to properly acknowledge and recognise the high risk involved with state-of-stock advice based on relatively short and unreliable data series … it is possible that if there had not been such a strong emotional and intellectual commitment to the notion that the $F_{0.1}$ strategy was working, the open and increasing scepticism of inshore fishermen might have been recognised as a warning flag demanding more careful attention to areas of recognised weakness in the assessment process' (Harris, 1990).

Harris recommended that the assessments be peer reviewed by those not involved in DFO. He warned that the models had become more important than the study of the species themselves; he said that what was needed was nothing short of a massive research effort to understand the life in the oceans. Ottawa

Panel 17.1 **Case study: The last hunters (cont.)**

accepted nearly all the recommendations made by Harris, but reducing the total allowable catch on cod was not approved. In 1992 the minister closed the northern cod fishery, saying it had collapsed due to unusual ecological and environmental conditions.

The collapse of the northern cod stock was one of the most catastrophic failures in fisheries and an ecological disaster. The social and economic consequences have been enormous and many communities remain devastated. DFO now admits that it had evidence as early as 1986 and that 'the model used to determine the status of most of the key groundfish stocks has consistently overstated their abundance and understated the level of mortality' (Auditor General of Canada, 1997).

Barents Sea cod

Meanwhile on the other side of the Atlantic Ocean, in Norway, the 1989 autumn survey results showed that cod stocks in the Barents Sea were at their lowest for over a hundred years. Scientists and fishermen had already been worried that the fish were too small and earlier estimates of abundance too high. Cod quotas were slashed and the capelin fishery also closed. Fishermen warned that the fish they were catching appeared to be starving. 'When scientists told the Norwegian politicians that there had to be severe quota cuts, the politicians acted immediately and backed the cuts despite a firestorm of criticism from their constituents. Oslo also immediately implemented policies to reduce the number of cod fishermen and vessels' (Harris, 1998).

In January 1990 the government imposed a moratorium. Fishermen's incomes dropped by up to 40 per cent and in the end the Norwegian government spent more than EUR 50 million to remove capacity from the fleet. However, the prompt action by the government meant that by 1991 signs of a recovery were seen and in 1992 the spawning biomass of the stock was larger than it had been for 25 years.

Second, key variables, such as recruitment and natural mortality, were treated as constants in the models used. This in combination with problems in the periods used to derive averages used to generate the constants also resulted in overestimates (Finlayson, 1994).

Thirdly, data from the fishing industry used in stock assessments, in combination with research vessel survey data, were seriously distorted by the practice of discarding undersized fish. There was also a bias towards the use of offshore versus inshore landings as an index of abundance to 'tune' the stock assessment model. Inshore fisheries landings were not systematically used in the assessments because of difficulties obtaining consistent measures of 'catch per unit effort' and otherwise dealing with messy and often anecdotal data. Therefore evidence of decline in the abundance and size of inshore migrating fish was apparently missed (Steele et al., 1992; Neis, 1992), contributing to DFO's inclination to dismiss the concerns of inshore fishers.

Why was the research on basic cod biology not being carried out? One obvious reason was the career structure of fisheries scientists who were assessed on their publications in peer reviewed journals. The number of papers published on northern cod, one of the most important resources in eastern Canada fell from more than 10 per year to 2 annually over a twenty year period, in contrast to the increase in papers seen in the Norwegian setting, where research was being actively encouraged.

Another problem however was the hubris amongst senior government officials in denying that there was anything wrong. This was a projection of the government's own crisis around its institutional authority and epistemological legitimacy. For example, in the February 1988 issues of *Fo'c'sle*, aimed at fishermen and the general public, the DFO Newfoundland office published an article entitled '*The Science of Cod*'. In the introductory statement the Director General says:

> 'It is reassuring that the conclusions of the Task Group [the Alverson Report, 1987] and CAFSAC about northern cod are quite similar with respect to the present stock size and the causes for the decline in the inshore fishery since 1982. The credibility of DFO scientific advice was not questioned. The northern cod stock continues to increase, but perhaps not as fast as projected several years ago'.

Finlayson and McCay (1998) also asked why it was that scientists who knew or suspected that there were problems with the stock assessment did not speak up. It is clear from the inside that some DFO scientists had misgivings about the quality of the scientific advice given about cod, but as in any civil service they were not allowed to speak publicly about the issues once it had become policy. It was also the case, however, that many assessment scientists had little contact with the fishing industry or actual fish, dealing rather with 'paper fish'. There was also a tendency when scientists were presenting their assessments to the relevant advisory body that they would minimise the problems associated with data reliability, uncertainty, the models and data-sets, issues of stock structures or even admitting to the possibility of unknown unknowns! ([1]).

17.2.4 Knowledge systems

The fisheries case studies serve to underline the fact that simple variable-oriented analyses are no match for the complexity of real socio-ecological systems. So why have these approaches not been replaced, especially given that it has long been recognised that the majority of the world's fisheries are over-exploited (Pauly et al., 2002; FAO, 2010)? One reason is perhaps the lack of consensus about which approaches could replace them in order to understand complex systems and manage resources more effectively. This partly stems from the low pedigree of knowledge about the causality linking many of the processes and elements in socio-ecological systems (Table 17.1).

The division of knowledge into political, disciplinary and geographic silos can lead to Yaffee's (1997) 'recurring nightmares' of short-term interests outcompeting long-term vision; situations where competition replaces co-operation because of conflicts in management; fragmentation of values and interest; fragmentation of authority and responsibility; and fragmentation of information and knowledge leading to inadequate solutions or even additional problems. In situations where strong counterfactual thinking is needed, for example in developing early warnings, the presence of silos of knowledge can become a real hindrance.

The fact that ecosystem and resource management is highly interdisciplinary, involving fields of varying states of maturity and with very different heuristic and social practices is also a challenge. Those involved in planning and policy development often find themselves having to use inputs from areas of expertise with which they are potentially unfamiliar, making it difficult to apply the same level of judgement as in their own core field. The result can be a dilution of quality control in the information gathering process and a weaker quality assurance of results. It is unsurprising that planning and management institutions have been unable to respond to crises or change, as in many instances, the organisations are suffering from a chaotic mixture of information, analysis and interpretation with no paradigmatic structure in which to incorporate all the various forms of scientific, interdisciplinary, and indigenous knowledge (McGlade, 2001).

In the pre-modern environment, knowledge was rich and adapted to the requirements of living locally. Individuals today are just as knowledgeable but they receive information from an enormous number of sources, some technical, some cultural. In this way we can see a form of second-order science emerging in which individuals must rely on other peer groups and experts to be able to evaluate the information within their own domains of expertise.

Table 17.1 Pedigree of knowledge

Pedigree	Theoretical paradigm	Data	Peer acceptance	Colleague consensus
4	Established	Experimental	Total	All but cranks
3	Theoretical model	Historical/field	High	All but rebels
2	Computer model	Calculated	Low	Competing schools
1	Statistical procedures	Educated guess	Low	Embryonic field
0	Definitions	Random guess	None	No opinion
∞	Unknown unknowns	Unknown	Unknown	Unknown

Source: McGlade, 2002.

([1]) This phrase, cited by many military experts, was made infamous by Donald Rumsfeld (2002) in his press briefing on weapons of mass destruction in Iraq, where he said '[T]here are known knowns; there are things we know that we know. There are known unknowns; that is to say there are things that, we now know we don't know. But there are also unknown unknowns — there are things we do not know we don't know.' 12 February 2002.

This type of interaction is especially important in ecosystem and resource management, because direct scientific evidence is likely to be missing but there is often a wealth of local and lay knowledge to be gained through the close observation of and proximity to nature, as Annie Dillard experienced during her year spent next to Tinker Creek. In this sense the concept of an expert as part of the system of governance has to be broadened to include those who have particular knowledge about a system but who do not necessarily walk the corridors of power and/or of science. It is interesting in this regard to note that the newly established Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) explicitly recognises the contribution of indigenous and local knowledge to the conservation and sustainable use of biodiversity and ecosystems, yet it is still struggling to find operational ways to include such knowledge into its work.

17.3 Planetary dynamics and ecosystem change

This section looks at ecosystem change through the lens of four interconnected concepts arising from the scientific field of non-linear dynamical systems behaviour: **planetary boundaries** (Rockström et al., 2009); **tipping points** (Lenton et al., 2008; Schellnhuber, 2009), **panarchy** (Gundersen and Holling, 2001) and **resilience** (Walker and Salt, 2006). Based on information drawn from socio-ecological systems around the world, we explore whether or not these concepts could help communities and managers anticipate sudden change or the collapse of a resource and provide a practical basis for sustainable management of our relationship to ecosystems.

17.3.1 Navigating the Anthropocene

The dynamical behaviour of the planet's natural systems is now changing more rapidly than at any time previously during the previous 10 000 years of the Holocene. Evidence of the scale, magnitude and significance of these changes has been sufficient for geologists to conclude that an epoch-scale boundary has been crossed and that we are now in a new epoch — the 'Anthropocene' (Steffen et al., 2011; Zalasiewicz et al., 2011). Living in the Anthropocene will require us to deal with ongoing and rapid or sudden onset threats such as oil spills, chemical and nuclear accidents, earthquakes, landslides, tsunamis, volcanic eruptions, severe weather, storms and cyclones, floods, wildfires and epidemics, and slow-onset threats such as air quality, droughts and desertification, food security and epidemics and climate variability (UNEP, 2012).

The 1980s and 1990s saw the emergence of the theories of chaos, non-linear dynamics and many other highly sophisticated mathematics as a source to explain the complexity of ecosystems (May 1982; McGlade 1999). At the same time, knowledge about the planet's own dynamics was growing: from debates about the impact of the Milankovitch cycles on climate to the idea that the 'flap of a butterfly's wing' could cause changes thousands of kilometres away.

The analytical basis of ecosystems science was also growing but the sophistication of the tools and computational methods meant that few field biologists could really make use of the ideas beyond concepts and definitions. Instead, the advances were largely taken forward by climate scientists, meteorologists, oceanographers and biogeochemists under the aegis of the Intergovernmental Panel on Climate Change. The models of global change which were developed, however, generated scenarios of the likely magnitude of global temperature increases, sea-level rise, melting of the ice caps, glaciers and sea ice, droughts and tropical storms which would have direct consequences for ecosystems.

It was with this information, that a network of theoreticians and mathematical ecologists began to expand their ideas on four major concepts: *planetary boundaries* (Rockström et al., 2009); *tipping points* or *elements*, (Lenton et al, 2008; Schellnhuber, 2009), *panarchy* and *resilience* (Holling, 1996; McGlade, 1999).

Rockström and colleagues have proposed nine hard global biophysical limits, or planetary boundaries, for human development — land-use change, biodiversity loss, nitrogen and phosphorous levels, freshwater use, ocean acidification, climate change, ozone depletion, aerosol loading, and chemical pollution. Each has its own metric, for example greenhouse gas emissions, concentrations of various pollutants in air and water, and aragonite concentrations in the ocean. At present, none of these limits can be entirely dismissed either by firmly ruling out a possible anthropogenic triggering of irregular dynamics or confirmed by providing relevant estimates for activation or reaction times. Nor can the response times of the various sub-elements be estimated beyond a certain resolution e.g. yearly in the case of aerosol loading and loss of summer sea ice or millennia in the case of ocean acidification. However, the widespread lack of in situ observations to validate the models underpinning these limits and the inbuilt latency of the planetary system itself, mean that there will be many decades of tantalising ignorance about whether or not any of these boundaries *per se* have been crossed.

Instead it is more likely that the effects of the tipping elements described by Schellnhuber, Lenton and co-workers, will come to define future surprises. We are experiencing some of them already — Arctic sea-ice loss; boreal forest dieback; melting of Greenland ice sheet; instability of the west Antarctic ice sheet; Atlantic deep water formation and permafrost and tundra loss. Others are potentially yet to come — climatic change-induced ozone hole; greening of the Sahara; chaotic multi-stability of the Indian monsoon; changes in the amplitude or frequency of the El Niño Southern Oscillation (ENSO); dieback of the Amazon rain forest; west African monsoon shift; and changes in Antarctic bottom water formation. The causality and inter-linkages between these potential tipping elements raises both long- and short-term questions. For example, will increasing levels of greenhouse gases lead to a permanent change in the ocean current system including the north Atlantic Gulf Stream and the El Niño regime that could ultimately suppress the Quaternary glacial 'cycles', while drastically altering the number of extreme weather events such as droughts, storms, cyclones and tornadoes?

Tipping elements pose one of the toughest challenges for contemporary science, because key emergent properties (and consequently early warning signals) are likely to arise on a range of spatial and temporal scales and be observed by scientists across many disciplinary silos, which are themselves populated by elites and people with their own paradigms and language. Global changes in climate, ocean acidification and even possibly ozone depletion may cause thresholds on a planetary scale to be crossed that alter or reconfigure the functioning of some ecosystems, leading to abrupt transitions and potential irreversible changes on a local scale. Identifying thresholds based on a generic model of tipping points is an exercise in futility; instead we will need to adopt an approach based on cascading thresholds, where early warnings and signals of change are linked to observations of key processes on a local and regional scale.

17.3.2 *Anticipating surprises — adaptive cycles and panarchy*

Over the past fifteen years, Buzz Holling, Brian Walker, Carl Folke, Terry Hughes, Steve Carpenter and colleagues have been exploring socio-ecological systems around the world (www.resalliance.org). The idea has been to create an empirical and theoretical base on which to understand abrupt change in managed resources and to develop a general theory with heuristics and principles to better understand resilience (Holling, 1973; Gunderson and Holling, 2002; Walker et al., 2006).

The concept of resilience in ecosystems was introduced by Holling in his classic paper on non-linear dynamic models that captured the relationship between stability and resilience in ecosystems (Holling, 1973). Whilst some ecologists considered resilience to be a measure of how quickly a system returns to an equilibrium state after a disturbance (what is now known as engineering resilience), Holling kept to the notion that ecological resilience was the measure of how far an ecosystem could be perturbed without experiencing a regime shift (Hogg et al., 1989; Holling, 1996; McGlade, 1999).

There are many examples where ecological resilience has been described and its loss recorded (Table 17.2). In most instances, the dynamics of the adaptive cycles are the product of the interlinkages between the ecosystem and people, and it is generally these, sometimes hidden, cycles that managers are actually coping with. As the diversity of the case studies shows, the scale of the management challenge is enormous. However, one aspect that is of particular importance is the anticipation of surprise or abrupt changes, and the rapid shift to a new regime. In some literature, the term 'alternative state' is used: this is a misnomer. Complex ecological and socio-ecological systems are better expressed as configurations of states with the same controls at work, i.e. the same feedbacks, but where the configuration describes the kinds and strengths of feedbacks and where the different internal controls on functions represent alternate regimes with thresholds between them. Striking examples of this are the desertified regions of the Sahel and the emergence of permanent summer algal blooms in the Baltic Sea.

As part of the development of a more general theoretical basis for managing socio-ecological systems, Walker and colleagues (Walker at al., 2006) proposed five heuristics: two describing the dynamics across scales — adaptive cycles and panarchy, and three describing the properties of the system — resilience, adaptability and transformability. Adaptive cycles in ecosystems generally follow a path known as 'ecological succession', involving growth (r) where resources are plentiful, and conservation (k). Most socio-ecological structures are not scale invariant but are built on combinations of slow and fast

Table 17.2 Case studies of socio-ecological systems

Location of case study (researcher; cited in Walker et al., 2006)	Socio-ecological characteristic	System change	Vulnerabilities	Resilience
Causse Méjan, France (Etienne & Bousquet)	Ecosystem diversity is totally dependent on grazing.	Pine trees from neighbouring forest stands are invading the steppic grasslands. Agriculture has destroyed many flatlands.	New social groups, including forest owners, secondary residents.	Keeping alive the Causse culture and traditions of environmentally friendly farming through sharing labour and knowledge and the co-evolution of habitat and farming.
Caribbean coral reefs (Hughes, 2003)	Coral reefs have been on a trajectory of serious decline. In the 1950s a single species of sea-urchin was keeping macro-algal blooms in check. In the 9170s a disease outbreak led to the catastrophic loss of urchins, precipitating blooms that persist today.	Collapse of many reefs due to overharvesting, pollution, disease and climate change. Loss of key habitat forming *Acropora* species.	Long-term trajectory of a shift from fish- to echinoid-dominated destructive herbivory.	Reefs exhibit numerous alternate states, but the resilience of these is unknown. Experiments with No Take Areas and protection of hotspots may help locally, but are unlikely to stem region-wide loss of resilience.
Dry spiny forests, southern Madagasar (Elmqvist)	High degree of endemism; inhabited by the People of the Thorn Bush who protect dense forest patches through strong informal institutions.	Fragmentation and loss of forest due to insecure land rights.	Tensions between Christianity ad customary institutions, government policies and local informal arrangements.	Strong social capital and the large capacity of spiny forests to regenerate.
Everglades, Florida (Gunderson, 2001)	Internationally recognised wetland, which was historically partitioned into agricultural, recreational and conservation areas. Area is now maintained through canals, pumps and levees.	Ecological crises brought on by changes in water quality and quantity caused by the volume and timing of flooding.	Institutional reformation and realignment, plus the need for large-scale, expensive, technologically based solutions. Conflicts over water use amongst institutions and actors.	Example of a perversely resilient social system based on conflict and a formal closed network of government agencies and policies.
Gorongosa National Park, Mozambique (Lynan)	Park was home to large herbivore and carnivore populations but these were decimated in the war of Independence in the 1980s. Now home to some 500 bird species and 10 000 people.	The loss of major species.	There are no schools, clinics or facilities for the people living in the park who provide local protection to the ecosystem. No local enforcement of existing conservation policies in the buffer zone.	Remains one of the prime protected areas in southern Africa.
Goulburn-Broken Catchment, Australia (Ryan)	Sub-catchment of the Murray River. Climate temperate with sparse vegetated plains. Originally occupied by Aboriginal people but subsequently populated by Europeans after the discovery of gold. Today heavily agricultural.	Irrigation infrastructure and clearing of more than 70 % of the native vegetation cover have substantially altered the hydrological balance.	Climatic variation causing changes in vegetation and groundwater recharge. Substantial land-use change, with dry-land areas delivering significant salt and nutrient loads to the waterways. Increasing demand for non-consumptive water and conflicts amongst property rights.	Property rights and downstream accountability in place. Costs of maintaining the regime mounting, resource base degrading, regional economy more brittle. System more vulnerable to shocks and disturbance (Anderies et al. 2006).
Northern Highland Lakes District, Wisconsin (Petersen & Carpenter)	Pristine wilderness with management focused on protection and promotion as a wilderness tourist destination.	Lakeshore development for tourism and second homes. Invasive species including rainbow smelt, rusty crayfish and Eurasian milfoil have reduced the quality of fishing and boating. Proliferation of suburban life.	Stakeholders with many divergent views. Natural resource management has been slow to adjust to ecological and social change. Invasive species and eutrophication.	Multiple states and thresholds are known relating to eutrophication, collapse of fisheries, trophic cascades, woody habitat and inertia of long-lived predator and tree populations. Non-reversible threshold may be caused by species invasions and a shift from old-growth timber harvesting to pulpwood rotation.

Source: Adapted from Walker et al., 2006. Detailed descriptions of each case study can be found at www.resalliance.org.

processes; panarchy is the term that describes how these different types of processes operate across time and space scales. Disturbances can lead to another connected regime in which resources that have been historically bound-up are released (Ω) and the fundamental structure collapses; this is followed by a phase of re-organisation (α) in which novel structures can take hold leading to another growth phase in a new cycle. There are many examples of disturbances causing shifts in this way, including forest fires (Dublin et al., 1990), forest pest outbreaks (Ludwig et al., 1978), algal blooms in eutrophied aquatic systems (Carpenter and Brock, 2004) and droughts.

17.4 Socio-ecological systems — institutional fit and resilience

In this section we look at socio-ecological systems from the perspective of institutional fit and resilience as sources of anticipation and adaptive capacity. As Elinor Ostrom (2005), Carl Folke and colleagues (Folke et al., 2007) have pointed out, the lack of institutional fit can confound the effectiveness of stewardship of ecosystem services and resource management, and can lead to unexpected surprises, excessive rent seeking and high transaction costs (Kofinas, 2009).

Despite innovations in institutional arrangements and a greater awareness of the importance of the need for more effective forms of governance, the loss of trust in bureaucracies has been growing. Deeply embedded differences in attitude towards conserving ecosystems versus exploiting resources have led to highly politicised public debates around false dichotomies, such as choosing between protecting the environment and employment or energy, or diversionary arguments such as the tragedy of the commons. In the case of the collapse of the northern cod, the commons were neither open-access or unregulated, but the use of this discourse meant that the only solution sought was downsizing of the fleets, rather than a closer examination of the complexity of the causes of the problem, such as flawed scientific advice, vested interests and government priorities.

The key question is what happens when there is a real crisis, brought about by sudden change in a resource or ecosystem? Do those institutions with most to lose become destabilised or do they attempt to renegotiate their power relations? Do those with most to gain seize the opportunity for restructuring?

In Newfoundland it has been the social structure of the fishery that has collapsed even though the inshore fishermen potentially had the most to gain in the aftermath. The resource scientists and managers on the other hand have only made modest changes despite being at the core of the problem. This might suggest that modern science is much stronger and more deeply embedded as a social and political authority than generally assumed. It means that it will take more than the collapse of a resource or a shift in an ecosystem to displace the existing form of authority that has been built on a certain control of science. It also raises questions about how to build up institutional fit and resilience and develop effective science-policy interfaces.

17.4.1 Institutional fit and governance

Institutional infrastructure, along with governance and leadership, heavily influence our capacity to manage complex systems and cope with abrupt change. It has been the lack of institutional fit that has often confounded the effectiveness of the stewardship of ecosystems and the systems they provide, and led to unexpected surprises, excessive rent seeking and high transaction costs. The causes of a lack of institutional fit are many and can stem from mere folly (Tuchman, 1984), complexity, uncertainty about roles, a lack of ownership and property rights, institutional frailty and vested interests.

An example of the consequences of the confounding effects of a poor institutional fit can be seen in the 1997 legal case of Nunavut Inuit concerning the Canadian Fisheries Minister's decision to increase the turbot quota against the advice of the NAFO scientific council and then to assign the additional tonnage to his own constituents rather than to the Inuit of the Nunavut region or Denmark ([2]). It was said in an internal memo to the Fisheries Minister that the Canadian government could be seen as hypocritical by the international community because it exhorts others to share the burden of conservation but was unwilling to do likewise.

Judge Douglas Campbell set aside the Minister's decision and referred the matter back for

([2]) Nunavut Tunngavik Inc. v. Canada (Minister of Fisheries and Oceans) (C.A.), [1998] 4 F.C. 405. 13 July 1998 (http://reports.fja.gc.ca/eng/1998/1998fc22910.html).

reconsideration of the quota. The Minister appealed, stating that he possessed:

> 'absolute discretion… to issue leases and licenses for fisheries or fishing. The rationale for such discretion is that Canada's fisheries are a common property resource belonging to all the people of Canada and licensing is a tool to manage fisheries which is given to the Minister whose duty it is to manage, conserve and develop that resource in the public interest. … The actual exercise of such discretionary power is influenced by numerous fluctuating policy concerns which go beyond the necessary issue of conservation and protection of fish to include cultural, political, scientific, technical and socio-economic considerations or policies.'

The Court of Judicial Review rejected the appeal for reasons that the Minister had not acted lawfully, but it made clear that the Court was 'not to become an academy of science to arbitrate conflicting scientific predictions, or to act as a kind of legislative upper chamber to weigh expressions of public concern and determine which ones should be respected… [it] is concerned with the legality of the ministerial decision resulting from an exercise of discretion, not its opportunity, wisdom or soundness'. There was clearly a lack of institutional fit between the legality of the defined role of the Minister and a legal framework in which the Minister's actions could be judged on the basis of evidence of fairness and long-term sustainability of the resource.

Over the past two decades, a number of important institutions and initiatives have been created to bridge the science-political divide and support international agreements on managing and protecting our global resources. These range from the UN Convention on Biological Diversity and the UN Conference on Straddling Fish Stocks and Highly Migratory Species to initiatives such as the Millennium Ecosystem Assessment, IPBES (International Platform on Biodiversity and Ecosystem), TEEB (The Economics of Ecosystems and Biodiversity) and ABS (Access and Benefit Sharing). These are primarily aimed at reducing the likely impacts of a growing human population and climate change on ecosystems and ensuring the sustainable use and equitable distribution of natural resources. However, as we show in the case study on European Union fisheries, even with highly cohesive, well-resourced institutions the consequences of a poor institutional fit remain one of the largest obstacle to the resilience of our fisheries (Panel 17.2).

There are a number of structures of governance; including the minimal state, corporate governance; new public management; good governance; sociocybernetic systems and self-organising networks (McGlade, 2001). This last type involves complex sets of organisations drawn from the public and private sector and is particularly interesting in relation to the governance of resources. The key to understanding their importance comes from the observation that integrated networks can resist government steering; they develop their own policies and mould their environment. This leads to interdependencies between organisations in order to exchange information and negotiate shared resources and a significant degree of autonomy. In the end, this form of governance can hollow out the state through privatisation and by limiting the scope of public intervention. A manifestation of this type of governance is swarms of amorphous groups that link together to tackle single issues such as dolphin-friendly tuna fishing and anti-sealing and whaling. In managing resources it is necessary to understand that governance is becoming increasingly operative, where lines of authority are less formal, legitimacy is more ambiguous and where people are choosing when and where they want to engage in collective action.

The majority of fisheries are operated through instrumental actions, i.e. where technical rules are developed and implemented. However, in many of the case studies listed in Table 17.2, the communities manage the resources through consensual actions and norms, such as religion, deity or faith, rather than legal ones. The effectiveness of this type of action and user participation is that in times of crisis, participants learn more quickly and show a greater capacity to adapt and even transform. For example, after the initial water-table crisis in the Goulburn Broken Catchment in the 1970s, conflicts gave way to networks that connected people and interests to deal with issues of flooding, waterlogging and drainage (Anderies et al., 2006). Leaders emerged to form committees to represent the concerns of the various networks throughout the catchment. They pooled existing knowledge, identified gaps and invested in research and effectively lobbied government agencies for support. Despite all this, government leaders opted for adaptation rather than transformation.

By contrast, the ecological crises in the Florida Everglades (Gunderson, 2001) which had originally given rise to a network dominated by government agencies and formal policies, gradually led to a network of government and non-governmental

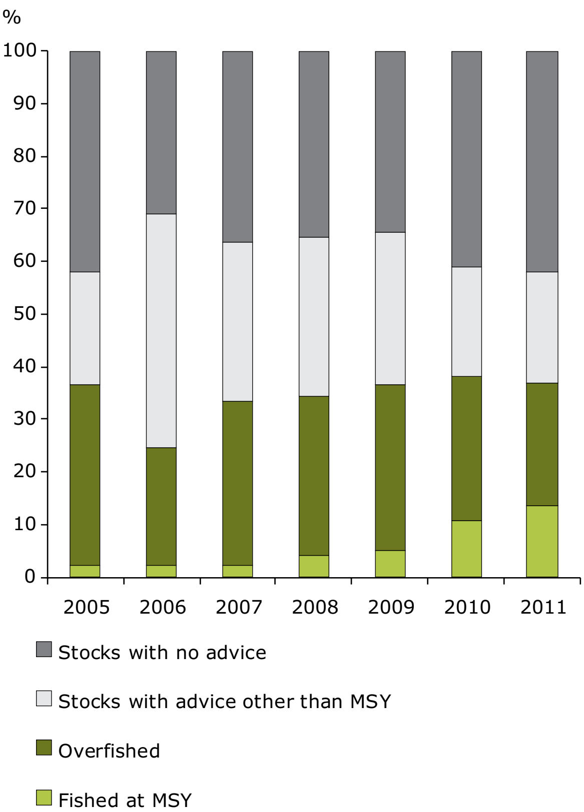
Panel 17.2 Knowledge-based management of EU fisheries — how much is scientific evidence being used?

Constança Belchior and Johnny Reker

Despite being managed under one of the most complex and expensive science-based management systems in the world, since 1983, the condition of Europe's fish stocks has continued to worsen (O'Leary et al., 2011; EU, 2011). The 2002 and 2012 reforms of the EU Common Fisheries Policy (CFP) aimed to deal with the failure to achieve the core objective of ecological, economic and social sustainability, where 72 % of all assessed EU fish stocks were estimated to be overexploited, and over 20% fished beyond safe biological limits, i.e. with a greater risk of collapse. (In the north-east Atlantic the number of stocks known to be overfished fell from 94 % to 63 % from 2004 to 2010, compared to 82% in the Mediterranean) (EC, 2010, 2011a).

One problem is that data of sufficient quality to support scientific advice on MSY and overfishing is missing for approximately two-thirds of the stocks for which quotas (Total Allowable Catches) are set in the north-east Atlantic (EC, 2011a) (Figure 17.1). This figure was intended to show fishing opportunities, but inconsistencies in the data on different stock parameters (e.g. number of stocks with no or insufficient data, or for which an excess TAC was set) point to the underlying difficulty of producing coherent assessments. For example, data quality and availability is so poor in the Mediterranean, that in 2010, only 16 out of 102 candidate species could be assessed (EC, 2010). Part of the problem is that Member States have not provided the relevant scientific data despite there being a legal responsibility to do so (EC, 2011a), introducing greater uncertainty into the scientific advice, and thus further undermining its credibility (Piet et al., 2010).

Figure 17.1 Trends in status and advice setting for north-east Atlantic fish stocks between 2005 and 2011



Source: EEA, based on EC, 2011a.

There have been many analyses of why EU fisheries management has not been successful (e.g. Sissenwine and Symes, 2007; Khalilian et al., 2010; EC, 2009; EU, 2011). The main conclusion, alongside the lack of scientific knowledge and ineffective management options to restore fish stocks and fisheries to profitable and equitable conditions, is the very nature of the decision-making process (Villasante et al., 2010; Piet et al., 2010; O'Leary et al., 2011). Overall, scientific advice has been largely overruled when setting fishing opportunities for EU fish stocks; between 1987 and 2006, the TACs only matched scientific advice in 8 % of the assessed stocks (Piet et al. 2010), and were consistently set well above the scientifically advised level by an average of 47 % since 2003 (EC, 2011a).

The actual impacts of such mismatches remains uncertain (O'Leary et al., 2011), but it is likely to be significant given the cumulative impacts of overfishing and increased capacity on the integrity of the wider marine ecosystem (Anticamara et al., 2011). For example, it has been estimated that the recovery time for benthic habitats in areas in the Greater North Sea where there was low natural disturbance, was between 7.5–15 years following only one pass of a beam trawl (OSPAR, 2010). In German waters some areas have experienced up to 4 000 hours of beam trawling (Pedersen, 2009). Fisheries are thus a significant contributor to pressures on European marine biodiversity where only 2 % of the species and 10 % of the habitats reported under the Habitats Directive are considered to be in favourable conservation status (HELCOM, 2010; EEA, 2010).

Panel 17.2 Knowledge-based management of EU fisheries — how much is scientific evidence being used? (cont.)

As a response to the current situation, an ecosystem-based approach to management has become one of the CFP's objectives under the EU Marine Strategy Framework Directive. The intention is to implement more holistic, integrated management strategies to achieve EU ambitions on securing healthy and productive marine ecosystems, including halting the loss of biodiversity, ensuring sustainable economic growth and improving resource efficiency.

The ecosystem approach sets out a framework for understanding the socio-ecological system, where the hidden long-term costs or externalities and subsidies are accounted for, in order that options that generate more societal value can be prioritised (e.g. ISU, 2012; Crilly and Esteban, 2011). In a recent study on the potential benefits of restoring 43 European fish stocks to their maximum sustainable yield from current levels (Crilly, 2012), the authors found that it could generate 3.53 million tonnes of additional landings, and an additional value of EUR 3 188 billion annually. This is more than five times the annual fisheries subsidies paid to EU Member States), and could in turn support the creation of more than 80 000 jobs in the sector in the EU.

Thus it seems that there is sufficient available knowledge to underpin informed decision-making to support an ecosystem approach to fisheries, but also one that prioritises solutions that will benefit society the most. At a time where the EU already depends on substantial imports to meet more than 65 % of total EU consumption of seafood (EC, 2011a) and where food security is becoming a global growing concern, managing fish stocks sustainably provides a competitive advantage to the EU which should not be overlooked by individual or national interests. However, as previously discussed, this is unlikely to happen as long as decision-making in the CFP allows for short-term economic interests to compete with and outcompete long-term sustainable and precautionary scientific advice at the very beginning.

The question remains: has Europe learned from past experiences? The short answer is yes, but we are still not reacting to our knowledge fast enough. Fisheries are still not being managed sustainably and the majority of European fish stocks are still overfished. Furthermore, there are considerable gaps in our knowledge regarding the status of fish stocks, yet on average TACs are still set well above scientific recommendations showing a disregard for scientific advice and also for the precautionary approach. From a societal perspective, further evidence also shows that overfishing also means the EU is getting much less out of its fish stocks than if they were restored and sustainably managed. This situation is mirrored at a global level, where the 'sunken billions' in world fisheries due to excess fishing capacity have been estimated at 50 billion US dollars annually (World Bank, 2009).

The new CFP proposal (EC, 2011b) features ambitious measures from the European Commission, namely the commitment to establish management measures 'in accordance with the best available scientific advice' and no longer just 'based on scientific advice'. Also, it proposes to give more power and responsibilities to the actual stakeholders, making them more accountable for the resource they are being allowed to exploit, alongside other measures which aim to better integrate the precautionary and ecosystem approaches into the CFP. Overall, it sets out a more flexible mechanism that should allow it to cope better with the inherent diversity in both EU fisheries and the changing marine environment.

It is questionable, however, whether a management system in which scientific evidence is consistently being undermined, either by lack of compliance by Member States in delivering sound fisheries data, or by disregarding it due to narrow political interests and negotiations, will ever be able to deliver its objective of long-term sustainability. This is a point recognised by the European Parliament in its review of the proposal for the new CFP regulation (EP, 2012). Therefore one of the greatest challenges in managing EU fisheries and specifically the EU 2012 CFP reform remains the level of respect for scientific advice as a fixed boundary condition for natural capital when negotiating political agreements.

A socio-ecological management system solidly grounded in science is undoubtedly a more objective way to manage natural resources following established criteria, whilst also coping and adjusting to uncertainties. Together with the precautionary approach, it could help to set out a long-term transparent management system for fisheries, unlike the vested political decision-making system that prevails in the CFP today. Governance arrangements in and around EU fisheries will need to respect scientific advice and ensure the compliance of national data obligations to support it, as well as allowing for more transparent and inclusive decision-making that favours a wider sectorial and public engagement. This could be through broader representative constituencies and greater societal benefits as opposed to the current practice that favours the exhaustion of natural capital whilst leading the fisheries sector towards a deteriorating future.

groups which opted for transformation. New institutions, technological solutions were created on the back of significant levels of investment. As many of the cases indicate, two of the most critical factors for adapting to change and transformation are institutional fit and leadership.

17.5 Future prospects

This final section looks at some of the key lessons that emerge from the various case studies and reflects on how they might be used to improve resource management and ecosystem stewardship in the future. The six major lessons that resource managers and those living in a particular socio-ecological system need to consider to ensure that sudden, abrupt changes do not lead to catastrophic collapse are as follows:

- Close observation of ecosystems and natural phenomena.
- Development of a diversity-oriented approach to resource management that reflects the complex causality of the real-world context.
- Widening the sources of information and knowledge about the dynamics of socio-ecological systems.
- Reducing delays between early warnings and actions.
- Developing a deeper understanding of the full adaptive cycle of the ecosystem and resource base being managed.
- Building up the learning, leadership and innovative capacities in the institutional and societal context to enable transformation rather than only adaptation. As seen in so many of the case studies there is a need for greater participation and transparency regarding vested interests.

The evidence used to develop management advice will also need to be far more explicit about the dynamics of processes across different time and space scales and uncertainty. Resource managers and the community at large will need to develop the skills and capacities to create consensus — and where not possible compromises (van den Hove, 2006) — about how to handle uncertainty and which diagnostic criteria and metrics will be used to elicit action in the case of early warning signals (Table 17.3). For example, thresholds in water use, size of patches of forest clearance, wildfire management and the extent of agistement have all been shown to be critical activities in determining the resilience of the socio-ecological systems examined.

Table 17.3 Examples of early warning and possible outcomes and responses

Type of early warning	Possible outcome	Examples	Possible solutions
Spatial	Potential rapid spread via multiple unknown pathways	Bird flu; various fungal diseases, invasive species	Establish broad jurisdictional authority to monitor spread and develop potential policy actions; develop in situ monitoring, and multi-scale and multi-interaction models
Temporal	Potential spread of problem on different time scales linked to ecological and physiological processes leading to collapse and a different regime	Drought, over-exploitation of key resources over time, invasive species	Develop an understanding of the adaptive cycle, multiple pathway and time-dependent models and ensure appropriate in situ monitoring of human and ecological systems
Demographic	Potential long-term impacts on the health of the ecosystem and human population	Age-related diseases	Develop more intense monitoring of entire adaptive cycle and long-term monitoring of age-related processes
Threshold behaviour	Potential for issue/events to create socio-ecological regime shifts with significant long-term economic and/or ecological impacts including irreversibility	Sustained over-harvesting of fish stocks leading to collapse of keystone species; runoff from nitrogen fertilizer leading to eutrophication	Develop integrated assessments with scenario analyses that include the potential to identify long-term physiological and ecological shifts
Cascading effects	Potential that problem effects cannot be buffered or can be amplified between domains leading to significant socio-ecological impacts	Reduction in the polar ice cap opens up northern sea routes to shipping; creating new forms of land use change and local harvesting of resources	Develop multi-jurisdictional approach to manage changes; develop integrated assessments and scenario analyses to understand the multi-dimensional dynamics and resilience of the socio-ecological systems; establish new monitoring systems

The fundamental assumption that the existing institutional landscape is fit for purpose should also be examined carefully. As Hobbes (in *Leviathan*, 1651) and Machiavelli (in *The Prince* ca. 1514) well understood, user participation and the frameworks of power are the most important elements to understand when mapping out the rights of the community. In ecosystem and resource management there are a number of regimes including: laissez-faire; market regulation; communal governance; state governance and international governance (generalising from McCay, 1993). As shown in each case study, property rights and the authority to constrain exploitation are at the heart of the matter and inevitably come under intense pressure during a crisis. Ensuring the resilience of socio-ecological systems requires an explicit understanding of the rights and responsibilities during periods of transformation.

A final observation is that many interventions in resource management are made on the basis of a belief that these would have predictable outcomes. The assumption has been that all interactions can be adequately understood and that all future states are contained within the present structure of the socio-ecological system. The hubris of this type of thinking parallels that of the financial world in which a constrained set of tools and those using them (known as 'quants') created short-term indebtedness, mispricing of securities and a false protection against unknowable uncertainties. Ultimately, the two worlds of finance and resources became intertwined via market volatility and the mispricing of commodities, and led to the catastrophic consequences of the economic crisis all over the world (McGlade, 2009).

We must avoid repeating the mistakes of the past, as these will ultimately result in the collapse of ecosystems and social crisis. Instead, we should acknowledge that resilience in nature contains the seeds not only of surprise but also of transformation.

Box 17.2 Definitions

Adaptive management
Adaptive approaches to management are defined as those that recognise uncertainty and encourage innovation while fostering resilience (after Chapin et al., 2009). It is often considered as an approach based on learning by doing and implemented through careful and regular observation of socio-ecological conditions, drawing on these observations to improve the understanding of the system's behaviour, evaluation of the implications of emergent conditions and various options for intervention and action and responding in ways that support the resilience of the socio-ecological system.

Configurational complexity
Characteristic of diversity-oriented analyses, where context matters. Cases are examined as configurations in which all relevant aspects are looked at in the form of combinations. Such analyses concentrate on the specific features of individual cases, identifying those that are most relevant, whilst considering how those features cohere with each other as distinct types (McGlade, 2003)

Counterfactual thinking
The dependence of *whether*, *when* and *how* one event occurs on *whether*, *when* and *how* another event occurs and the possible *alteration* of events.

Diversity-oriented approach
Analyses of socio-ecological systems based on detailed case studies using measurements of many system-specific attributes with configurational complexity (McGlade, 2003).

Earth System
The Earth System is defined by Schellnhuber (1999) as the conglomerate formed by human civilization and its planetary matrix, i.e. all parts of the Earth that interact with the members and manifestations of our species.

Institutional fit
This refers to the linkages between ecosystems and socioeconomic and cultural systems in their local, regional, national, continental and global contexts. The use of the word 'fit' in English refers to a match of sizes, e.g. if the shoe fits, then it is a good match for the foot. Social and ecological systems and processes have sizes too: they have spatial and temporal dimensions which interact and depend on each other within a specific geographical space. The degree to which these match is meant by 'institutional fit.'

Box 17.2 Definitions (cont.)

Panarchy
Describes the way in which nested evolving hierarchical systems with multiple interrelated elements interact on different time and space scales (Gundersen and Holling, 2001). Panarchy is the structure where natural systems (e.g. fish stocks) and of humans (e.g. capitalism), as well as combined human-natural systems (e.g. institutions that govern fisheries resource use), are interlinked in continual adaptive cycles of growth, accumulation, restructuring, and renewal. These transformational cycles can occur on scales ranging from a drop of water to the biosphere, over periods from days to geologic periods. Understanding these cycles and their scales can help identify leverage points to foster resilience and sustainability within the overall system.

Polythetic scheme
Characteristic of a variable-oriented approach in which the cases that are grouped together can differ substantially from each other for one or more attribute as long as they are similar for the majority of attributes selected by the researcher (McGlade, 2003).

Regime shift
An abrupt large-scale transition to a new state or stability domain characterised by a very different structure and feedbacks (Chapin et al., 2009).

Resilience
The capacity of a social-ecological system to absorb a spectrum of shocks or perturbations and to sustain and develop its fundamental function, structure, identity, and feedbacks as a result of recovery or reorganisation (Walker and Salt, 2006; Chapin et al., 2009).

Tipping point and tipping elements
Tipping points are popularly understood as a situation where at a particular moment in time, a small change can have large, long-term consequences for a system, i.e. popularly understood as 'little things can make a big difference' (after Gladwell, 2000). Lenton et al. (2009) offer a more formal definition for the earth system, introducing the term 'tipping element' to describe subsystems of the Earth system that are at least sub-continental in scale and can be switched — under certain circumstances — into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point — in forcing and a feature of the system — at which the future state of the system is qualitatively altered. The term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point.

Variable-oriented approach
Analyses of systems based on the measurement of a small number of attributes relating to global patterns emerging from surveys of a large number of cases (McGlade, 2003).

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