UNIVERSITY OF TROMSØ UIT

Faculty of Health Sciences
Department of Medical Biology

# Mapping Uncertainties in Policy–Relevant Science

## - Treating Modern Biotechnology in Aquaculture with Precaution

**Frøydis Gillund**

A dissertation for the degree of
Philosophiae Doctor

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***Papers***

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*Frøydis Gillund, Tromsø, June 2010*

## Project Summary

Inspired by precautionary and participatory approaches to risk governance of novel technologies, this thesis concerns how to acknowledge and handle scientific uncertainties in policy-relevant science. I have addressed this topic by mapping perspectives on uncertainties, benefits and concerns related to the use of modern biotechnology in aquaculture, among scientists, policy advisors and other impacted parties. More specifically, I have applied (i) the Walker and Harremoës uncertainty framework to identify uncertainties associated with DNA vaccination of fish, (ii) the Q-methodology to explore scientists' perspective on the deliberate release of GM crops and (iii) Multicriteria Mapping to evaluate alternative feed resources (including GM feed) for farmed salmon. Based on the insights I have achieved from conducting these studies, I recognise four strategies as particularly important in order to facilitate precaution and participation, and thereby deal more appropriately with scientific uncertainties in policy-relevant science:

*Identifying a broader range of uncertainties* is a necessary first step in order to deal more appropriately with uncertainties in policy-relevant science. Scientific uncertainties have traditionally been conceived as and handled purely quantitatively. A precautionary approach implies recognition of a broader range of uncertainties such as ambiguity, indeterminacy and ignorance, which are not necessarily reduced with more research.

*Promoting reflection and communication about uncertainties* may improve the quality of policy-relevant science as this helps to clarify the basis for policy recommendations. Moreover, it may contribute to social learning and stimulate changes in scientists' way of thinking and acting that may further enhance precautionary and participatory approaches.

*Facilitating deliberation and participation of impacted parties* may contribute to a broader range of perspectives and uncertainties being addressed in decision-making processes, and, hence, better management of complex problems.

*Maintaining plurality in perspectives and policy options* may strengthen our ability to adapt to changing and uncertain future conditions, and ultimately lead to the identification of more sustainable pathways.

## List of papers

Paper 1:

Gillund, F., Dalmo, R., Tonheim, T.C., Seternes, T. and Myhr, A.I. (2008). DNA vaccination in aquaculture — Expert judgments of impacts on environment and fish health, *Aquaculture*, 284, pp. 25-34.

Paper 2:

Gillund, F., Kjølberg, K.A., Krayer von Krauss, M. and Myhr, A.I. (2008). Do uncertainty analyses reveal uncertainties? Using the introduction of DNA vaccines to aquaculture as a case, *Science of the Total Environment,* 407, pp. 185 -196.

Paper 3:

Kvakkestad, V., Gillund, F., Kjølberg, K.A. and Vatn, A. (2007). Scientists` perspectives on the deliberative release of GM crops, *Environmental Values*, 16, pp. 79-104.

Paper 4:

Gillund, F. and Myhr, A.I. (2010). Perspectives on Salmon Feed: A Deliberative Assessment of Several Alternative Feed Resources, *Journal of Agricultural and Environmental Ethics*, 23, pp. 527-550.

## 1.0 Introduction

Technological innovations have, throughout history, brought about new possibilities and solutions that have improved our ability to master, control and manipulate nature. Through this, technology has played a crucial role in shaping society and has resulted in profound environmental changes. While technological innovations first and foremost were perceived as ‘goods’ — tools that improved our capacity to utilise natural resources and to manage the risks imposed upon us by nature — we are now increasingly experiencing unanticipated side effects from technological applications (Beck, 1992; Harremoës et al., 2001). Technology itself has become a source of risks with which we must cope.

The development of modern biotechnology, dating back to Watson and Crick’s discovery of the double helix in the 1950s, is one example of a technology that was (and by many views still is) perceived as increasing humanity’s control over nature. Based on a mechanistic view of nature, scientists have sought to understand how genes function — e.g., determine what specific trait each gene codes for — in order to manipulate the genome or move genes within and between species. In this way scientists seek to control the traits of organisms, and develop organisms with particular desirable characteristics. Modern biotechnology is currently applied in a wide range of fields within medical and biological sciences. Different bacteria, virus, plants and animals have been genetically modified (GM) for medical, agricultural and scientific purposes. The adoption of the technology has grown quickly. For instance, since the first commercial cultivation of GM crops in the U.S. in the mid-1990s, GM crops are currently cultivated on approximately 134 million hectares of farmland spread throughout the world (GMO compass, 2010; James, 2009).

In turn, modern biotechnology is an example of a technology that has brought about a number of unanticipated consequences. With time, scientists have become more aware of the complexity of the genome. This has challenged the mechanistic view of molecular biology upon which modern biotechnology rests. For instance, it was originally believed that one gene codes for one — and only one — trait (protein). Consequently, when introducing a new gene to an organism, that trait (encoded for by this particular gene) would be expressed. Many were, however, surprised by the results from the Human Genome Project presented in February, 2001. The project set out to map the entire human genome. As it is estimated that a human body has somewhere between 250,000 and 500,000 unique proteins, it was subsequently assumed that the number of genes in the human genome would be within this range. The results, however, showed that the human genome has approximately 30,000 –

40,000 genes — about 15 times fewer than initially expected (International Human Genome Sequencing Consortium, 2001). Hence, it became evident that one gene must code for several different traits. This finding brought with it a new understanding of gene functionality, recognising that gene expression is influenced by a number of factors including interactions between genes, organs, the organism and the environment within which it lives. Consequently, many scientists (see for instance Le Curieux-Belfond et al., 2009) have raised concerns regarding the unpredictability of modern biotechnology, and particularly the development of GM organisms (GMOs) as genetic modification, by its very nature, entails the chance of unintended modifications to genetic sequences in a highly complex and partly unknown genome. Many also emphasise the difficulty of predicting long-term consequences when GMOs are introduced to highly complex natural and social systems, described in scientific studies and reviews on environmental and human health impacts of GMOs (see for instance Andow and Zwahlen, 2006; Weaver and Morris, 2005 and references therein), as well as discussions over their ethical, cultural, economical and social implications (de Melo-Martin and Meghani, 2008; Wynne, 2001). As the adoption of GM crops, particularly, has soared, so too has the debate over their use intensified.

Decisions about the use of novel technologies are generally based on risk analyses, which typically consists of three stages — risk assessment, risk management and risk communication. According to this approach, scientists first perform risk assessments, where potential adverse impacts associated with introducing a given technology are identified and their probabilities calculated. The risks identified by the scientists are then evaluated by policymakers, who decide the relative importance of the risks in question and how they will be managed. Finally, once decisions have been made, the general public is informed about both the risks and the chosen management initiatives. Thus, scientists play a central role in the introduction of novel technologies — they are the ones who develop technologies and often the ones who are called upon as experts to evaluate safety aspects. As knowledge obtained through scientific investigations is generally perceived as verifiable and objective fact, scientists have traditionally, and continue to, play a dominant and privileged role as advisors for policymakers (Millstone, 2007).

The numerous examples of unanticipated and undesirable impacts from technologies, which most often become evident only after a technology is introduced (such as deleterious impacts of chemical pesticides, asbestos, lead, PCB, etc., (Beck, 1992; Harremoës et al., 2001), have however questioned the ability of this approach to predict consequences and resulted in increasing attention about the existence of uncertainties in policy-relevant science (e.g., Faber et al., 1992; Felt and Wynne, 2007; Funtowitcz and Ravetz, 1993; Stirling, 1998,1999a; Stirling and Gee, 2002; Walker et al., 2003; Wynne, 1992). Importantly, uncertainties can not be conceived and handled purely as incomplete knowledge which will be sufficiently reduced with more research. Instead, more research might actually increase uncertainty (Funtowitcz and Ravetz, 1993) as it reveals more of the complexity characterising the system under investigation (which for instance was the case with the Human Genome Project). The variability and complexity of natural and social systems create irreducible uncertainties, allow for multiple scientific interpretations, and consequently open up fault lines of scientific disagreement over possible beneficial and adverse consequences.

Acknowledging the many forms scientific uncertainties may take, and developing tools and frameworks within which to handle them, is particularly important for policy-relevant science, as this knowledge forms the basis upon which scientists make their judgements and policymakers their decisions (Krayer von Krauss, 2005; Walker et al., 2003). Failing to adequately deal with uncertainties undermines — sometimes fatally — the quality of the knowledge and consequently the quality of the decisions. This project deals precisely with how to acknowledge and handle scientific uncertainty in policy-relevant science. To address this, I have mapped perspectives on uncertainties, benefits and concerns related to the use of modern biotechnologies (DNA vaccines and GM feed) in salmon aquaculture. In addition, one of my studies focuses on exploring scientists' perspective on the deliberate release of GM crops in general. Less background information will be provided for this case study. I have included it in my thesis because the method applied is designed to explore a particular kind of qualitative uncertainty, namely ambiguity. Moreover, this study is of relevance to the overall theme of modern biotechnology in aquaculture as a large proportion of salmon feed is currently based on plant material, including GM plants.

In the following chapters I intend to present the theory underpinning my work; the cases chosen for the studies conducted for this thesis; and the methodologies I have applied. I start with a presentation of different approaches to risks governance of novel technologies, highlighting how the currently dominating expert-led risk-based approaches often fail in the face of 'real world' complex problems that are characterised by irreducible uncertainties. I suggest precautionary and participatory approaches as a means to better deal with these conditions. Finally, I briefly discuss how to promote sustainability, as this is currently a major concern in environmental policy making. In Chapter 3, I describe the development of the salmon farming industry and outline some of the main constraints this industry faces and possible solutions to these, focusing on strategies that involve the use of modern biotechnologies. Relevant regulatory frameworks, such as the Norwegian Aquaculture Act and the Gene Technology Act, are presented in Chapter 4. Chapter 5 specifies the aims of the project; Chapter 6 presents the methodologies applied in the studies; and Chapter 7 provides a brief summary of the studies conducted. I end with an overall discussion and reflection of my experience from conducting these studies in Chapter 8.

## 2.0 Uncertainty, Precaution, Participation and Sustainability — Implications for Policy-Relevant Science

What is the role of scientific advice in technological governance? Or perhaps a more important question is; what should its role be? In a world of rapid change, where technological interventions are developed and applied at an increasingly faster rate, it is crucial to address questions concerning the relationship between science and governance[1]. Here, questions of both epistemology and politics come into play. I have chosen to focus on a particular component of this relationship, namely the scientific assessments of technological risks and particularly the treatment of scientific uncertainties in policy-relevant science[2]. In this chapter, I describe how scientific risk assessments have been given an increasingly dominant role in decision-making processes related to novel technologies. I demonstrate how this approach often fails in the face of complex 'real world' problems characterised by irreducible uncertainties, raising questions about the legitimacy and authority given to scientific advice in decision making. I advocate alternative approaches, based on precaution and participation, as a better means to deal with complexity and uncertainty. Finally, I elaborate on the concept of sustainability, which is currently a major concern for governance, and briefly discuss the relationship between precaution, participation and sustainability. I recognise that taking the insights presented in this chapter seriously would require profound changes to decision-making processes and the institutions of contemporary society. Dealing with this important task is, however, beyond the scope of my work.

### 2.1 Scientific Risk Assessments

The practise of scientific risk assessment as a way of analysing the possible harms of products and technological inventions is widely exercised in modern societies. Risk is typically defined as the 'magnitude of a possible hazard' multiplied by the 'probability that a hazard will occur' (Stirling and Gee, 2002). Thus, the basic steps of risk assessments are to identify the possible hazards associated with a given technological invention and to calculate the magnitude and the probability associated with each hazard occurring. The exercise is commonly performed

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[1] Voß and Kemp (2006) define 'governance' as a process by which society defines and handles its problems, and describes it as the result of interactions among different actors who have their own particular problems, define goals and follow strategies to achieve them. Hence, the term 'governance' tries to capture how societal development is shaped by a wide range of actors, structures and processes. Here, I discuss the role of some of these actors (scientific policy advisors) in some of these processes (risk assessment and decision making related to novel technologies). I will therefore use the terms 'decision making' more frequently than 'governance'.

[2] 'Policy- relevant science' covers scientific activities that aim to provide information and advice for decision making.

by scientists with expert knowledge in relevant fields[3]. Importantly, the practise of risk assessment is based on the assumption that every hazard can be accurately predicted and its respective probabilities calculated using scientific methods.

The prominent position of expert-led risk-based approaches in decision making rests upon the general and widely shared image of science as a process that produces verifiable, reproducible and therefore trustworthy and objective facts and theories about the material world — an image rooted in the modern tradition of the European Enlightenment. This tradition considers reductionism as the best way to reveal facts and theories — expressed in both the methodological belief that the best way to pursue an understanding of complex systems and processes is to reduce them to their smallest or most fundamental functional components, and/or in the ontological belief that the system itself is nothing more than the sum of these components. Consequently, the conventional approach in science has been to study isolated sub-systems under controlled conditions, to use this knowledge to generate an understanding of the system's function and, by extrapolation and synthesis with other reductive investigations, to predict the future behaviour of the overall system. This image of science and scientific knowledge, born at the time of the European Enlightenment, secures the view that scientific advice and risk assessment deserve a privileged position in decision-making processes. Policymakers manage risks by evaluating the information and advice given by scientists, and weigh the perceived benefits against the risks. Thus, a defining characteristic of this approach is the assumption of a clear distinction between factual and objective expert-led risk assessment and normative and value-based risk management (Felt and Wynne, 2007).

Wynne (1992), among others, is critical of the dominant role of scientific risk assessment in decision making. He gives a brief account of the history of scientific risk assessment, which describes how this practise was originally developed for analysing relatively well-structured mechanical problems characterised by deterministic processes, such as aircraft technologies. Later, risk assessment was gradually adopted to analyse problems of a much broader (both spatially and temporally) and less well-defined nature, such as the treatment of toxic waste, pesticides and greenhouse gasses, which Wynne characterises as problems that (in contrast to aircraft technologies) "...cannot be designed, manipulated and

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[3] Scientists conduct various tasks, such as basic research, product development and policy advice. My focus here is on the latter of these tasks. Providing policy advice does generally not involve conducting scientific research (e.g., in the sense of producing scientific knowledge). Rather, it implies that scientists, due to their expertise in a certain field, are asked to evaluate current scientific data (e.g., in relation to a given product), identify the risks involved (e.g., perform risk assessments), or asked to provide an expert opinion.

reduced within the boundaries of existing analytical knowledge" (Wynne, 1992: 113). Still, due to the dominance, familiarity and tractability of these reductionist and risk-based approaches and the significant political and institutional capital invested in them, they have remained the preferred approach when analysing impacts of more complex and ill-defined problems.

However, recent experiences of unexpected and undesired consequences from industrial and technological developments (such as the negative health and environmental impacts of chemical pesticides, asbestos, lead etc., see for instance Harremoës et al. (2001)) have proven that knowledge generated through these reductionist approaches is insufficient as a basis for decision making. In the following, I will highlight how complexity and uncertainty — which are essential features of the relationship between novel technologies, environment and society — pose serious challenges to reductionist approaches in policy-relevant science and the dominant position of scientific risk assessment in decision-making processes.

### 2.2 Complexity

There are many ways to describe complexity and the properties of complex systems/problems (see for instance Cilliers, 2005; Funtowicz et al., 1999a; Holling, 2001; Mazzochi, 2008; Krayer von Krauss, 2005; UNESCO, 2005). In the following, I will give a very brief synthesis of the main properties addressed by these scholars. First and foremost, complexity relates to the structure of a system — complex systems are open and composed by several *dynamic and non-linear output-input interactions* operating at different but interrelated hierarchical levels. This makes *unpredictability* an intrinsic property of complex systems — changes in initial conditions of the system can have pervasive and unpredictable effects or result in completely novel properties of the overall system, e.g., the systems may appear chaotic. This does not, however, necessarily imply that all complex systems are inherently unstable. Under some circumstances the diversity of complex systems may result in a high *resilience* and a *strengthened ability to adapt* to shifts in environmental conditions, while in other circumstances complex systems may be particularly *vulnerable to change*. Importantly, complex systems can, due to their diversity and multidimensionality, be *described in several equally plausible ways*, depending on the assumptions made and the framing of the analysis. This implies that scientists become intrinsic components in the process of gathering knowledge and performing research, and that their choice of approach influences the knowledge generated. Based on this, it can be argued that there is no unique, more-plausible or more-legitimate approach through which to analyse complex systems, although there may of course be approaches that are more useful (to some purposes) than others. Importantly, *knowledge of complex systems is necessarily partial,* e.g., all descriptions could, in some sense, be correct, but as no description can provide the full picture, they could all possibly, in some sense, be wrong.

An illustrative story of how complex systems can be understood in different, but equally plausible ways, and how each of these understandings only accounts for a partial description of the system as a whole, is the Hindu fable of five blind men feeling an elephant. It tells how five blind men each described an elephant as a completely different phenomenon, depending on the part each of them happened to touch. The man who touched the side of the elephant described it as a wall. Another, who touched one of the elephant's ears, said it was a large leaf from a tree. The third blind man was holding one of the elephant's legs and was sure it was a tree trunk. The one who got hold of the elephant's trunk said it was a snake, while the one who touched the tail said it was a rope. Thus, each of the five blind men believed that he could describe the elephant, but as each of these descriptions were only partial understandings, none was able to capture the whole elephant.

The Hindu fable is commonly referred to by scholars (for instance Funtowicz et al., 1999a; Krayer von Krauss, 2005) who want to highlight the necessarily partial nature of knowledge describing complex systems. The fable is a simple and good illustration of this point. Nonetheless, other aspects, such as the element of value-ladenness in choice of approach, are not illustrated by the story. As the men were blind, their descriptions of the elephant were rather arbitrary — simply depending upon the part they happened to touch. Similarly, when scientists are facing a complex problem, they too can be perceived as blind men, unable to know in advance what will be the best way to address the problem, but nonetheless, they have to make a choice. In some situations these choices may be contingent. However, increasing attention has been given to the fact that these choices are often based on predefined assumptions that reflect scientists' values and interests (Stirling, 2007). Along with this line of thinking, studies have been carried out to explore how scientists' judgements and perspectives are related to contextual factors such as their disciplinary background, place of employment and research funding (Krayer von Krauss et al., 2004, Kvakkestad et al., 2007).

Moreover, as readers of the fable, we are given a 'god's eye view': We know all along that the real phenomenon is an elephant. We can know this because an elephant is a well-bounded, concrete object that is possible to define. When facing less-defined and real-world complex problems, no one is equipped with such a 'god's eye view'. Hence, the essential question of how to deal with complex problems remains unaddressed. In fact, if all the blind men tried to combine their partial descriptions they would perhaps reach the conclusion that they had encountered an elephant, given that they have some predefined knowledge of what an elephant is. Interpreted in this way, the fable can be used to support reductionist approaches. However, scientists often lack the necessary predefined understanding when facing complex problems. Furthermore they are in many cases not only asked to describe the problem/system, they are expected to predict future changes and impacts (e.g., what may the elephant do). Seen in this perspective, I would argue that the fable serves as a good illustration of the limitations of applying only reductionist approaches in risk assessments, as increasing the number of blind men that are sent to touch the elephant would not necessarily increase the probability for making correct characterisations of the elephant and particularly not its future behaviour.

The brief theoretical description of complexity presented here is, in many ways, superficial and I have not provided concrete examples of complex systems from real life. In fact, despite theoretical definitions, it is not a straightforward task to distinguish simple, complicated and complex systems in real life. For instance, Wynne (1992) notes that even deterministic aircraft technologies could result in highly unexpected consequences (e.g., if an airplane suddenly explode). As I see it, deliberate release of novel technologies, such as biotechnology applications, into the environment involve complex interactions. Recognising this complexity implies acknowledging uncertainties — both due to the unpredictable nature of complex systems, scientists' limited capacity to fully describe this complexity and the value-laden choices of scientific approaches. In the following, I will describe different types of scientific uncertainties, emphasising why it is important to recognise uncertainties that go beyond the traditional notions of quantitative and reducible.

### 2.3 Scientific Uncertainties

Reducing uncertainties is a central feature of — and driving force behind — science, in the sense that science aims to generate knowledge in order to improve the understanding of the world we live in. These uncertainties have typically been conceived as: (i) 'knowledge related (epistemological) uncertainties': described as a lack of scientific knowledge or a lack of tools and methodologies resulting in imprecise measurements/observations in experiments and (ii) 'variability related (ontological) uncertainties': arising due to the inherent variability and diversity in the population or system under study (Walker et al., 2003). Methods for characterising these uncertainties were developed early, particularly through the use of statistics. Quantitative statistical measures, such as estimates of standard deviations, standard errors, confidence intervals or statistical tests for significance, etc., have been the principal language to express uncertainties in scientific findings. Importantly, these uncertainties have simply been perceived as incomplete knowledge — reducible through further investigation.

More recently, there has been an increasing awareness of the fact that there are other dimensions of uncertainty, of which not all are adequately expressed in these quantitative terms (Walker et al., 2003). This has become particularly evident when investigating potential impacts from introducing novel technologies into complex systems. The multidimensional and unpredictable nature of these systems has revealed other dimensions of uncertainty, generally referred to as 'qualitative dimensions'. Several typologies characterising these different dimensions of uncertainty have recently emerged (e.g., Faber et al., 1992; Felt and Wynne, 2007; Funtowicz and Ravetz, 1993; Stirling, 1998, 1999a; Stirling and Gee, 2002; Walker et al., 2003; Wynne, 1992). Despite the somewhat different terminologies used, I will present a brief synthesis of the ideas expressed by these scholars, based on Wickson et al. (2010). This synthesis is centred around the concepts of risk, inexactness[4], indeterminacy, ambiguity and ignorance (summarised in Table 1, pp.12 and Table 2 pp.16).

Each of the typologies takes the concept of risk as a starting point. As already explained, *risk* is typically defined as 'magnitude of a possible hazard' multiplied by the 'probability that a hazard will occur' (Stirling and Gee, 2002). This implies that a situation characterised by risk is quite well known — the range of possible hazards is known, and it is possible to calculate the probability that each of these hazards will occur. Still, a situation characterised by risk implies some degree of uncertainty as we cannot know in advance whether an identified hazardous outcome will occur or not (we only know the likelihood for it to occur).

*Inexactness* describes situations where all hazards associated with an activity are known, but there is a lack of sufficient knowledge to calculate the probabilities that each of the hazards will occur. This is, however, assumed to be solvable with more research. Thus, both risk and inexactness are quantitative types of uncertainty which can be adequately expressed in statistical terms, reduced through more research and managed through the conventional approach of risk assessment (e.g., in the sense that scientists are able (or by

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[4] In current literature on scientific uncertainties the term 'uncertainty' is often used both as a generic term, describing uncertainty in general (as I have also done in the title of this section) and specifically, describing a specific dimension of uncertainty (e.g., Wynne, 1992). This double usage of the term does easily cause confusion. To avoid this, I use the term 'inexactness' to describe the dimensions which by some scholars (e.g. Stirling, 1999a; Wynne, 1992) is termed 'uncertainty'.

conducting more research will eventually be able) to identify the range of possible hazards and the respective probabilities for their occurrence).

Table 1: Typology of quantitative uncertainty in policy-relevant science (adapted from Wickson et al. 2010)

| **Type of uncertainty** | **Explanation** | **Approach/ Implications** |
|---|---|---|
| **Risk** | We can imagine the range of possible hazards and calculate the probability of those hazards occurring, even though whether any of the hazards will occur or not remains unknown. | Can be dealt with through conventional risk assessments. |
| **Inexactness** | We can imagine the range of possible hazards, but we don't know the probabilities for their occurrence. It is however possible to calculate that probability, but we do not have enough knowledge to do so yet. | Can be dealt with through conventional risk assessments. More research should be initiated to reduce the level of inexactness. |

### *2.3.1 Qualitative Dimensions of Uncertainty*

*Indeterminacy*, *ambiguity* and *ignorance*, in turn, describe qualitative dimensions of uncertainty. *Indeterminacy* is a type of uncertainty that arises due to the complexity of various open-ended social and natural systems. As already described, it is impossible to include all the relevant factors and interactions when investigating complex systems. Hence, knowledge generated about complex systems will always be inherently incomplete. In other words, all scientific studies select frames of reference and each of these is limited in its ability to include all factors of a complex and dynamic reality — or to use the Hindu fable as a metaphor: one study cannot describe the whole elephant, only a part, and this part might be very different from another of the elephant's parts.

*Ambiguity* results from contradictory information and/or the existence of divergent framing, assumptions and values among different knowledge providers such as scientists, policymakers, impacted parties and the public. Krayer von Krauss (2005: 19) describes it in these words:

> In policy-relevant sciences, different analysts will use different data and different methodological approaches, adopt different assumptions, and include different factors within the scope of their studies. Scientific knowledge of the underlying processes may evolve with time. Furthermore, ethical values of different analysts will invariably influence the judgements that often must be made in the course of decision-support exercises. All of these factors represent sources of uncertainties which are difficultly communicated using the traditional, statistical approaches to uncertainty.

Again, this relates to the characteristics of complex systems — they can be described in several equally plausible ways, as there are different ways to understand and approach complex problems and to interpret results. This potential for plural framings exists both in science (especially apparent in the way different disciplines approach the same issue in different ways) and in the socio-political arena (apparent in the way in which diverse interests, perspectives and value frameworks shape understandings of particular issues). Stirling (2007) provides a useful list of places where ambiguity can manifest itself in the framing of scientific risk assessments, starting from how problems are defined and hypotheses formulated, to the choice of tools and methods for the study and its analysis, and how the level of significance for hypothesis testing is defined, and, finally how the results are interpreted and communicated.

Choices made by scientists when formulating and testing hypotheses give a good, simple, illustration of how values influence the scientific assessment of risks. Typically, one of two types of hypotheses will be tested in risk research — $H_0$; ‘There is no adverse impact’ and $H_1$; ‘There is an adverse impact’. When testing these hypotheses and determining the statistical level of significance, more concern is traditionally given to avoiding Type I errors (false positives — situations where one rejects $H_0$ and claims there will be an adverse effect, but in fact no adverse consequences manifest themselves). What this focus does, however, is to increase the chance of Type II errors (false negatives — situations where one rejects $H_1$, claims there will be no adverse effect, but in fact adverse consequences do occur). The current scientific focus on avoiding Type I errors (false positives), means that strong evidence is required in order to claim that hazardous consequences may occur. This practice has been accused of favouring the developers of new technologies at the possible expense of human, animal and environmental health. The choice of which type of errors a scientist strives to avoid is in itself a value judgement, and both choices have their respective pitfalls.

Finally, *ignorance* can be described as our inability to conceptualise, articulate and consider the outcomes and causal relationships that lie beyond current frameworks of understanding. It has been described as the things ‘we don’t know that we don’t know’ and represents an inability to ask the right questions, rather than a failure to provide the right answers. The idea here is that there will be potential impacts which we have not considered, which we have not yet even imagined as possible. An illustrative example is our initial ignorance about the potential for chemicals to act as endocrine disrupters, or the ozone-depleting potential of chlorofluorocarbons.

### *2.3.2 Recognising Uncertainty in Policy-Relevant Science*

There are many reasons why it is important to acknowledge uncertainties in policy-relevant science and decision making. Obviously, the communication and handling of uncertainties is a means with which to avoid unintended hazardous consequences, and, hence, have important ethical implications. This is at the core of the Precautionary Principle, which will be presented in more detail in the next section. As all scientific findings and advice are associated with uncertainties, dealing with these openly and explicitly will also improve the quality of the information upon which decisions are based, which may lead to better risk management, and possibly to more trust in the assistance scientists provide to policymakers. Walker et al. (2003) argue that the existence of uncertainties is generally well understood by policymakers and scientists, but that there is little appreciation for the many forms uncertainty might take, and the importance of addressing these dimensions through different approaches. To express all uncertainties in quantitative terms and treat them as if they will be sufficiently reduced through more research is misleading. The degree of indeterminacy, for instance, cannot easily be quantified. Rather, acknowledging indeterminacy implies to expect surprises and consequently to treat scientific findings as partial and conditional explanations, and therefore possibly fallible. Recognising ambiguity implies to acknowledge the diversity of possible framings, negotiating across different ones where possible, and at least being transparent about the particular frames that are chosen and the reasons for their selection. In regard to ignorance, it might be best suggested that there is little we can do about the things we don’t know we don’t know. The best approach may be to not ‘put all our eggs in one basket’ and instead to pursue a range of policy options to maintain flexibility, resilience and reversibility, as well as to consistently and vigilantly monitor for potential surprises (Stirling, 1999a).

Table 2: Typology of qualitative uncertainty in policy-relevant science (adapted from Wickson et al. 2010)

| **Type of uncertainty** | **Explanation** | **Approach/ Implications** |
|---|---|---|
| **Indeterminacy** | For complex, open, interacting systems, it is impossible to include all the relevant factors and interactions in the calculations | Scientific findings must be treated as partial and conditional explanations, and therefore possibly fallible. Hence, we must expect and be prepared for surprises. |
| **Ambiguity** | We can variously frame both the impacts we are interested in and the way we approach, interpret and understand the knowledge and calculations generated about them. | To acknowledge the diversity of possible framings, negotiating across different ones where possible, and at least being transparent about the particular frames that are chosen and the reasons for their selection. |
| **Ignorance** | We cannot imagine the possible impact. Not only have we not yet calculated the probability of the event, we are unaware of what we should make calculations for. | To pursue a diverse range of policy options to maintain flexibility, resilience and reversibility, as well as to consistently and vigilantly monitor for potential surprises. |

To reduce all questions concerning governance of novel technologies to questions of risk is also problematic because it assumes that what constitutes a risk can be scientifically and objectively defined (de Melo-Martin and Meghani, 2008). This narrow view is reflected in the importance given to 'evidence of harm' in decision-making processes, focusing primarily on harm to human health and the environment. Consequently, according to this view, if someone disagrees with the use of a specific technology, the most legitimate grounds for opposition is to prove the harmfulness of the technology in question, and this should be proven through scientific evidence, based on scientific investigations. Still, the debate on the use of modern biotechnology in food production, to provide one example, shows that there are diverging views of what constitutes a harm, and that many concerns go beyond human and environmental safety, including social, ethical and cultural aspects. People have different perceptions of hazards and risks, which may be influenced by a number of factors such as profession, gender and political ideologies. Moreover, people tend to treat risks differently depending upon their level of knowledge about potential consequences, whether the risk is familiar and whether the risk exposure is undertaken voluntarily versus being forced upon them (Slovic, 1987). De Melo-Martin and Meghani (2008) argue that it should be recognised that defining what counts as a serious risk is a value-laden choice, as are choices of the time frame for investigating risks and what counts as evidence of risk (e.g., what level of statistical significance is used in the studies and what constitutes the baseline for comparison of harms). Hence, although risk assessment can be a useful tool for decision making on its own, it is inadequate for addressing the many social, ethical and cultural concerns relevant to the future of food production. Worse still, in a democratic society the privileged role of science in framing risk and its assessment is exclusionary: it effectively limits who can legitimately participate in discussions, namely scientific experts.

### 2.4 Precautionary and Participatory Approaches

Precautionary approaches are intended to facilitate more appropriate management of complexity and uncertainty in science and decision making. The approaches are based on the Precautionary Principle. This principle has typically been regarded as a decision rule that describes specific measures for decision making in the face of uncertainty (Foster et al., 2000; Sandin, 2004; Stirling, 2007). In my presentation of the principle, I will highlight some of the challenges associated with such a prescriptive understanding of precaution and its practical implementation. In line with Stirling (1999a, 2006, 2007, 2009), I argue that rather than treating precaution as a decision rule, it is more useful to talk about precautionary approaches, e.g., how precaution can inform wider processes for governance and decision making and promote social learning. I emphasise the role of participatory approaches, both as a means to broaden the notion of risk, and to deal more explicitly with the different dimension of uncertainty.

### *2.4.1 The Precautionary Principle*

There are many examples of actions and decisions that have been inspired by the idea of precaution throughout history. It was not, however, until the 1970s that it appeared as a principle for environmental policies, with some scholars nominating a Swedish and some a German (*Vorsorgeprinzip*) origin of the Precautionary Principle (UNESCO, 2005). Currently, the most widely cited formulation of the Precautionary Principle is from the Rio Declaration on Environment and Development, Principle 15:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. 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 (Rio Declaration on Environment and Development, 1992).

A wide range of alternative formulations, with diverging legal status, exist (Foster et al., 2000) and are usually referred to as either weak or strong versions of the principle. Strong versions generally promote an active approach based on ecocentric values, whereas weak versions (like the one stated in the Rio Declaration) do not necessarily suggest any specific actions, and reflect a more anthropocentric worldview. Despite the various formulations, four central components are commonly associated with the principle; (i) taking preventive action in face of uncertainty, (ii) shifting the burden of proof to the proponents of an activity, (iii) exploring a wide range of alternatives to possible harmful actions, and (iv) increasing public participation in decision making (Kriebel et al., 2001).

Importantly, indications of harm must be identified to implement the Precautionary Principle. These indications cannot be based on crude speculations, but require some manner of scientific documentation. This documentation, for instance regarding the impacts, severity or cause of the harm, is, however, characterised by scientific uncertainties. Furthermore, a threshold of evidence of harm (e.g., the point at which both the magnitude of the harm is considered serious enough, and there is enough certainty about the probability for its occurrence, to implement the Precautionary Principle) has to be decided upon (Myhr, 2010).

The Precautionary Principle has been widely adopted in national and international policies and agreements. For the regulation of modern biotechnology in food production, the principle has been implemented in regulations such as the Norwegian Gene Technology Act (1993) (in the preparatory work and in the Regulations relating to impact assessment pursuant to the act (2005)) and the EU directive 2001/18/EC on deliberate release of GMOs into the environment (where it is specifically mentioned in the objective of the directive). As described in Chapter 4, the Cartagena Protocol on Biosafety (2003) is bounded on the recognition of a precautionary approach in decision making. The Precautionary Principle also informs GMO regulations at very practical levels such as the 'case-by-case' and 'step-by-step' approach taken by many countries when evaluating applications for commercial release. The 'case-by-case' approach implies that a scientific evaluation is mandatory every time a new GMO is evaluated for approval. The 'step-by-step' approach implies that scientific research on environmental impacts of GMOs is conducted as a series of experimental setups of decreasing physical or biological containment (e.g., from greenhouse experiments, to small scale and large field tests, to market approval). Additionally, monitoring programs are often conducted after commercialisation. These approaches are also intended to establish a learning practice for the authorities and companies developing GMOs (Myhr, 2010).

Despite the fact that the Precautionary Principle has been widely adopted in various national and international policies, the concept and its practical implications are contested. The most outspoken opponents fear that it will reduce the incentives for technological developments and economic growth, as the developer of a product must prove its safety (Morris, 2002). Others claim that current requirements for safety testing are already precautionary, and question the appropriateness of the principle as different formulations are found to be vague, circumscribed and underdetermined (Peterson, 2007). For instance, in the definition given in the Rio Declaration, different opinions prevail regarding how to understand terms such 'threat', 'serious', 'irreversibility', 'degree of scientific certainty' and 'cost to whom', depending on the situation and the interests of the actors involved (Stirling, 2006).

Wynne (1992) and Dovers and Handmer (1995) argue that some of the existing interpretations of the Precautionary Principle do not appropriately engage with ambiguity, indeterminacy and ignorance, since expressions such as 'lack of scientific uncertainty' imply that all uncertainties are reducible through further research. Additionally, Levidow (2001) notes that since full scientific certainty is rarely, if ever, claimed in judgements of safety (i.e., nothing is deemed to be safe with 100 percent certainty), the degree of uncertainty demanded by the Precautionary Principle is itself ambiguous. This relates to the 'shifting the burden of proof' aspect of precaution, as the issue of how far along the axis of 'guilty until proven innocent' decision makers need to slide is also problematic. Additionally, Levidow (2001) questions the usefulness of the 'cost-effective' criterion because it necessarily implies that there is adequate knowledge to predict the degree of potential damage and therefore conduct an assessment of what a 'cost-effective' measure for avoidance might be.

Thus, several challenges arise from treating the Precautionary Principle as a prescription for specific decision rules. Perhaps most importantly, as highlighted by several scholars (e.g., Dovers and Handmer, 1995; Funtowitcz and Strand, 2007; Stirling 1999a; Wynne, 1992) the Precautionary Principle is only of value in situations characterised by inexactness and risk, e.g., quantitative and reducible types of uncertainties, and does not recognise the other forms uncertainty may take and that these may require different approaches. As a response to this, Stirling (1999a, 2006, 2007, 2009) argues that rather than understanding precaution as a putative decision rule it is more valuable and useful to see it as an opportunity for reflexivity and social learning. By treating precaution as an approach, its application is extended from a mere prescriptive guide to decision making and risk management, to an approach that can inform decision making and scientific research, and which can inspire other modes of knowledge generation through participatory and transdisciplinary processes. This process-based view of precaution acknowledges to a larger extent the full scope of uncertainties. In the following, I describe what precaution as a process-based approach entails in more detail, and highlight the role of participation as a means to 'open up' decision making and knowledge generation (Stirling, 2006, 2008a, 2009).

### *2.4.2 Precautionary Approaches*

Many scholars have engaged in the discourse on precautionary approaches and tried to describe what they entail in practise for science and decision making (see for instance Foster et al., 2000; Harremoës et al., 2001; Kriebel et al., 2001; Stirling, 1999a; Stirling and Gee, 2002; UNESCO, 2005). At the core of precautionary motivated research is the notion of 'a broader scope' in research, which is seen as a means to acknowledge the complex nature of, and the uncertainties associated with, natural and social systems. To 'broaden the scope' has multiple implications for how research is carried out; of these, I have chosen to emphasise the following:

1. *Broadening the problem framing of research,* to better acknowledge and understand the multidimensional nature of complex systems/problems. One way to do this is to promote interdisciplinary research. Another is to develop more comprehensive models that better represent complex systems. When evaluating the safety and benefits of a particular product, broadening the scope would also imply consideration of the wide range of ecological, social, and ethical implications of introducing the product, as well as investigation of alternative products/solutions and their implications.
2. *Broadening the spatial and temporal scale of research*, as expanding the geographical scale and duration of studies may help reveal more of the complexities and uncertainties involved and detect delayed responses and long-term consequences. This point also includes the question of when to carry out research. For instance, a broad scope can imply that research on a product is carried out during the innovation process of a product, before it is evaluated by decision makers or put on the market, to promote a discussion of the wider implications for developing and marketing the product, as well as evaluating alternative solutions. It can also mean carrying out risk associated research and monitoring after the approval and release of a product to detect unexpected consequences.
3. *Broadening the notion of expertise*, reflects the view that scientific evidence and analyses are essential but not sufficient to properly deal with complexity and uncertainty. Consequently, expert-led risk assessments should not have an authoritative and privileged role in the decision-making process. To expand the range of knowledge providers implies that one must gather knowledge, experience and viewpoints of all impacted parties and the general public (often facilitated through transdisciplinary research and participatory processes), and to treat these as legitimate and valuable sources of knowledge for informing decisions.

By adopting this process-based view of precaution, it becomes evident that conducting more research is insufficient to promote precaution, as it does not necessarily reduce uncertainties nor necessarily lead to consensus about the relevant risk issues among scientists and impacted parties. Furthermore, conducting more research does not automatically broaden the scope of nor the involvement with knowledge generation, as outlined above.

In turn, a process-based approach underlines the idea that scientific knowledge can legitimately be interpreted in different ways to yield competing views of a problem. As mentioned earlier (in the description of ambiguity), different scientific interpretations of a problem may be the result of differences in disciplinary backgrounds, values and assumptions, or particular interests and priorities. These may influence the questions posed by scientists and their interpretation of the results (Krayer von Krauss, 2005; Kvakkestad et al., 2007; Stirling, 2007). Instead of striving for scientific consensus, which may mask competing views, these differences should be dealt with openly and explicitly, so as to uncover the wide range of views held by scientists and the assumptions upon which they are based. This requires transparency, reflexivity and communication between scientists from different scientific disciplines. Evaluation of scientific evidence should not, however, be restricted to scientists only, but should also involve impacted parties and the general public, for instance through the type of 'extended peer review' described by Funtowicz and Ravetz (1990, 1993, 1994). As well as making underlying assumptions and priorities more explicit, these processes may contribute to the identification of a broader range of alternative solutions to a given problem.

Perhaps the most important implication of precautionary approaches for policy-relevant science is a call for humility — to question the idea that conducting scientific assessments of risk adequately covers all important and legitimate concerns related to a given product. As already described, this is not to say that expert-led risk assessments do not contribute valuable insights about environmental and health impacts. Nonetheless, these should not be considered the only source of legitimate knowledge, and consequently should not have the authoritative position which they currently hold in decision-making processes. This call for humility reflects both a recognition of the limits of reductionist science's ability to describe complex systems, and the idea that scientific evidence is not a set of objective and value-free facts, but rather is shaped by values and interests. Furthermore, it underlines the fact that making decisions about the use of novel technologies involves more than evaluating human and environmental safety, and that other considerations such as ethical justifiability, societal needs and cultural concerns are not well addressed through the narrow and expert-led assessments of risk.

Many of the characteristics described for precautionary motivated science also apply for decision making. Drawing on previous work with colleagues (Wickson et al., 2010) precautionary approaches in decision making can be summarised as:

1) The use of scientific research that is broadly framed, interdisciplinary, able to consider indirect causal mechanisms, and contributory to a lifecycle approach to analysis.

2) Recognise the limits of this scientific knowledge and expose the knowledge to critical reflection and 'extended peer review', particularly to create transparency about embedded choices and hidden assumptions.
3) Promote vigilance, follow-up research and surveillance of commercialised products and incorporation of these insights into ongoing decision-making processes, as a means to reduce uncertainties and minimise surprises arising from ignorance.
4) Handle ambiguity and indeterminacy through interdisciplinary approaches and broad based public participation. This includes the consideration and implementation of a range of socio-technical alternatives and policy options. The aim should be to employ a diversity of options so as to increase the resilience of social and naturals systems.

As precaution is more about the process than the outcome of an exercise, methodologies aimed at facilitating precautionary approaches will have to be continuously developed and adapted to specific contexts or issues. Thus, the methodologies are far from being fully developed and further discussion of the practical implications of these approaches is necessary. Perhaps the most important outcome of the discourses on precaution will be that research and decision-making processes to a larger extent are 'opened up' (Stirling, 2006, 2008a, 2009) allowing for deliberative discussion on science and technology at an early stage of the developmental process. Stirling (2006, 2008a, 2009) emphasises the role of precaution as an approach that broadens both the inputs and outputs to assessments or processes of risk analysis. This implies not only that a broad range of alternatives and their pros and cons are taken into account (the inputs), but that the assessment exercise is designed to maintain diversity in the recommended actions and solutions (outcomes).

### *2.4.3 Precaution and Participation*

Using participatory processes as a way to open up research and decision making has recently received a lot of attention. This recent interest could partly be a result of critical questioning of the authoritative role of science in decision making and may be seen as an attempt to increase the legitimacy of and trust in decision-making processes. Importantly, it is also proposed as a response to the challenges posed by uncertainties, as a means to explore ambiguities and reveal different dimensions of risk, as well as a way to broaden the range of possible alternative solutions to a problem. Post Normal Science (PNS) was introduced by Funtowitcz and Ravetz (1990, 1993, 1994) as a contrast to normal and applied science. PNS applies for policy-relevant science which typically deals with post normal problems where "facts are uncertain, values in dispute, stakes high, and decisions urgent" (Funtowicz and Ravetz, 1990). Their ideas primarily concern replacing 'truth' as the standard for evaluating science, with a focus on 'quality assurance' based on increased participation in knowledge generation. E.g., when managing post normal problems decisions cannot be made based on the advice of experts alone, but require the involvement of an 'extended peer community' consisting not merely of persons with some form of institutional accreditation, but rather of all those with a desire to participate in the resolution of the issue. These ideas are also reflected in the call for 'upstream public engagement' (e.g., involvement of the public at an early stage of development process (Felt and Wynne, 2007; Wynne, 1992)), the 'negotiated science' approach presented by Carr and Levidow (1999) and in the notion of 'opening up' the process of knowledge generation and decision making and in this way increase the diversity of opinions and knowledge generated about a given problem (Stirling, 2006, 2008a, 2009).

As with precaution, the idea of public participation is also contested, and can easily be misused for instrumental purposes. Different opinions prevail, for instance, with regard to why these processes should be carried out, who to involve, how to initiate them, when is the right time to conduct them, and where they should be generated and carried out (Delgado et al., 2010). Stirling (2006, 2008a, 2009) addresses some of these questions by describing substantive, instrumental and normative rationales for participation. Under a substantive rational participation is perceived as a means to achieve better ends. Hence, attention is put on the outcome of the process, reflecting the idea that the best outcomes will emerge through deliberative and open participatory processes. Under an instrumental rationale, emphasis is also placed on the outcome of the exercise, but here the focus is not necessarily to identify the best outcome according to societal values, but rather to design the exercise in such a way that a specific outcome, often reflecting the interests of the designers of the exercise, is reached. A normative rationale, in turn, puts emphasis on process of participation rather than the results of the exercise. Under this rationale, participation is simply perceived as 'the right thing to do' — as an end in itself. Stirling advocates for this process-based view on participation and emphasises the importance of practising participation as a means to 'open up' decision-making processes, which he describes as "…systematically revealing how alternative courses of action appear preferable under different framing conditions and showing how these dependencies relate to the real world of divergent contexts, public values, disciplinary perspectives and stakeholder interests" Stirling (2009: 211). Hence, the purpose is not to specify a particular policy option, but rather, to phrase it in Stirling's own words, to convey 'a series of plural and conditional' recommendations (Stirling, 2006, 2008a, 2009).

## 2.5 Precaution and Participation for Sustainable Development

Sustainability has become a key concept for governance, both nationally and internationally. As described in Chapter 3, it is also of great concern for salmon aquaculture. Here, I will elaborate on the concept of sustainable development and particularly highlight the difficulties related to its practical implementation. I will relate sustainability to precaution and participation. As for precaution and participation, I emphasise the value of process-based approaches to sustainability.

### *2.5.1 Defining Sustainable Development*

The concept of sustainability has deep historic roots dating back to 13th century England where it was used in everyday language, for instance when discussing renewable and reusable raw materials. Other traces of the concept can be found in German literature on forestry from the 17th century (Kamara and Coff, 2006). More recently, it was extensively used in radical environmental literature in the 1970s. It was, however, not until the UN World Commission on Environment and Development (WCED) published their landmark 1987 report, *Our Common Future*, that the concept of sustainable development entered the international policymaking arena. The report defines sustainable development thusly: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED, 1987)

The WCED definition extended the traditional understanding of sustainability. From an initial focus on purely environmental protection, it is now understood as a three dimensional concept focusing on the interaction between environmental protection, social development and economics (Dovers and Handmer, 1995; Kamara and Coff, 2006). Economic growth is considered indispensable in promoting development and satisfying human needs, but the report emphasised that this growth should be qualitatively different, described as a growth based on an absolute — and not only a relative — efficiency improvement in the use of energy and other natural resources. Technological development is recognised as a key strategy to achieve this. Furthermore, the benefits from growth must be shared more equally between poor and wealthy nations (NBAB, 1999). Importantly, sustainability implies taking long term environmental and human safety concerns into account, as part of meeting future needs. Kamara and Coff (2006), summarise the basic normative and ethical ideas of the concept of sustainable development in the WCED report as:

1. meeting needs
2. social fairness

3. maintenance of natural resources and nature
4. a sustainable economy

With the publication of the WCED report, sustainability has received widespread support and is a major theme in both national and international policymaking. Nevertheless, the idea of promoting human wellbeing and economic growth, while at the same time conserving the natural environment has proven difficult to carry out. Many would argue that the state of the planet has become worse — not better — in the two decades since the WCED report was published. Many criticise the report for defining sustainability too broadly and vaguely, pointing to the myriad and often contradictory ways that sustainability has been employed, claiming that this makes it a concept without any real content or significance (Kamara and Coff, 2006). Redclift (1993), on the other hand, argues that this is precisely why it has gained currency and so many have adhered to it. Another criticism raised against the WCED report is that it does not give any specific prescriptions as to how to achieve sustainability and how to define the criteria for assessing it. Stirling (1999b), however, highlights that the concept of sustainability is, by its very nature, multidimensional and ambiguous, and warns that these characteristics can easily be masked by defining concrete criteria for measuring sustainability. He emphasises that searching for sustainable solutions implies making long term predictions of complex and constantly evolving systems — predictions that necessarily are characterised by indeterminacy, ambiguity and ignorance. Voß and Kemp (2006) agree with this and emphasise that goals such as social justice, reduction of environmental risk and economic growth can seldom be achieved simultaneously or to the same extent, which makes choices over sustainability highly contingent on the pre-eminence of particular sets of values.

As for participation, Stirling (2009) also describes sustainability in terms of substantive, instrumental and normative — process-based — perspectives. A substantive perspective relates to how sustainability is defined. It concerns human wellbeing, social equity and environmental quality — with all the challenges related to fulfilling these sometimes conflicting goals. To treat sustainability instrumentally primarily implies using the concept in a way that sustains privately favoured features of the status quo. It relates to how the ambiguities in the definition of the concept can be exploited to support the continuation of a wide range of activities, whose consequences are not necessarily true to the original spirit of sustainability. Finally, a process-based perspective on sustainability focuses on the process of searching for possible sustainable pathways, rather than the specific outcomes or solutions. According to Dovers and Handmer (1995) and Stirling (2009), this implies making decisions that secure diversity in alternatives and solutions, as a means to maintain flexibility, reversibility and resilience, and consequently be better prepared for changes in future conditions. It is in this process-based approach that the concepts of precaution, participation and sustainability become interlinked.

### *2.5.2 Sustainability as a Process*

Despite the fact that the linkages between precaution, participation and sustainability are not explored much in current literature (Stirling, 2009), it is not difficult to describe areas where they are related. A common theme of both precaution and sustainability is to protect the natural resource base. Since precaution is about preventing irreversible damage to nature and natural resources, it becomes a prerequisite for sustainability as a means to secure future needs. Uncertainty is another aspect that links precaution, sustainability and participation. While precaution concerns questions of how to act in the face of uncertainty, judgements about sustainability involve making long term predictions which are based on current and inherently uncertain knowledge as well as on contemporary societal and ethical values. Moreover, since knowledge evolves and values change, sustainability goals can never be determined once and for all. Voß and Kemp (2006) and Stirling (2006, 2009) describe participatory processes as an attempt to acknowledge this by involving all relevant parties in the search for sustainable solutions.

As phrased by Voß and Kemp (2006: 15) “Sustainability is an ambiguous and moving target that can only be ascertained and followed through processes of iterative, participatory goal formulation.” This is also in line with Funtowicz et al. (1999b) who claim that deep involvement of policymakers and the public in the quality assurance of innovations in science and technology is crucial when searching for sustainable solutions. Again, Stirling (2006, 2009) emphasises that the real potential for participatory processes as a means to explore sustainable solutions lies in the facilitation of processes that intend to ‘open up’ appraisals. The key issue is to maintain plurality and diversity in policy options. According to a process-based view, the drive for sustainable development and better handling of uncertainties lies in the identification of a diverse range of options and in the maintenance of this diversity when making governance choices, as a way of strengthening the adaptability, reversibility and resilience of governance (Stirling, 2006, 2009). Stirling (2008a, 2009) of course recognises that governance choices must be made — still, he argues that it is through an ‘opening up’ approach that a more diverse portfolio of options and choices may be illuminated. In this view, the prime concern when promoting sustainability is not to identify the most sustainable solutions or pathways, but to make decisions that maintain a diversity of possible solutions.

Sustainability is about securing future needs, and as we are uncertain of future challenges, maintaining a diversity of options implies a strengthened ability to adapt to changing conditions. Furthermore, evaluating a range of alternative solutions to a problem, rather than assessing the risks of only one specific product/alternative, provides an opportunity to address broader questions, such as: What are the societal needs? How may choosing one alternative influence the ability to pursue other alternatives in the future? As advocated previously, these types of questions cannot be answered by scientists alone, but require the participation of other impacted parties and the public.

My presentation of precaution, participation and sustainability, and the support for process-based approaches which I have advocated here, can easily, and perhaps rightly, be criticized for being nice in theory, but impossible in practice. I am aware that even though I point to some of the challenges and criticism raised against these concepts, I do not deal much with practical questions such as; how and under which circumstances these approaches should be carried out, and what changes are required in structures and institutions of science and decision making? Other important aspects that remain unaddressed are for instance, power dynamics (which in real life often work against the idea of pluralism in policy advice and options); legitimacy in decision making (if everyone is considered a legitimate knowledge provider, to whom will decision makers turn when they need to legitimise their decisions?); costs (facilitating participatory approaches is costly, as is prolonging the decision-making process and delaying technological developments); and the need to 'close down' after a problem has been 'opened up' (e.g., should all alternatives be pursued, and if not, then which?). As always, even the best intentions can be exploited instrumentally and used for purposes that were not intended or considered initially, and this list of unresolved issues could be made much longer. I recognise these challenges and acknowledge that adopting precautionary and participatory approaches will require profound changes to current processes and institutional arrangements. However, within the focus and scope of this thesis, I will not do more than merely acknowledge this. Even though carrying out processed-based approaches in relation to precaution, participation and sustainability is ambitious, it is nonetheless important. I recognise that it would be impossible to implement all the strategies that I have suggested here, at least in a short term. They are better to be perceived as goals — a move in a different, and in my view better, direction.

## 3.0 Salmon Farming

Fish farming has been practiced for centuries. It originated in China, with the domestication of carp, 4 – 5000 years ago. Here, farmed fish constituted an essential source of food for rural families. It was part of an integrated production system, where recycled animal wastes were used as fish feed. In more recent times, particularly during the last 50 years, aquaculture has grown into a highly commercialised global industry. About half of the fish found on grocery shelves today comes from a farm (FAO, 2009). As catches from capture fisheries are declining due to overfishing, and lack of arable land and fresh water limit further growth of agricultural food production, fish farming is considered an important strategy to meet future demands for food, particularly fish and seafood products, from a growing human population (Diana, 2009; Duarte et al., 2009; FAO, 2009). Since 1970 aquaculture has grown with an annual average growth rate of 8.7 percent worldwide (FAO, 2009). It is expected to grow at significant rates through 2025, and thereby remain the most rapidly growing food production system (Diana, 2009). Asian countries continue to dominate aquaculture production, with China alone producing 67 percent of the total quantity and 49 percent of the total value of aquaculture worldwide. (FAO, 2009). Carps, barbells and other cyprinids, typically raised in simple pond systems, continue to dominate among farmed fish species (FAO, 2009; Sommerset et al., 2005), but the production of high value species, particularly Atlantic salmon (*Salmon salar*), has grown tremendously during the last four decades (Figure 1 pp. 30) (Fishstat Plus, 2008; Deutsch et al., 2007; Le Curieux-Belfond et al., 2009).

The cases chosen for the studies conducted for my thesis (with exception of the study presented in Paper 3) concern the use of modern biotechnologies in salmon aquaculture. Here, I provide information about these case studies. I start by describing the history of salmon farming in Norway, as Norway was the first country to raise Atlantic salmon in farms and is currently the main producer of farmed salmon, with approximately 50 percent of the world's total salmon production (e.g., around 740,000 tonnes) in 2007 (Fishstat Plus, 2008, see Figure 1 pp. 30). Then I present the main biological factors that pose constraints on the salmon aquaculture and possible solutions to these, focusing on strategies involving the use of modern biotechnology. I end the chapter by describing the main environmental problems associated with salmon aquaculture and briefly presenting some applications of modern biotechnology that are suggested as means to promote more sustainable production practises.

## 3.1 Salmon Aquaculture

Salmon aquaculture is a young industry in tremendous growth. Atlantic salmon is currently one of the most intensively farmed fish species in the world, and represents the largest proportion of salmon production. It is typically raised in floating sea cages (or net pens) anchored to the seabed. Two species of Pacific salmon, Chinook salmon (*Oncorhynchus tshawytscha*) and Coho salmon (*Oncorhynchus kisutch*) are also domesticated, but produced at a much smaller scale than Atlantic salmon. Norway, Chile, Scotland and Canada are currently the largest producers of Atlantic salmon (Figure 1). Production occurs both within the native range of the species (Northern Europe and Eastern North America) and beyond (Western North America, Chile, Australia).

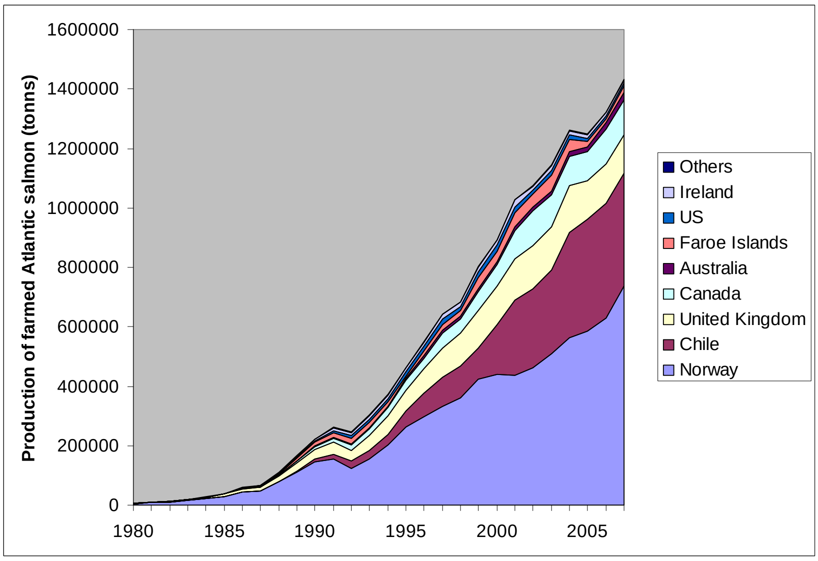

Figure 1: Main producers and development of farmed Atlantic salmon production. (Based on data available at Fishstat Plus, 2008).

### *3.1.1 Salmon Farming in Norway*

Norwegians were the first to experiment with salmon farming. The first intentions date back to the end of the 1960s and were a result of practical experiments conducted by local fish farmers, based on experience gained from trout farming. Berge (2000) points out three steps that were crucial for the development of Norwegian salmon farming; (i) farming rainbow-trout in salt water rather than fresh water, (ii) successful breeding of Atlantic salmon, and (iii) moving salt water fish farms from concrete dams on land into the sea itself. The long and protected Norwegian coastline constitutes ideal conditions for salmon farming and by the end of the 1970s a small scale industry emerged along the Norwegian coast, with steady production growth in the decades to follow (Figure 2, pp. 32). The only major crisis in the industry occurred during the late 1980s/early 1990s, primarily due to massive attacks of fish diseases and a lack of measures to combat these at the time. Today, salmon aquaculture represents the second most important export industry in Norway, after oil and gas, with an export value of approximately 18 billion Norwegian Kr (NOK) (approximately 3 billion US dollars) in 2008 (FHL, 2009). Most of the salmon farmed in Norway (90-95 percent) is exported, primarily to France, Denmark, Poland, Japan and Russia (Norwegian Directorate for Fisheries, 2009a). Scenarios made for 2020 predict that the growth in salmon production in Norway will most probably continue and that there is potential for a two-to-threefold increase (ECON, 2002). Since the report making this prediction was published the production of salmon has almost doubled (Figure 1, pp. 30). About 2,700 people were directly employed in Norwegian salmon and trout production in 2008, while the total number of man-years which directly and indirectly depend on fish farming in Norway is estimated at 19,500 (SINTEF, 2005). Since the 1990s there has been a shift towards privatisation and ownership concentration in Norwegian salmon aquaculture with aquaculture firms merging into multinational corporations (ECON, 2002; Oglend and Tveteraas, 2009). Data from the past ten years shows that while the number of licences for salmon and trout production has increased, from 799 in 1999 to 988 in 2009, the number of companies has decreased from 1,100 in 1990 to 186 in 2008 (Hjelt, 2000; Norwegian Directorate of Fisheries, 2009b).

## 3.2 Factors Limiting Salmon Production and Possible Technological Solutions

In this section I describe the main biological factors that pose constraints on the salmon industry, notably infectious fish diseases and lack of high quality feed resources (Dunham, 2009; Myhr and Dalmo, 2005; Naylor et al., 2009). I give examples of how these factors have impacted the salmon farming industry, particularly in Norway, and describe past, present and possible future solutions to these challenges, with particular emphasis on strategies involving modern biotechnology applications. Furthermore, I describe how modern biotechnology is used in selection and breeding programs, with the intention of increasing the efficiency of breeding schemes. Finally, I present the main environmental problems associated with salmon farming and briefly describe some applications of modern biotechnology which are suggested as a means to promote more environmentally sustainable salmon farming practices.

### *3.2.1 Infectious Fish Diseases*

Farmed salmon are highly exposed to the surrounding environment, as the fish are raised in floating cages in the sea. Infectious diseases are easily transmitted in water, and the high density of fish in the cages creates ideal conditions for fish pathogens, such as bacteria, virus and parasites. This causes major losses for the salmon farming industry (Biering et al., 2005; Dunham, 2009; Sommerset et al., 2005), with Chile experiencing some of the most dramatic production losses in the last couple of years, primarily due to the viral disease *infectious salmon anaemia* (ISA) (Barrionuevo, 2008). Additionally, diseases from fish farms may spread to, and harm, wild salmonid species, thereby posing a threat to native populations.

The first major losses due to fish diseases in Norwegian salmon farming occurred in the late 1980s, when a bacteria disease caused by *Vibriosis* spp wiped out large proportions of farmed salmon, followed by outbreaks of cold water *vibriosis* and *Furunculosis* in the early 1990s. At first, these diseases were primarily combated with large doses of antibacterial drugs. Due to intensive vaccine research and development, the antibiotic usage was however quickly reduced to a minimum (Grave et al., 1999) (Figure 2).

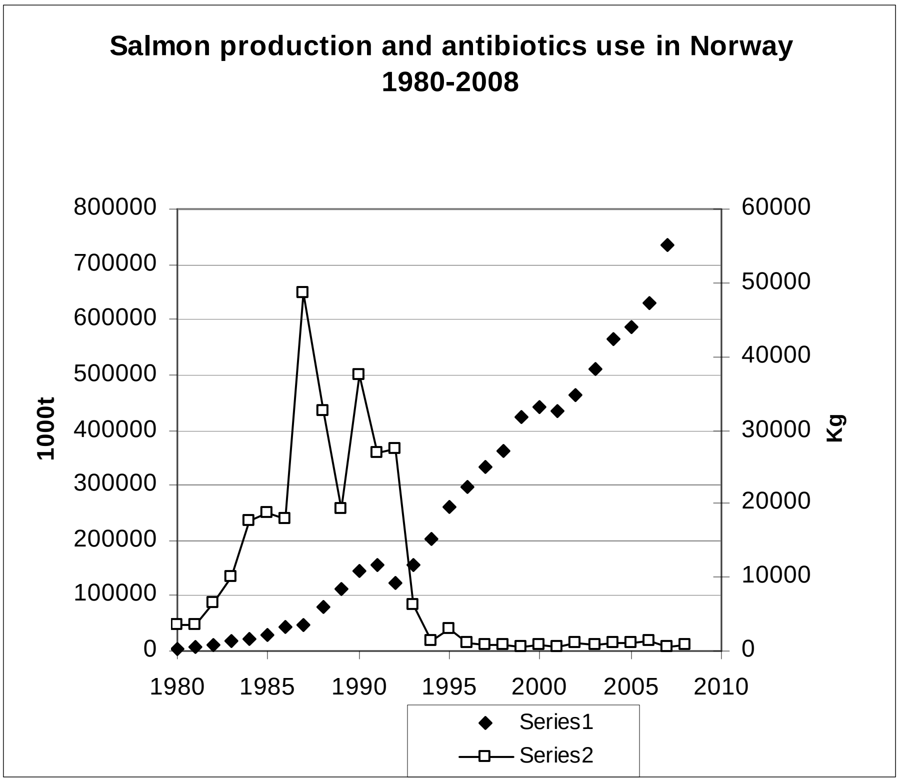

Figure 2: Salmon production and antibiotics use in Norway. Data on salmon production is based on Fishstat Plus, 2008. Data on antibiotics use is based on Norwegian Institute of Public Health (1986, 2007, 2009).

Vaccine development is often described as one of the most important strategies to combat infectious fish diseases (Hill, 2005). Vaccination induces immunity against a specific disease by introducing weakened or purified forms of the pathogen causing the disease, thereby stimulating the immune system of the vaccinated organism. The immune system will then produce antibodies against the antigens specific to the injected pathogen. The idea behind vaccination is that once these antibodies are produced the vaccinated organism will be better prepared to combat the pathogen in case of later attacks. The vaccine can either consist of live but weakened (attenuated) forms of the pathogens, killed or inactivated forms of the pathogens, or purified material such as antigenic proteins/recombinant proteins or a gene coding for the specific antigen.

The first vaccine to be introduced to salmon aquaculture was an immersion vaccine (against salmonid Vibrio diseases in the 1980s), but injectable vaccines turned out to be more efficient and suitable as these vaccines could contain antigens against several different pathogens. Thus, injectable multivalent adjuvant[5] vaccines, using oil emulsions as adjuvants, did quickly become the preferred option for vaccine administration. All farmed salmon in Norway are currently vaccinated before being transferred to seawater. One of the most extensively used vaccines contains antigens for six different pathogens (Sommerset et al., 2005). The use of oil emulsions as adjuvants does, however, have drawbacks in terms of unwanted side-effects such as internal organ adhesions, melanin deposits and effects on appetite and growth (Berg et al., 2006). Additionally, while these vaccines have proven to be an efficient strategy to prevent bacterial diseases, it has been much more difficult to combat viral and parasitic diseases through vaccination (Biering et al., 2005; Sommerset et al., 2005). The industry is still struggling to find efficient means to combat these pathogens[6], and this is perceived as one of the main problems facing fish vaccinology today (Biering et al., 2005). Most virus vaccines available for aquaculture are based on inactivated virus or recombinant subunit proteins[7], as vaccines based on attenuated live viruses are considered unsafe for the environment and consumer health. Inactivated virus vaccines and subunit proteins are non-replicating and non-infective. High doses, and sometimes more than one injection during the lifespan of the salmon, are therefore required for the vaccine to be effective. No vaccines against parasites are currently commercially available (Sommerset et al., 2005).

### Modern biotechnology applications for disease protection

Modern biotechnology is considered a useful tool to enhance disease protection among domesticated fish and prevent the spread of diseases. This includes tools to detect, identify and screen for the presence of pathogens, and tools for vaccine development (Adams and

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[5] An adjuvant is an agent that may stimulate the immune system and increase the response to a vaccine, without having any specific antigenic effect in itself.

[6] Some of the economically most important virus diseases are Viral haemorrhagic septicaemia virus (VHSV), infectious haematopoietic necrosis virus (IHNV), infectious pancreatic necrosis virus (IPNV) and infectious salmon anaemia virus (ISAV) (Biering et al., 2005; Lorenzen and LaPatra, 2005). The most significant parasite is Salmon lice (copepods of the family Caligidae) (Costello, 2009).

[7] Recombinant vaccines are created by utilizing bacteria or yeast to produce large quantities of a single viral or bacterial antigenic protein. This protein is purified and injected into the receiving organism which will then make antibodies to the disease agent's protein.

Thompson, 2006). In fact, modern biotechnology has already made significant contributions to fish vaccine development, primarily through the development of recombinant virus vaccines (based on recombinant subunit proteins) and Deoxyribonucleic acid (DNA) vaccines (Sommerset et al., 2005). In the following, I will describe DNA vaccination in more detail as this constitutes the empirical case for one of the studies conducted for this thesis.

DNA vaccination is currently considered one of the most efficient and promising strategies to combat viral diseases in fish (Lorenzen and LaPatra, 2005). DNA vaccines consist of a bacterial plasmid which contains a gene that codes for an antigen against a specific pathogen. The vaccine is typically delivered by intramuscular injection. If the injected plasmid DNA is taken up by an antigen presenting cell, the specific antigen will be produced by the cell's own apparatus (e.g., through gene expression) and transported to the surface of the cell where it will be recognized by immune cells, thereby stimulating the immune system. The development of DNA vaccines against infectious fish diseases has several attractive benefits such as low cost; ease of production and improved quality control; heat stability; identical production processes for different vaccines; and the possibility of producing multivalent vaccines (Hew and Fletcher, 2002).

A number of DNA vaccines have already been approved for commercial use in both pet and livestock (Redding and Weiner, 2009). The first DNA vaccine to obtain licensure was the IHNV DNA vaccine (Apex-IHN®) used against infectious pancreatic necrosis virus (IHNV) in farmed Atlantic Salmon. It was developed by Aqua Health, Ltd, (an affiliate of Novartis, Charlottetown, Canada) and was approved for marketing by the Canadian Food Inspection Agency in July, 2005 (Novartis, 2005). A number of other DNA vaccines for fish have been tested with varying degrees of success, including for VHSV, IPNV and ISAV (Redding and Weiner, 2009; Tonheim et al., 2008).

Despite the attractive characteristics of DNA vaccination, a number of questions remain to be solved related to potential undesirable biological impacts such as unintended immune responses; the fate of the DNA construct after injection of the vaccine; and the possibility of spread to the aquatic environment (Gillund et al., 2008a; Myhr and Dalmo, 2005; Tonheim et al., 2008). In addition, there are legislative and ethical issues involved. For instance, due to uncertainties with regard to whether DNA vaccines persist, degrade and remain in the tissues/ organs, Norwegian authorities will regulate and label DNA-vaccinated fish as GMOs (Foss and Rogne, 2007). Due to consumer concerns regarding GMOs, this may affect the market price.

Development of disease-resistant fish through genetic modification represents another biotechnological strategy for disease protection. Disease resistant transgenic fish have already been successfully developed for several fish species (Dunham, 2009), but no such fish has yet been commercialised. As will be described in more detail in section 2.3.1, a major concern related to the commercialisation of transgenic fish is the potential for adverse environmental consequences in case of fish escape.

### *3.2.2 Lack of High Quality Feed Resources*

Salmon is a carnivorous species; fish meal and fish oil produced from wild caught marine species constitute the main feed ingredients in salmon feed (Ellingsen et al., 2009; Naylor et al., 2009). These resources satisfy the nutritional requirements of salmon and secure high levels of marine fatty acids (omega-3 polyunsaturated fatty acids) in the fish fillets, conveying health benefits to humans consuming the fish (Connor, 2000). Aquaculture currently absorbs approximately 56 and 87 percent of the world supply of fish meal and fish oil, respectively (FAO, 2009). Lack of high quality feed resources is currently considered one of the main constraints for future development of salmon aquaculture and feed represents its largest expense. Between mid-2005 and mid-2008, the cost for fish meal and fish oil rose 50 and 130 percent, respectively (Naylor et al., 2009). Thus, limited availability and increasing costs of marine resources has resulted in a shift toward the search for alternative feed ingredients (Naylor and Burke, 2005; Tacon and Metian, 2008).

A number of alternative feed resources are currently being explored or are already in use (see for instance Gatlin et al., 2007; Tacon et al., 2006; Turchini et al., 2009; Waagbø et al., 2001). Plant derived proteins and oils are currently most commonly used to replace marine resources. For instance, salmon diets in Norway are now based on approximately 60 percent marine ingredients, the remainder being made up of plant oils, plant proteins and various minerals, vitamins and colour (Ellingsen et al., 2009). Other potential alternative resources include species from lower trophic levels, by-products and by-catch from fisheries and aquaculture, animal by-products, GM plants, and products from microorganisms and GM microorganisms (Gillund and Myhr, 2010).

#### Modern biotechnology applications on feed resources and feed utilisation

Plants and microorganisms can acquire new characteristics through genetic modification, so that they are more suitable as resources for salmon feed. A lot of research has been invested in the development of GM plants that can synthesise high levels for omega-3 polyunsaturated fatty acids, as marine resources currently constitutes the source of these fatty acids (Napier et al., 2006; Robert, 2006). Additionally, research is carried out to produce plants with altered levels of antinutrients (e.g., phytic acid), nutrients (e.g., lysin, β-glucan and micronutrients such as vitamin E) and changed starch structure and oil content (Gatlin et al., 2007). Qi et al. (2004) were the first to report the successful accumulation of omega-3 polyunsaturated fatty acids in GM plants, but despite intensive research the level of fatty acids in these GM plants remains low. Furthermore, there is a lack of understanding as to whether unintended metabolites with potentially unintended impacts on health and/or the environment may be produced in the plants along with the nutritional molecules (Schubert, 2008).

As an increasingly larger proportion of salmon feed is based on plant resources, currently cultivated GM crop plants also represent an application of modern biotechnology that is of relevance with regard to salmon feed. Major GM crop plants are soy and maize. About 77 percent of the soy and 26 percent of the maize cultivated around the world today is GM (GMO Compass, 2010). The most commonly introduced traits are herbicide tolerance and insect resistance or a combination of these. GM plants are widely used in animal feed in the EU and North and South America. Whereas labelling is not required in the Americas, EU requires labelling of feed products containing more than 0.9 percent of an approved GM ingredient (Regulation No. 1830/2003). Animals fed GM feed are, however, not labelled as GM, neither in the Americas nor in the EU. 19 processed GM feedstuffs from maize, oilseed rape, cotton and soy are currently approved for feed production in Norway (Norwegian Food Safety Authorities, 2009), but has not yet been utilised as the aquaculture industry fears consumer reactions. The cultivation and use of GM plants in food and feed have revealed a broad range of views among scientists with regard to their documented and potential health and environmental impacts (see Andow and Zwahlen, 2006; Weaver and Morris, 2005 and references therein). The Norwegian Scientific Committee for Food Safety (2009) have not drawn any clear conclusions about effects on fish health when GM plants are used in salmon diets, but claim that growth, digestibility, feed utilization and other health parameters seem to be more influenced by the plant material as such, rather than whether the plant is GM.

Bacteria, yeasts and unicellular and filamentous algae can, through a fermentation process, produce proteins and fatty acids for fish feed production (Miller et al., 2008; Naylor et al., 2009; Tacon et al., 2006). As with plants, these microorganisms can also be genetically modified and thereby improve their qualities for fish feed production (Waagbø et al., 2001). There is, however, currently no commercial production of microorganisms for fish feed production, and very little research on GM microorganisms for fish feed production is carried out.

Furthermore, research has been carried out to develop transgenic salmon with improved feed efficiency or altered metabolism so that they can better utilise vegetarian feed resources (Delvin et al., 2006; Le Curieux-Belfond et al., 2009; Maclean, 2003; Maclean and Laight, 2000). Most research on transgenic fish, however, concerns growth enhancement (Delvin et al., 2006; Maclean, 2003). This research has shown that in some instances growth enhancement is accompanied with changes to other traits, including improved feed efficiency. For instance, the transgenic growth enhanced ‘Aqua Advantage Salmon’, which is currently awaiting approval for commercialisation in the US and Canada, is also reported to have improved feed efficiency (Aerni, 2004; Du et al., 1992). This is described in more detail in section 2.3.1.

### 3.3 Salmon Selection and Breeding Programs

Investments in the selection and breeding of aquaculture species are small compared to species used in livestock and crop production. Atlantic salmon is, however, one of the aquaculture species where the genetic material has been improved through family-based selection programs. The European aquaculture industry is now largely based on a few selectively bred strains of mostly Norwegian origin. Breeding programs have also been put in place in Canada and Chile. Growth rate is the most important trait for selection, and major advances have taken place in recent years. Additionally, salmon is now bred for traits such as increased disease resistance (particularly against IPNV and ISAV), delayed sexual maturation, fillet quality and colour, as well as reduced aggressiveness. There are, however, major challenges related to family-based selection programs, such as inbreeding depressions and selection for traits where measurement techniques for live fish are lacking (e.g., traits such as disease resistance, fillet quality, feed efficiency and maturation) (Sonesson, 2003). Research in aquaculture genetics, particularly the use of DNA-based genetic markers for marker-assisted selection and the development of transgenic fish, are examples of modern biotechnology applications which hold promise for further advancements in salmon breeding.

**Timeline: Development of Norwegian salmon aquaculture and technological innovations**

**During the 1960s:** Atlantic salmon are successfully bred in cages in sea water in Norway.

**During the 1970s:** A small industry of salmon farming emerges along the coast of Norway.

**During the 1980s**: Norwegian salmon farming really begins to take off.

**Mid-1980s:** The first transgenic fish is successfully developed (Zhu et al., 1985).

**Late 1980s:** First severe outbreaks of bacterial and viral diseases in Norwegian salmon aquaculture.

**1987:** Peak year in antibiotic usage in Norway (48.5 tonnes) (Norwegian Institute of Public Health, 2007).

**Early 1990s:** Intense vaccine development results in introduction of polyvalent oil-based adjuvant vaccines.

**From 1990 and onwards:** Increased awareness about farmed salmon escapes: On average, 11 – 35 percent of all spawning salmon populations in Norway are reported to be escaped farmed salmon (Hindar and Diserud, 2007).

**1995:** First recombinant subunit viral vaccine for fish commercialised in Norway (Sommerset et al., 2005)

**1999:** AquaBounty, Inc. first applies to the US FDA (Food and Drug Administration) to release a transgenic growth-enhanced Atlantic salmon (Aqua Advantage Salmon). They are still awaiting approval.

**Early 2000:** Export value of aquaculture exceeds export value from capture fisheries in Norway (Statistics of Norway, 2008).

**During 2000:** Increasing attention to the environmental consequences from using marine resources in salmon feed (Naylor et al., 2000). Increasing adoption of alternative feed resources, particularly plants, with diets currently consisting of approximately 40% plant oils and proteins (Ellingsen et al., 2009).

**2004:** Study shows that farmed salmon contains significantly higher concentrations of PCB compared to wild salmon. The feed used to farm the salmon is believed to be the cause of the high contaminant levels (Hites et al., 2004).

Successful accumulation of omega-3 polyunsaturated fatty acids in GM plants (Qi et al., 2004).

**2005:** IHNV DNA vaccine approved in Canada (Salonius et al., 2007).

**2006:** 19 processed feedstuffs are approved for Norwegian fish feed production, but have not yet been used (Norwegian Food Safety Authorities, 2009).

**2008:** Approximately 740,000 tonnes of salmon produced for sale in Norway (Statistics of Norway, 2010).

**2009:** Severe outbreaks of salmon lice infestations in Norway, causing increased used of chemicals (Norwegian Institute of Public Health, 2010)

### *3.3.1 Transgenic Fish*

The first transgenic fish, developed in 1984, was a common goldfish with a human growth hormone gene (Zhu et al., 1985). Since then, a number of species have been genetically modified in order to improve various traits (Aerni, 2004). A lot of research has been devoted to the development of transgenic fish with traits intended to improve productivity. As already mentioned, most research efforts have so far been invested in growth enhancement. The first transgenic fish awaiting regulatory approval for human consumption is the transgenic growth-enhanced 'Aqua Advantage Salmon'. This transgenic salmon, which was developed by Aqua Bounty Farms, contains a gene construct consisting of a Chinook salmon growth hormone gene and a regulatory sequence for control and expression (a promoter sequence derived from another fish, called ocean pout). The growth rate has been increased by as much as 400 to 600 percent, while feed inputs have simultaneously been reduced by up to 25 percent per unit compared to conventionally-bred farmed salmon. The fish is claimed to be sterile through chromosomal manipulation and the ultimate size of the fish at maturity remains the same as other farmed salmon (Aerni, 2004). In addition to growth enhancement and improved feed efficiency, research on transgenic fish also aims to improve traits such as altered metabolism (to reduce the requirement of fish-based diets by salmonid fish), increased disease resistance, control of reproduction and sexual differentiation and strengthened tolerance to specific environmental conditions such as temperature or polluted waters, but these are all at the developmental stage (Aerni, 2004; Le Curieux-Belfond et al., 2009; Maclean, 2003; Maclean and Laight, 2000; Pew Initiative, 2002; Wong and Eenennaam, 2008).

Fish may also be genetically modified for traits other than those intending to increase productivity. This includes traits such as reduced allergenicity for humans who are allergic to fish meat; transgenic fish that produce valuable pharmaceutical products; and fish used as pollution detectors. Research in these fields is all at a developmental stage (Aerni, 2004; Le Curieux-Belfond et al., 2009; Maclean, 2003; Maclean and Laight, 2000; Pew Initiative, 2002). Importantly, a lot of the research on transgenic fish is primarily done for basic research purposes, particularly to gain more understanding of gene functionality and regulation in fish. The first transgenic animal to be commercialised was actually an aquarium fish, the transgenic zebrafish (GloFish) expressing a red fluorescent protein from a sea anemone, making it glow red. It was produced and patented by a group at the National University of Singapore and has been sold as a novel pet in the US since 2003, as well as in several Asian countries (Gong et al., 2003; Stewart, 2006).

As in the debates and scientific disagreements about safety issues related to GM plants, concerns have also been raised with regard to documented and potential health and environmental impacts and socioeconomic considerations of transgenic fish (see for instance Delvin et al., 2006; Le Curieux-Belfond et al., 2009; Kapuscinski, 2005; MacLean, 2003; Pew Initiative, 2002). As escapes of farmed fish from sea cages seem unavoidable, environmental consequences in case of escape are of prime concern if transgenic fish are to be commercialised (Delvin et al., 2006; Kapuscinski, 2005). The consequences (e.g., whether the transgenic fish will survive, establish, interbreed with or outcompete natural populations) will depend on the relative fitness of the transgenic fish under natural conditions and their invasiveness. Delvin et al. (2006) emphasise that this is influenced by a myriad of interacting factors and that this complexity limits scientists' ability to identify possible scenarios in the case of escaping transgenic fish, particularly because conducting fitness tests in simple aquarium environments has little value and field studies (e.g., releasing transgenic fish into natural environments and observing their survival rates) are not acceptable due to the obvious threats to natural populations.

## 3.4 Salmon Aquaculture and Environmental Sustainability

Salmon aquaculture, like most contemporary industries, faces increasing demands to establish sustainable production practices from environmental groups, consumers, and policymakers. Due to the ambiguities inherent to the concept of sustainability (discussed in Chapter 2, section 2.6.1) and the conflicts which easily arise when striving to achieve economical, social and ecological sustainability, there is however no common agreement of what sustainability implies for salmon farming or whether the industry, as practised today, can at all be regarded as sustainable. At the core of the disagreements are differing sets of values for describing sustainable development and how to set priorities between these. For instance, Norwegian authorities and the salmon farming industry tend to highlight the industry's contribution to economical and social sustainability by pointing to the fact that salmon farming now represents the second largest export industry in Norway and is particularly important in order to secure employment and development of coastal districts. Yet, in debates over salmon farming and sustainability, more attention is given to the environmental aspects of sustainability (Frankic and Hershner, 2003), an outlook which is also reflected in a number of policy documents (see for instance; EC, 2002; FAO, 1995; Holmenkollen guidelines for sustainable aquaculture, 1998; Norwegian Ministry of Fisheries and Costal Affairs, 2009). This is also my focus here. In the following, I describe the main environmental impacts associated with salmon farming, focusing in particular on the use of marine feed resources for farmed salmon. Finally, I briefly describe some applications of modern biotechnology that have been suggested as means to promote environmental sustainability.

The main environmental threats posed by salmon aquaculture are the escape of farmed salmon (as these may invade and establish in local rivers and possibly outcompete native species); the spread of fish diseases to native fish populations; pollution (e.g., fish excrement, feed waste, dead fish and chemicals) in the local environment; and increasing demands for finite marine resources for feed production. Positive environmental impacts of aquaculture are, among others, that it can reduce fishing pressure on overexploited wild fish stocks and that natural production in areas surrounding a fish farm may increase due to discards of organic material (Diana, 2009).

The use of marine resources as feed for farmed salmon has caused particular concern. Feed production represents the most energy demanding stage of salmon production, and feed production and transportation are some of the major contributors to greenhouse emissions in the salmon production chain (Ellingsen et al., 2009). Despite major advances in feed formulation, feed manufacturing technology, and feed management at the farm level in recent years, salmon farming continues to consume more marine resources than what it produces. The reported ratios of wild fishery inputs to farmed fish outputs presented in current literature are conflicting. For instance, according to Naylor et al. (2009) the ‘fish-in fish-out’ ratio for farmed salmon is currently 5.0, which is close to estimations made by Ellingsen et al. (2009), who calculated that 4.6 kg of fish are needed to produce enough oil for one kg salmon fillet. FHL (2009b), on the contrary, claims that it takes about 2 kg of wild fish to produce 1 kg of farmed salmon in Norway.

Duarte et al. (2009) expect that space and water constraints will most likely drive all aquaculture growth towards marine aquaculture in the long term, as this type of food production requires much less fresh water compared to the production of plants and animals on land, and to the needs of freshwater fish species. They argue, from a sustainability perspective, that the use of wild caught fish for feed production should be abandoned and that marine fish at lower trophic levels should be the species of choice for fish farming. Others approach this controversy by pointing to the fact that many other feed industries are currently also large consumers of marine resources (primarily poultry, pig and pet feed industries). As salmon is a cold-blooded species with low metabolic rates, it is more efficient in converting feed to tissue compared to other land animals used in food production, such as poultry and pig. Seen in this context, Tidwell and Allan (2001) argue that salmon aquaculture represents a more efficient and environmentally friendly form of food production. Ellingsen and Aanondsen (2006), on the other hand, report on a life cycle assessment which compared energy demands for chicken farming, salmon farming and wild cod fishing. This study showed that chicken production was most energy effective, due to the extensive use of wild caught fish in salmon feed. A few companies produce organic salmon (see for instance www.villaorganic.com). One of the main differences between conventional and organic fish farming concerns requirements regarding feed. For instance, Debio (the Norwegian organic certification agency) requires that a certain amount of the fish meal that is used in feed shall come from fishery by-products. Additionally, plant material which is used in feed shall be produced organically and other additives such as vitamins, minerals, antioxidants and colouring shall come from natural sources or be as close to their natural form as possible (Debio, 2008).

As for aquaculture in general, the development of salmon aquaculture has caused conflicts with traditional uses of the coast (such as fishing and shipping activities), as well as leisure activities, tourism and nature conservation concerns. These conflicts may arise due to the physical space aquaculture constructions occupy (which may limit access to fishing grounds in fjords or hinder shipping); organic and chemical discharges from the fish farms (which may both pollute marine areas or attract wild fish stock that feed on feed effluents); visual disturbance caused by the presence of floating cages (particularly in areas of high scenic value); or impact on wild salmon due to interbreeding and the spread of diseases (which causes biodiversity concerns and may restrict leisure activities such as wild salmon fishing) (Dempster and Sanchez-Jerez, 2008). This potential for user conflicts is recognised in the Norwegian Aquaculture Act (2006) which requires that the relationship with other users of the coastal zone shall be given special attention when locating fish farms. Furthermore, Norwegian authorities have identified areas (called national salmon river systems and fjords) which are of particular importance to native salmon populations along the Norwegian coast. Today, a total of 52 national salmon river systems and 29 national salmon fjords are protected; e.g., the establishment of new fish farms is banned and previously established fish farms are highly regulated (St. prp. 32, 2006- 2007). Norwegian authorities are concerned with the protection of wild salmon because salmon has an important value as a cultural icon in Norwegian society and wild-salmon fisheries are considered important both for recreation and income. Furthermore, Norway has the world’s largest population of native Atlantic salmon and is signatory to a number of international agreements which give Norwegian authorities a special management responsibility for wild Atlantic salmon (described in more detail in Chapter 4, section 4.1.1).

### Modern biotechnology applications for environmental sustainability

Different applications of modern biotechnology have been proposed as strategies to promote more environmentally sustainable practices for salmon aquaculture (see for instance Dunham 2004; NACA/ FAO, 2000; Napier et al., 2006; Robert, 2006). The advocates of these technological solutions point to several possible areas of application. For instance, transgenic salmon with improved traits such as growth enhancement, improved feed efficiency and altered metabolism may contribute to increased productivity. Hence, less time and resources would be required to produce larger quantities of fish. Moreover, research into sexual control and sterility of fish through genetic modification (Wong and Van Eenennaam, 2008) can reduce the potential for adverse effects on native populations in case of fish escape. Another area of research relevant to questions of environmental sustainability is the effort invested in the development of GM plants with increased levels of omega-3 polyunsaturated fatty acids (Gatlin et al., 2007; Napier et al., 2006; Qi et al., 2004; Robert, 2006) which is considered by its proponents a much more sustainable source of omega-3 polyunsaturated fatty acids than that from marine sources (Napier et al., 2006; Robert, 2006). As briefly described in previous sections of this chapter, concerns have also been raised with regard to the environmental and human safety of introducing these GMOs. Thus, even though these technologies may promote more efficient resource use or reduce the demand upon other, vulnerable, resources, they may also result in unintended adverse consequences, and consequently pose new threats to the environment.

## 4.0 Legal Frameworks

In this chapter I present regulatory frameworks of relevance for salmon aquaculture and the deliberate release of GMOs in Norway. Focus is placed on the regulatory framework at the national level, notably the Norwegian Aquaculture Act and the Norwegian Gene Technology Act.

### 4.1 The Norwegian Aquaculture Act

The development of the salmon farming industry in Norway has always been strongly supported by the Norwegian government, as it has been considered an important strategy for promoting infrastructure and employment in coastal districts. Regulatory measures were put into place from the industry's infancy. The first provisional act was drawn up in 1973 and in 1981 the first permanent Aquaculture Act was passed. This was replaced by the Fish Farming Act of 1985, which was more recently replaced by the Aquaculture Act of 2006. The acts passed in the 1980s were designed to promote local ownership, for instance through license requirements on all fish farms; size restrictions on the fish cages; and limitations on the maximum license pen volume that could be controlled by a single company. Initially, one company could not own more than 20 percent of the total national capacity, but this was later increased to 35 percent in 2004 (Aarset and Jakobsen, 2009). Due to extensive development of the aquaculture industry since 1985 a new Aquaculture Act was passed in 2006. While the previous acts provided strong regulations governing the ownership of aquaculture enterprises, the 2006 Act is more concerned with how the enterprises are managed, giving the industry more freedom in seeking optimal solutions for development, by, for instance, allowing the transfer of licences within specific regions (the coast is divided into seven regions); the mortgaging of licenses; and simplifying the application process required for establishing a fish farm. More specifically, The Ministry of Fisheries and Coastal Affairs developed the most recent Aquaculture Act (2006) on the basis of four focus areas:

- Growth and innovation in the industry — profitability and innovation in light of Norway's international competitive situation
- Simplification for the industry and public administration — greater efficiency and user friendliness
- The environment — modern and comprehensive environmental regime
- Relationship to other user interests in the coastal zone — efficient land utilisation

### *4.1.1 Other National Acts and International Agreements of Relevance to Aquaculture*

In addition to the Aquaculture Act, there are a number of other acts and regulations that are of relevance to aquaculture. This includes various environmental acts such as The Nature Conservation Act (1970), The Nature Diversity Act (2009), The Pollution Control Act (1981), The Planning and Building Act (2008), (each regulating environmental issues such as protection against pollution and technical requirements of fish farming installations to prevent fish escapes); The Food Act (2003) (ensuring the quality and safety of seafood products, the quality and safety of feed ingredients, monitoring, control and measures for combating relevant diseases); and The Animal Welfare Act (2010) (ensuring the welfare of farmed animals). Norway has the world's largest population of native Atlantic salmon. As signatory to a number of international agreements, such as the Convention on Biological Diversity (1992), the Bern convention (1979), and particularly the Convention for the Conservation of Salmon in the North Atlantic Ocean (1982), Norwegian authorities have a special responsibility to protect and conserve Norway's native Atlantic salmon, which has experienced severe declines in recent decades.

## 4.2 The Norwegian Gene Technology Act

Norway was one of the first countries in the world to implement an Act on Gene Technology in 1993. The act regulates production and use of all viable GMOs in Norway except for human biotechnology. In keeping with regulations of GMOs in other countries and regions, the act demands that deliberative release of a GMO can only take place if there is no risk of adverse effects on health or the environment. Additionally, it is unique in demanding that the deliberate release of a GMO should be of 'benefit to the community', 'enable sustainable development', and take place in an 'ethically justifiable and socially acceptable manner' (Gene Technology Act, 1993; Myhr and Rosendal, 2009; Myhr and Traavik, 2003; NBAB, 1999; Plathe, 2002). These requirements are mentioned both in the purpose of the act (§ 1) and as an explicit criterion for approval (§ 10). How to assess these criteria is addressed in the revised version[8] of the Regulations relating to the impact assessment pursuant to the Gene Technology Act (2005).

Moreover, the Act prescribes the establishment of the Norwegian Biotechnology Advisory Board (NBAB), whose main task is to evaluate the social and ethical consequences of modern biotechnology and to discuss usage which promotes sustainable development.

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[8] The regulation was revised to meet requirements of the new EU Directive 2001/18/EC (2001) on deliberate release.

Amongst the board's 21 members, 13 are personally appointed due to their expert knowledge in the field, 8 represent various organisations (such as Friends of the Earth, Norway; Norwegian Farmers and Smallholder Union; and The Norwegian Seafood Federation, to mention a few) and 7 act as observers on behalf of different governmental ministries. Three citizen juries have been organized by the NBAB. The most recent, on stem cells, took place in 2001, while the two previous (conducted in 1996 and 2000) both treated GM food. The conference on GMO food in 2000 recommended a moratorium on the production and commercialisation of GM food and feed in Norway. Both conferences received good public attention, and their conclusions were taken into account by the Norwegian authorities (The National Committee for Research Ethics, 1996; NBAB, 2000).

### 4.3 The Decision-making Process on GMOs in Norway

Figure 3 gives a schematic overview of the consultative bodies that are involved when applications for deliberate release/import of viable GMOs are evaluated and decided upon in Norway.

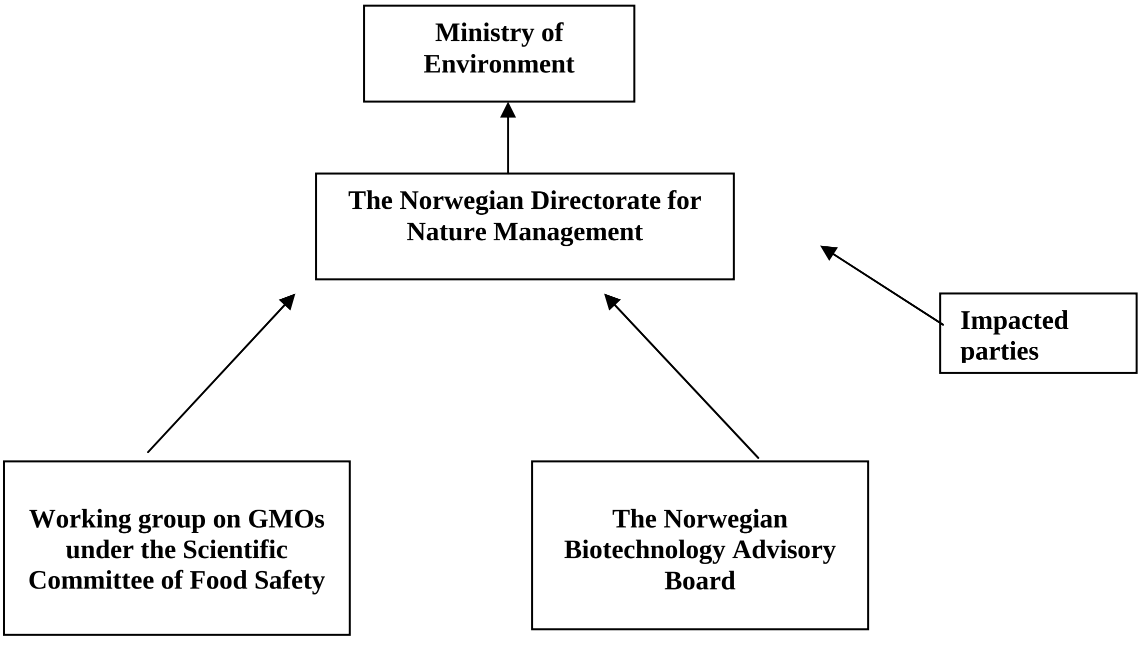

Figure 3: The consultative bodies involved in decision making of viable GMOs in Norway.

The Ministry of Environment has the authority to make the final decision with regard to the applications under evaluation. The decision is based on policy recommendations from The Norwegian Directorate for Nature Management. These recommendations are based on advice from officially appointed consultative bodies (e.g., NBAB and the working group on GMOs under the Scientific Committee of Food Safety) and viewpoints from impacted parties as all applications of deliberate release/import of GMOs are subjected to open hearings. The NBAB assesses aspects related to ethics, social justification and sustainable development; their advice reflects both the views of scientific advisors and impacted parties. A working group currently consisting of ten scientists appointed according to their expertise, assesses the impact on human health and the environment on behalf of the Norwegian Food Safety Authority and The Directorate for Nature Management. The working group is organised under the Scientific Committee of Food Safety in Norway and represents the main body of scientific advisors in the decision-making process.

Norway currently practises one of the world's most restrictive policies on the production and use of GMOs. Some applications for contained experiments have been accepted, but only four applications for commercialisation have been approved since the Act came into force. This includes three varieties of carnations (as cut flowers) and one variety of tobacco, which were approved in the mid 1990s (Ministry of Environment, 2010). The tobacco is, however, not suitable for the growing conditions in Norway and is resistant to a herbicide which is not legal to use in Norway. The specific requirements on sustainability, social utility and ethical issues have not played an essential role in the assessment of these GMOs (Myhr and Traavik, 2003; Myhr and Rosendal, 2009; Plathe, 2002), primarily due to lack of specific requirements for how to assess these, as well as a lack of relevant information. Even after the revision of the Regulations relating to the impact assessment pursuant to the Gene Technology Act (2005), it has still been difficult to assess these criteria, as the applicant generally does not provide the required information (since they are generally not asked for this by other regulating bodies) and also because the criteria are broad and challenging to address (Myhr and Rosendal, 2009).

## 4.4 Other National Acts and International Regulations and Agreements

### *4.4.1 EU Directives and Regulation on GMOs*

As Norway is a part of the European Economic Area (EEA) agreement, EU Directives and Regulations relating to deliberate release, import and trade of GMOs generally apply to Norway. This includes Directive 2001/18/EC on Deliberate Release of GMOs, Regulation No. 178/2002 on Food Safety Authority, Regulation No. 1830/2003 on traceability and labelling and Regulation No. 1829/2003 on genetically modified food and feed. All applications regarding deliberate release within the European Union (EU) are also received by Norwegian authorities. A GMO application that has been approved in the EU will automatically be opened to commercialisation in Norway as well, unless the Norwegian authorities decide against it within three months. The Norwegian authorities may decide not to approve the specific GMO, if it is considered a risk to health or the environment, or if it breaches other aspects of the Gene Technology Act, particularly those relating to ethics, social justification and sustainable development.

### *4.4.2 The Norwegian Food Act — Regulating Non-viable Processed GMOs*

Non-viable GMOs, such as processed food and feedstuff are regulated under the Norwegian Food Act (2003) which does not have the same criteria regarding ethics, social justification and sustainable development as the Gene Technology Act. The Norwegian feed regulation which constitutes a part of the Food Act is currently under revision in order to be harmonised with EU regulations (Regulation No. 1829/2003). During this transition time, GM-processed feedstuffs to be used in Norway must be reported to the Norwegian Food Safety Authority. The Norwegian Seafood Federation (FHL) notified the Norwegian Food Safety Authority that they wanted the to use 24 GM-processed feedstuffs from maize, oilseed rape, cotton and soy in the production of feed in Norway in March 2007, arguing that it was becoming increasingly more expensive and difficult to ensure that imported feed resources are free from GM. 19 of the reported products were approved for commercialisation in Norway in November 2007; these products must be labelled if the GM content of each ingredient exceeds 0.9 percent. The approval extends until 2010 when new regulations are expected to be in place (Norwegian Food Safety Authorities, 2009).

### *4.4.3 The Cartagena Protocol and Other International Agreements*

There are also various international conventions and treaties of relevance for GMOs, particularly the Cartagena Protocol on Biosafety (2003). Norway played a very active role during the negotiations and continues to do so in the meetings of the parties of the protocol that have followed since it entered into force. The Cartagena Protocol is a legally binding international agreement under the UN's convention on Biological Diversity (1992) (CBD). The protocol is based on a precautionary approach and recognises that GMOs may have biodiversity, human health and socio-economic impacts and that these impacts should be assessed and taken into account when making decisions on GMOs (Lin, 2007).

Additionally, there are a number of other international laws and forums that set standards for biosafety and the regulation of GMOs. This includes the World Trade Organisation (WTO) Agreements, particularly the WTO's agreement on the Application of Sanitary and Phyotsanitary Measures (SPS agreement) (1994). Other relevant international standard-setting bodies are the Codex Alimentarius Commission for food safety, the

International Plant Protection Convention (IPPC) for plant health and the World Organisation for Animal Health (OIE) for animal health and zoonoses. There are also international efforts to set up standards and guidelines for GMOs such as the UNEP International Technical Guidelines for Safety in Biotechnology and the FOA Draft Code of Conduct on Biotechnology as it relates to genetic resources for food and agriculture. In addition, the International Organisation for Standardisation (ISO) has developed international standards related to detection methods for GMOs and derived products in foodstuffs (Ching, 2007).

### *4.4.4 Regulation of Novel Applications of Modern Biotechnology Such as DNA vaccines*

So far, I have presented how GMOs are regulated according to The Norwegian Gene Technology Act, EU directives and in various international agreements. There are, however, emerging applications of modern biotechnology that are currently not covered under the definitions of GMOs (or living modified organisms, which is the term used in the Cartagena Protocol), and consequently not regulated under these frameworks. One such example is the regulation of animals treated with DNA vaccines. Different regulatory authorities have treat DNA vaccination in different ways, primarily due to uncertainties with regard to whether the injected DNA plasmid constructs are stored and can possibly integrate with the genome of the vaccinated organism (as described in Chapter 3, section 3.2.1). For instance, the U.S. Food and Drug Administration (FDA) has asserted that genetic constructs distributed to animals fall under the legal definition of a drug substance (FDA, 2007), a practice that corresponds with regulation in Europe where the European Agency for Evaluation of Medical Products (EMEA) authorize pharmaceuticals based on genetic engineering through a centralised procedure (EMEA, 2001). The Norwegian Directorate for Nature Management has, on the contrary, concluded that a DNA vaccinated animal is to be labelled and regulated as a GMO as long as the added DNA is present in the animal (Foss and Rogne, 2007).

## 5.0 Aims of the Project

The overall aim of this project is to identify and analyse different types of uncertainties associated with the use of modern biotechnology in aquaculture and the deliberate release of GM crops. These analyses are used as a basis for reflection on what acknowledging uncertainties entails for risk governance and decision making in relation to novel technologies.

In order to meet these aims I have gathered perspectives on uncertainties, benefits and concerns related to modern biotechnology applications, particularly with regard to DNA vaccines for fish, alternative feed resources (including GM feed) for farmed salmon, and the deliberate release of GM crops, among scientists, scientific policy advisors and other impacted parties.

More specifically, I had the following aims:

- To identify different types of scientific uncertainties associated with modern biotechnology in aquaculture.

  This was accomplished by applying the Walker and Harremoës (W&H) uncertainty framework using DNA vaccination in aquaculture as a case study. (Paper 1)

- To contribute to the debate about the applicability and adequacy of the W&H uncertainty framework. (Paper 2)

- To explore how scientists' and other impacted parties' perspectives are influenced by contextual factors, and elaborate on how to facilitate broader participation in decision-making processes.

  This was accomplished by applying:

  1. The Q-methodology to explore scientists' perspectives on the deliberate release of GM crops. (Paper 3)
  2. Multicriteria Mapping to explore interest groups' perspectives on alternative feed resources for farmed salmon. (Paper 4)

## 6.0 Methodologies Applied in the Studies

The aim of this chapter is to describe the different methodologies and frameworks that I have applied in my studies, notably:

1. The Walker and Harremoës (W&H) uncertainty framework: applied to identify and analyse scientific uncertainties.
2. The Q-methodology: applied to explore scientific ambiguities.
3. Multicriteria Mapping (MCM): applied to explore ambiguities among scientists and other impacted parties and to facilitate participation in evaluation processes.

### 6.1 The Walker & Harremoës (W&H) Uncertainty Framework

The aim of the W&H uncertainty framework is to provide a conceptual framework for the systematic treatment of uncertainties in model-based decision support. The framework was developed by a group of leading researchers from different scientific disciplines who represent various perspectives on uncertainty. The lack of a commonly shared terminology for addressing uncertainties had been considered a constraint when diagnosing and dealing with uncertainties, particularly in policy-relevant science. The group sought to integrate the wide variety of terminologies used to describe uncertainties into a single coherent conceptual framework. The framework was designed to illustrate how the different types of uncertainties highlighted in the literature relate to one another, and to use this insight constructively in order to diagnose uncertainties. Importantly, the framework's structure gives scientists an opportunity to express and reflect upon different forms of uncertainties associated with their field of interest (Walker et al*.,* 2003). According to Krayer von Krauss et al. (2006) the most important aim of the framework is to contribute to the communication of uncertainty. The developers of the framework define uncertainty broadly as "any departure from the unachievable ideal of complete determinism" (Walker et al., 2003). At the core of the framework is the notion that uncertainty is best thought of as a concept with three dimensions: *location*, *level* and *nature*.

#### *6.1.1 Dimensions of Uncertainty*

The *location* dimension refers to where the uncertainty manifests itself within a given system or model. This relates to how the context of the study is defined, e.g., questions such as: Which aspects should be included, which should be left out and which allow for alternative interpretations? There are various understandings of what a model is among scientists. Still, some constituents are generally agreed upon as central. According to Walker et al. (2003) all models are characterised by *context*, *model structure*, *inputs*, *parameters* and *model outcomes*. When developing a model, scientists first define its *context*. This determines the boundaries of the model, e.g., the framing of the issue to be investigated and the formulation of problems to be addressed within the defined boundaries. *Model structure* relates to the characterisation of the dominant relationships within the system, e.g., between model inputs and parameters and the cause-effect relationships between these. *Inputs* refer to data that describe the reference system and the external driving forces that have an influence on the system and its performance, whereas *parameters* are constraints in the model, supposedly invariant within the chosen context. Finally, *model outcome* is the prediction scientists make based on the results obtained from using the model. The *location* dimension covers uncertainties associated with the scientists' choices about each of these model constituencies. The uncertainties may arise due to a lack of understanding about the current behaviour of the system (e.g., when determining the dominant relationship within the model), but may also be a result of different framings, reflecting different values and interests among scientists (e.g., when deciding on the context). Hence, this dimension captures some of the characteristics described as ambiguity — recognising that different scientific framings allow for several plausible ways to describe a system, and indeterminacy — recognising scientists' limited ability to fully characterise complex systems, as described in Chapter 2, section 2.3.1).

The *level* dimension characterises the severity of the uncertainty, or how extensive the lack of knowledge is considered to be. It is described as a gradual change from 'knowing for certain' (determinism), to 'not even knowing what you do not know' (total ignorance) (Figure 4):

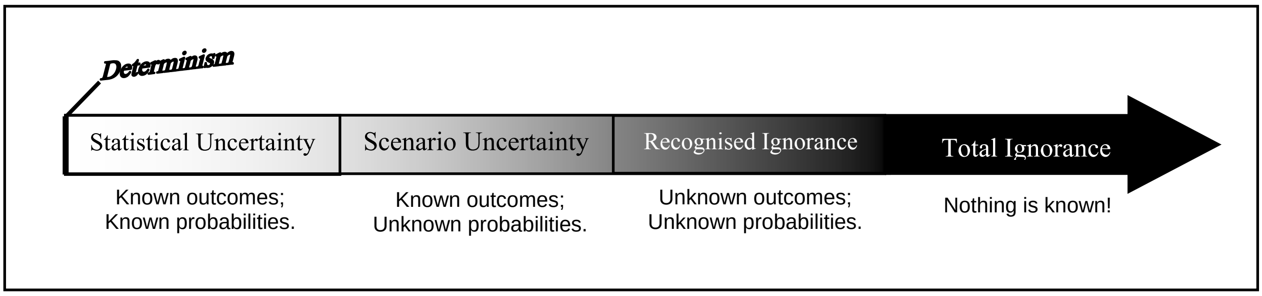

Figure 4: The scale of levels of uncertainty (Adapted from Walker et al., 2003).

*Determinism, statistical uncertainty* and *scenario uncertainty* represent situations where the possible outcomes (consequences) of an activity are known, but where it is increasingly difficult to estimate the probabilities for these outcomes to occur. The levels *recognised* *ignorance* and *total ignorance* represent a qualitative shift in the understanding of the problem, where neither the possible consequences nor the probability for these consequences to occur can be known. Obviously, the different categories of the *level* dimension relate to risk, inexactness and ignorance as described in Chapter 2, section 2.3.1, where risk and inexactness cover *statistical* and *scenario uncertainty* respectively, and ignorance covers what is defined as *recognised* and *total ignorance* in this framework.

In addition to identifying the *location* and *level* of uncertainty, the W&H framework also seeks to characterise the *nature* of uncertainty, defined as either epistemological or ontological. *Epistemological uncertainty* refers to a lack of knowledge or lack of appropriate methodologies to sufficiently investigate a scientific problem. With more research and/or improved methodologies or models, *epistemological uncertainty* can in theory be reduced. *Ontological uncertainty*, on the other hand, describes uncertainty that is due to inherent variability and complexity of a given problem or system under investigation. In the latter case, the system and/or the technology is of such complexity that scientific methods can never bring full understanding of the processes involved. Hence, the consequences of the technological introduction in question can never be fully described or predicted by scientific investigations. Again, *epistemological uncertainty* relates to the quantitative dimensions of uncertainty described in Chapter 2, section 2.3.1, whereas *ontological uncertainty* relates to the qualitative dimensions.

### *6.1.2 Uncertainty Matrix*

Walker et al. (2003) suggest that the data from elicitations where the framework has been applied should be fed into an uncertainty matrix. This matrix would serve as a map of the identified uncertainties, indicating the *level* and *nature* of each of the *locations* identified as uncertain. Presented in this way, policymakers would get a systematic and graphical overview of the uncertainty involved when deciding on management strategies for a given system or technology. Walker at al. (2003) do however emphasise that when filling the matrix, one should be aware that the *level* and *nature* of the uncertainty that occurs at any *location* can manifest itself in various forms simultaneously. For further analysis it is also necessary to assess the size of the various uncertainties and their influence on the outcomes of interest, for instance by applying tools such as sensitivity analysis (Saltelli et al., 2000) and pedigree analyses, based on the NUSAP system for uncertainty assessment (Funtowicz and Ravetz, 1990; van der Sluisj et al., 2005). Finally, it should be noted that the matrix characterises uncertainties associated with a particular issue at a particular point in time. Thus, the matrix will necessarily change with more information or new circumstances.

Martin Krayer von Krauss was the first to apply the W&H uncertainty framework for expert elicitations (Krayer von Krauss, 2005). He analysed scientist judgements of uncertainties associated with GM crops (Krayer von Krauss et al., 2004) and gene silencing (Krayer von Krauss et al., 2008). I based my work on his experience and applied the framework to analyse uncertainties associated with DNA vaccines in aquaculture (Gillund et al., 2008a, b). The framework has also been used by Grieger et al. (2009) to characterise and describe uncertainties in published and peer-review report- and review-articles concerning environment, human health and the safety of nanomaterials. Janssen et al. (2005) present an adapted and extended version of the uncertainty matrix proposed by Walker et al. (2003), but this version has, to my knowledge, not yet been applied to literature reviews or empirical case studies.

## 6.2 The Q-methodology

The Q-methodology is designed to reveal multiple viewpoints on an issue and is a type of discourse analysis that enables the identification of common patterns of opinion held by a certain group of people. Rather than identifying patterns of opinions across individual traits (such as gender, age, class, etc.), which is generally the outcome of standard survey analysis, researchers applying the Q-methodology are interested in identifying patterns within and across individuals. In other words, the Q-methodology aims to explore the spectrum of opinions held on a certain issue amongst a certain group of people (represented by the participants of the study) (Barry and Proops, 1999). It was developed in the 1930s by William Stephenson, a British physicist-psychologist and was initially used within the field of psychology, later expanding to sociology, social psychology, political psychology and political science. More recently, it has been subject to growing academic interest and is consequently being used in an increasing number of research areas, including environmental issues (see Hall, 2008 and references therein). With regard to GMOs, Hall (2008) has used Q-methodology to identify farmer attitudes towards GM crops in Scotland; Wilkins et al. (2001) have investigated viewpoints on GM food and crops among faculty and country-based extension educators at the Land Grant University in New York State; while Roberts et al. (2006) have used the methodology to explore the viewpoints on GM food among dietetics professionals.

### *6.2.1 Practical Steps of the Q-methodology*

After deciding on the discourse which one wishes to explore, the application of the Q-methodology consists of the following stages:

1) Statement generation and selection: The researcher gathers statements about the topic to be analysed through interviews with a sample of the relevant population and from literature and media reviews, etc. From this series of statements the researcher makes a selection of statements to include in the study, i.e., deciding on the set of statements the participants will be asked to rank (usually about 30 – 40 statements).

2) Participant's ranking: The participants are asked to rank the statements on the scale 'Agree with most strongly' to 'Disagree with most strongly'. As shown in Figure 5 the participants are asked to rank the statements according to a predetermined distribution which implies that they can only place a limited number of statements at the extremes of the scale.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| -5 | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 |
| | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | |
| | | -3 | -2 | -1 | 0 | 1 | 2 | 3 | | |
| | | | -2 | -1 | 0 | 1 | 2 | | | |
| | | | | -1 | 0 | 1 | | | | |
| | | | | | 0 | | | | | |

Figure 5: Distribution of 36 statements in a Q-sort on a scale from strongly disagree (-5) to strongly agree (5).

In this way they must consider carefully which statements they feel most strongly about and compare every statement with every other statement while assigning the rankings. Hence, the final set of ranked statements demonstrates their overall attitude to the topic under consideration. This set of ranked statements constitutes the Q-sort for each participant.

3) Identification of 'typical' Q-sorts: statistical analysis of the individual Q-sorts allows the extraction of a few 'typical' Q-sorts, capturing the common essence of several individual Q-sorts. The first stage of the analysis involves correlating every sort with every other sort. Sorts are then factor analysed and rotated in order to reduce the data to a limited number of defining sorts, usually three or four, maximum eight. These 'typical' Q-sorts represent a 'pure' or 'ideal type' version of a way of seeing the world expressed among the participants in the study. The analysis identifies which of the

participants load significantly for each of the 'typical' Q-sorts, but, importantly, the identified Q-sorts are generally not closely represented by any particular individual. Finally, the results must be interpreted verbally to give the social discourse uncovered by the statistical analysis.

The strength of Q-methodology is that it allows individual responses to be collated and correlated so as to extract 'idealized' forms of discourse latent within the data provided by the individuals involved in the study. In this way the methodology helps to explore the spectrum of viewpoints expressed on a certain issue (Barry and Proops, 1999). When developing the methodology Stephenson was primarily interested in providing a way to reveal the subjectivity involved in any situation (Brown, 1996). As described in more detail in Chapter 7 and 8, we used the Q-methodology to identify perspectives on the deliberate release of GM crops among scientists trained in natural science. We also looked at how these perspectives related to the scientists' contextual background (e.g., disciplinary background, place of employment, research funding and type of research conducted). Used in this way, the Q-methodology helps to identify scientific ambiguities and how scientific perspectives and consequently policy recommendations may be based on subjective judgements.

### 6.3 Multicriteria Mapping

Multicriteria analyses (MCA) cover a variety of non-monetary evaluation techniques sharing a basic framework under which a number of alternatives can be scored against a series of defined criteria and to which users attach weights reflecting the relative importance of the criteria (Gaugh and Shackley, 2006). MCA is often contrasted with cost-benefit analysis which has been one of most dominant decision-making tools in recent times. Cost-benefit analysis is based on the assumption that all criteria can be transformed to a single dimension, typically monetary. This makes it possible to weigh costs and benefits, and consequently identify the best solution where benefits are maximised and costs are minimized. As the name indicates, MCA, on the contrary, is based on a recognition that criteria are multidimensional and therefore cannot be transformed into one dimension. The criteria's incommensurability restricts trade-off possibilities between them and the ability to identify 'best solutions', as this will depend on the range of criteria used in the evaluation of alternatives and the priorities given to these. Hence, MCA is proposed as a tool to better handle decision making related to complex problems as it promotes deliberative and participatory processes that intends to broaden the scope of issues taken into consideration in the assessments. The emphasis on the *process* is important, reflected in the view that the diversity of viewpoints explored is important for understanding the complexity of the problem at hand, and seeing this approach as a way to foster learning. New alternative solutions may come about or alternatives may be changed as an effect of the learning implied by the process. In some situations this results in a reformulation of the initial problem that was the basis for the exercise. Furthermore, MCA is based on a recognition that socially constructed perceptions of a problem influence, in a crucial sense, what is defined as a problem, who it concerns and the ways in which it can be solved. Done properly, MCA can make these issues more transparent and secure more self-reflection in decision-making processes (Vatn, 2005). Stirling (1997, 2005) is especially concerned with the divergent uncertainties, interests, priorities and values that are associated with different expert and socio-political perspectives; he developed Multicriteria Mapping (MCM) in an attempt to 'open up' assessment processes in order to "explore the way in which different pictures of strategic choices may change, depending on the view that is taken — not prescribe a particular 'best choice" (Stirling, 2005:5).

### *6.3.1 Practical Steps of Multicriteria Mapping*

MCM is a rigorous form of appraisal that allows for systematic mapping of people's views and a comparison between alternatives. It is distinctive from other MCA methodologies as it requires that the participants themselves develop their own appraisal criteria, define their own additional alternatives, and perform their own assessments (Burgess et al., 2007). In this sense MCM is a heuristic and process-oriented tool which does not intend to provide any clear guidance to policymakers, but rather explore the different framings underpinning assessments. The exercise is based on individual interviews (lasing 2 – 3 hours) where participants, supported by the researcher, work interactively with a piece of dedicated computer software (MC-Mapper). The MCM interview takes the participant through a structured series of stages (Figure 6, pp. 58):

1. Discuss alternatives and possibly define additional alternatives.
2. Define criteria under which the alternatives should be assessed. The participants are asked to explain what these criteria mean to them in as much detail as possible.
3. Assess scores of the performance of each alternative under each criterion. The participants are asked to assign two scores to each alternative — one reflecting performance under the most favourable assumptions, the other under the most pessimistic assumptions. In this way the participants are able to express any uncertainties; and to take account of variability in performance under optimistic or

pessimistic assumptions; or to account for context-specific factors that influence the performance of the alternative. Criteria can also be defined as principles where the judgements over alternative performance involve absolute decisions, e.g., each alternative is evaluated as either ‘acceptable’ or ‘unacceptable’ under the given principle.

4. Assign weights to each criterion in terms of its relative importance, reflecting the participant’s individual judgements and values.
5. Consider the ranks which are displayed in real-time simple charts visualising the overall performance of each alternative. These charts are produced by the software using a weighted sum of normalized criteria scores (Figure 6). (See Stirling 2005 for a more detailed presentation on the mathematical operations performed by the software.) Because participants are asked to provide ‘best’ and ‘worst’ performance scores, the rankings are expressed not as single numbers, but as intervals.

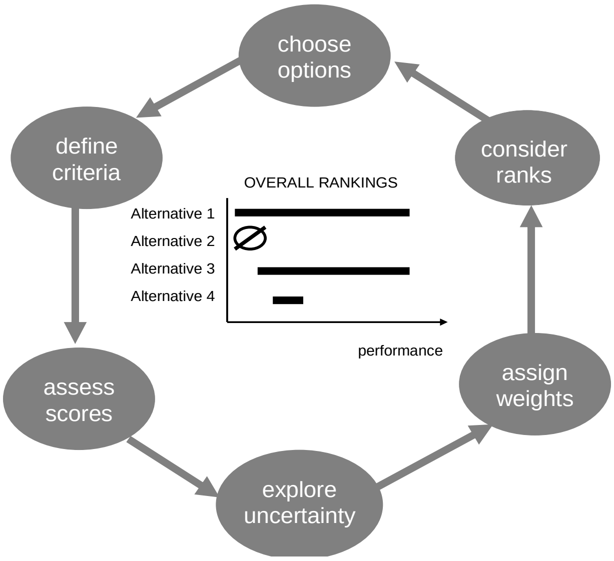

Figure 6: The steps in the MCM exercise (Stirling, 2008b). The chart in the centre shows the final performance ranking of each alternative (the further the bar extends to the right the higher ranking. The bars also indicate the interval between the scores given under the most pessimistic and optimistic assumptions. The length of the bar indicates the degree of uncertainty associated with the ranking of each alternative.
∅ indicates that the alternative has been ruled out under a principle.

The interview is audio recorded and the participants are asked to explain the rationale behind their choices and assessments in as much detail as possible. In this way the exercise provides both quantitative and qualitative data.

MCM was initially used to assess perspectives on risk related to food production (Stirling and Mayer, 2001) but has now been tested for appraisal of alternatives and management strategies in a number of fields ranging from energy policy (McDowall and Eames, 2007); development of criteria for the evaluation of public consultation and engagement processes (Burgess and Clark, 2006); strategies to prevent obesity (Stirling et al., 2007); carbon storage alternatives (Gough and Shackley, 2006); and public health responses to the shortage of kidney donors (Burgess et al., 2007). As described in the next chapters we used MCM to explore perspectives on feed alternatives for farmed salmon among different interest groups associated with Norwegian aquaculture (Gillund and Myhr, 2010). Similar to the Q-methodology, MCM is also especially designed to explore ambiguities by mapping the perspectives held by impacted parties on specific issues, and to explore how these relate to contextual factors. MCM may also function as a decision-making tool, but, importantly, the purpose of the exercise is not to define the best policy solution, but rather to raise the awareness about the plurality of solutions that exist for a specific problem.

## 7.0 Summary of Papers

### Paper 1

In this expert elicitation twelve Norwegian scientists were interviewed about environmental and health consequences of DNA vaccination in aquaculture. DNA vaccination is considered a promising solution to combat pathological fish diseases. There is, however, a lack of knowledge regarding its ecological and social implications. The intention of this study was to elicit scientists' judgements of potential sources of uncertainty associated with the use of DNA vaccines. Emphasis was put on three incidents: i) Immune response following the DNA vaccination, ii) Tissue distribution and expression of the injected plasmid DNA (pDNA) and iii) Environmental release of DNA vaccines. Here we present what the experts identified as the potential consequences of introducing DNA vaccines to aquaculture. Our findings support the need for more research on the stability of the pDNA, unintended immunological impacts and integration of the pDNA in the chromosome of the recipient organism. The study suggests that expert elicitation can improve communication of scientific uncertainty and thereby advance the scientific discussion. We argue that our findings support the importance of including several experts in the process of risk assessment and decision support, as different scientists express diverging opinions of the consequences involved.

### Paper 2

The Walker and Harremoës (W&H) uncertainty framework is a tool to systematically identify scientific uncertainty. We applied the W&H uncertainty framework to elicit scientists` judgements of potential sources of uncertainty associated with the use of DNA vaccination in aquaculture. Our findings indicate that scientists are open and aware of a number of uncertainties associated with DNA vaccination e.g., with regard to immune response, degradation and distribution of the DNA plasmid after injection and environmental release, and that they consider most of these uncertainties to be adequately reduced through more research. We proceed to discuss our experience of using the W&H uncertainty framework. Some challenges related to the application of the framework were recognised; this was especially related to the respondents' unfamiliarity with the concepts used and their lack of experience in discussing qualitative aspects of uncertainties. As we see it, the W&H framework should be considered a useful tool to stimulate reflection on uncertainty and an important first step in a more extensive process of including and properly dealing with uncertainties in science and policymaking.

**Paper 3**

In this paper we analyse scientists' perspectives on the release of genetically modified (GM) crops into the environment, and the relationship between their perspectives and the context that they work within, e.g., their place of employment (university or industry), funding of their research (public or industry) and their disciplinary background (ecology, molecular biology or conventional plant breeding). We employed Q-methodology to examine these issues. Two distinct factors were identified by interviewing 62 scientists. These two factors included 92 per cent of the sample. Scientists in factor 1 had a moderately negative attitude toward GM crops and emphasised the uncertainty and ignorance involved, while scientists in factor 2 had a positive attitude toward GM crops and emphasised that GM crops are useful and do not represent any unique risks compared to conventional crops. Funding had a significant effect on the perspective held by the scientists in this study. No ecologists were associated with factor 2, while all the scientists employed in the GM-industry were associated with this factor. The strong effects of training and funding might justify certain institutional changes concerning how we organise science and how we make public decisions when new technologies are to be evaluated. Policymakers should encourage more interdisciplinary training and research and they should make sure that representatives of different disciplines are involved in public decisions on novel technologies.

## Paper 4

The future of salmon aquaculture depends on the adoption of alternative feed resources in order to reduce the need for fish meal and fish oil. This may include resources such as species from lower trophic levels, by-products and by-catch from fisheries and aquaculture, animal by-products, plants, genetically modified (GM) plants, nutritionally enhanced GM plants and products from microorganisms and GM microorganisms. Here, we report from a deliberative evaluation of these alternative feed resources. 18 participants from different interest groups within Norwegian salmon aquaculture participated in the study by conducting a Multicriteria Mapping exercise. The participants defined a broad range of appraisal criteria concerning health and welfare issues, economical issues, environmental issues, and knowledge and social issues. A number of uncertainties, in the form of incomplete knowledge, diverging opinions and context specific factors were identified when the participants evaluated the alternatives. Our findings support the need for more research on the suitability of alternative feed resources for farmed salmon. Additionally, the study underlines the importance of facilitating deliberative evaluations in order to map the plurality of perspectives and explore qualitative aspects of uncertainty. Such initiatives may improve the information base upon which decisions on future feed resources for farmed salmon are made.

# 8.0 General Discussion

My work with this thesis has been motivated by a belief that there is a need for precaution in relation to governance of novel technologies. In light of this perspective, an overriding research question for the three studies conducted is: ‘How to acknowledge and handle scientific uncertainties in policy-relevant science?’ Here, I reflect upon this question, focusing on the insights I have achieved by conducting these studies. The chapter is structured around four strategies that I consider central for a precautionary approach in governance of novel technologies; (i) identifying a broader range of uncertainties, (ii) promoting reflection and communication about uncertainties, (iii) facilitating deliberation and participation, and (iv) maintaining plurality in perspectives and policy options.

## 8.1 Identifying a Broader Range of Uncertainties

A necessary first step when dealing with scientific uncertainties is to identify them. As described in Chapter 2, scientific uncertainties have traditionally been conceived as and handled purely quantitatively, (e.g., expressed in statistical terms and regarded as reducible through further research). This narrow understanding has been challenged by a growing awareness that scientific findings and judgements are also characterised by qualitative dimensions of uncertainty. Efforts have been invested in the development of methodologies and tools that are better suited to identify and analyse these types of uncertainties. One attempt is the Walker and Harremoës (W&H) uncertainty framework. I chose to apply this framework to identify uncertainties associated with DNA vaccination of fish.

We conducted an expert elicitation of scientific uncertainties, involving twelve Norwegian scientists working in the fields of fish vaccination or fish immunology. The study showed that DNA vaccination of fish is associated with a number of uncertainties. In fact, all the parameters describing possible pathways for the injected DNA plasmid (see Figure 2 in Paper 1) were identified as uncertain by the scientists participating in the study. A few scientists described some of the uncertainties, particularly those related to environmental release of DNA vaccines, as due to the inherent variability and complexity of the system (e.g., as indeterminacy). Still, most uncertainties were described purely as knowledge gaps and considered to be reducible through more research or improved methodologies. Hence, even though the framework was developed to explore broader dimensions of uncertainties, the uncertainties identified in the study were primarily characterised as quantitative. Similar findings have also been reported from other uncertainty analyses based on the W&H uncertainty framework (Krayer von Krauss et al., 2004, 2008; Grieger et al., 2009).

The fact that the scientists characterised most uncertainties as quantitative may partly be explained by the relatively young history of, and therefore limited experience with, DNA vaccination. More research is consequently needed in order to improve current understandings of the working mechanisms of DNA vaccines and to address possible unintended consequences (Myhr and Dalmo, 2005; Tonheim et al., 2008; Redding and Weiner, 2009). Our study supports such a need, and points specifically to questions about the stability of the injected DNA plasmid, unintended immunological impacts and integration of the DNA plasmid in the genome of the vaccinated organism as areas to prioritise in future research. Moreover, some of the scientists participating in the study expressed that they were not used to talking about qualitative dimensions of uncertainties, nor relating their work to the broader implications of DNA vaccination, as depicted in Figure 2, Paper 1. During the interviews we sometimes struggled to communicate a basic understanding of the uncertainty theory and the framework that formed the basis for our analysis. Thus, another reason for our findings may be that the terms used in the framework were new and to some extent difficult to understand for many of the scientists participating in the study. Another important consideration in this respect is that scientists can never know in advance whether the uncertainties they face in their research are reducible or not. E.g., the nature of uncertainties cannot be defined without further investigation. Science is, however, typically based on the assumption that more research will ultimately reduce uncertainties. Hence, it should perhaps not be a surprise that this was also the dominant view among the scientists participating in this study.

Paper 3 describes a study where we wanted to explore a particular kind of qualitative uncertainty, namely scientific ambiguity (e.g., uncertainties arising due to divergent framings, assumptions and values among scientists). We applied the Q-methodology to explore scientists' perspectives on environmental impacts from the deliberate release of GM plants. The study involved 62 Scandinavian scientists trained in natural science (either molecular biology, ecology or conventional plant breeding) and currently working within the field of GM crops. The scientists were asked to describe their level of agreement or disagreement with a number of statements that reflect four central dimensions of the GM debate: 'The consequences of releasing GM crops', 'Our ability to predict these consequences', 'Whether GM crops are fundamentally different from conventional crops' and 'The moral status of nature'. The study revealed two dominant and contrasting views among the scientists. While 32 of the scientists shared a view which we labelled as: *'The environmental effects are unpredictable'* (Perspective 1), 25 of the scientist shared the view that: *'GM crops present no unique risks and are useful'* (Perspective 2). Furthermore, we found that the scientists' perspective was influenced by contextual factors such as the academic discipline they were trained within, their current workplace, type of research and research funding. Moreover, the scientists differed strongly in their view on uncertainties. The ones who belonged to Perspective 1 strongly emphasised that the present scientific knowledge relating to environmental consequences from releasing GM crops is insufficient, highlighting that environmental effects from GM crops are unpredictable due to the complexity of natural ecosystems. The scientists who belonged to Perspective 2, in turn, had no strong opinions with regard to the predictability of environmental consequences from GM crops and claimed that GM crops are not fundamentally different from conventional crops. Interestingly, similar to our findings in Paper 2, none of the scientists, independent of their perspective, had any strong opinion on whether we are faced with irreducible uncertainties or not.

The study presented in Paper 4 was also designed to reveal ambiguities in the sense that it aimed to identify perspectives on alternative feed resources for farmed salmon and to explore how these perspectives were influenced by the assessors' values and interests. In addition to scientists, this study involved a number of other relevant interest groups, including fish farmers, market analysts, policy advisors and people working in the feed industry and environmental NGOs. Each participant conducted a Multicriteria Mapping (MCM) exercise which was designed to evaluate a range of alternative feed resources. The participants were particularly asked to describe different types of uncertainties that influence their judgements about the alternatives' performance. A number of uncertainties were identified, including areas characterised by incomplete knowledge, diverging opinions amongst the participants, and context specific factors that influence the performace of the alternatives. Interestingly, the participants differed most in their judgement about the occurrence and significance of uncertainties when assessing GM soy and maize, nutritionally enhanced GM plants, and species from lower trophic levels. This finding underlines that ambiguities particularly prevail in judgements about highly complex systems.

### 8.2 Promoting Reflection on and Communication about Uncertainties

In Chapter 2, I describe how scientific experts have traditionally enjoyed a privileged role as policy advisors, due to the dominant position scientific risk assessments have been given in decision-making processes. There are many examples of how these approaches have failed in the face of complex 'real world' problems (e.g., where unexpected adverse consequences occur with time) (Harremoës et al., 2001). Nevertheless, they continue to dominate risk governance and decision-making processes (Millstone, 2007; Stirling, 2006). As a result, questions of risk are typically limited to technical scientific questions and less attention is generally given to other concerns (e.g., ethical and social consideration) (de Melo-Martin and Meghani, 2008). Moreover, these approaches generally do not acknowledge scientific uncertainties beyond quantitative forms (Stirling, 2007).

Recognising the limitations of these expert-led risk-based approaches, alternatives such as precautionary and participatory approaches, have been proposed. These are intended to broaden the scope of, and strengthen the involvement in, decision-making processes. Many scholars have engaged in the discourse on precaution and participation and some have developed frameworks and methodologies that are intended to facilitate these approaches (see for instance Stirling, 1997, 2005; Van der Slusj et al., 2004; Walker et al., 2003). However, they emphasise that further discussion of the practical implications of precaution and participation is necessary and that the methodologies aimed at facilitating these approaches will have to be continuously developed and adapted to specific contexts or issues. Hence, discussion and reflection about the theory upon which the approaches and methodologies are based, as well as about the particular design of a specific methodology are important elements in research where any of these methodologies are applied. Besides providing valuable insights for the further development of these methodologies, promoting reflection about uncertainties may also contribute to social learning, and consequently stimulate changes in, for instance, scientists' way of thinking and acting, which can then enhance precautionary and participatory approaches.

In line with this, one of the main purposes of using the W&H uncertainty framework is to promote reflection and communication about uncertainties (Krayer von Krauss et al., 2006). In Paper 2, I reflect upon my experience with applying the W&H uncertainty framework and to what extent it fulfilled this ambition. Many of the scientists participating in our W&H study expressed that they had gained new insights during the interview and that the framework helped them to see their work within broader frames and to reflect upon the limitations of the scientific understanding in their field. At the same time, it was evident that the terms used in the framework were unfamiliar to most of the scientists. This created confusion and lack of consistency in the way the terms were used as the scientists either did not quite understand the meaning of the terms, or understood them differently. Krayer von Krauss (2005) also experienced these challenges; along with him I argue that better ways to communicate the terms used in the framework are needed in order to reduce potential inconsistencies, biases and ambiguities. One way to do this could be to exemplify our understanding of the terms used and the questions we posed by providing examples from related technologies. Moreover, we could also have, to a greater extent, challenged the scientists to give examples that illustrated their views and to argue for their opinions. I believe that this could help to improve the quality of the study as more perspectives on uncertainties could have been revealed. It is, however, important to be aware of the fine line between explaining in detail and of guiding the scientists in a specific direction, a pitfall we tried to avoid in our study.

The original purpose of the W&H framework was to establish a common language among scientists and policymakers when talking about uncertainties, which would ultimately allow for an absolute description of uncertainties (Krayer von Krauss, 2005). One of my concerns while working with this framework was that this could lead to oversimplified descriptions of uncertainties. I consider any characterisation of uncertainty as uncertain in itself and, hence, open to multiple descriptions. Krayer von Krauss (2005) explains how he came to a similar understanding: "While the concepts put forth in the W&H framework seemed intuitive to its authors, this has not always proven to be the case in practice, and different, equally legitimate, conceptual arrangements could undoubtedly be devised to describe uncertainty" (Krayer von Krauss, 2005:65). Consequently, an important lesson from applying the framework to different case studies is that the original purpose of the framework was too ambitious. Nonetheless, and despite the challenges I have pointed out, my experience is that the framework can serve as a useful tool for identifying and promoting reflections about uncertainties.

The three methodologies that I have applied in the studies for this thesis share common characteristics in the sense that they are all based on a quite rigid set of questions or exercises that the interviewed participants are expected to complete. They do, of course, allow for some adaptations and flexibility, in fact, flexibility is one of the key characteristics of MCM; the participants are free to develop their criteria and define their own alternatives (which is not always the case for other multicriteria assessment tools). Still, my experience was that the methodologies I used to some extent posed constraints on the participants during the interviews, and consequently limited our dialog. For instance, the Q-methodology requires the participants to sort predefined statements in a forced distribution. Even though we asked the participants to explain the position of the statements they felt most strongly about (the three statements they agreed with the most and the three statements they disagreed with the most) and allowed for final comments at the end of the interview, I believe more or other aspects could have been addressed in a more typical in-depth interview where the participants could express their viewpoints more freely. In turn, the statements could also help the participants to reflect on issues they would not necessarily come to think of by themselves. In this way the statements could contribute to broadening the scope of issues addressed during the interview.

In a MCM exercise the participant is asked to define appraisal criteria, assign performance scores to the alternatives and give weights to the criteria, using a software called MC-Mapper. Before I started the series of interviews, I was very curious as to whether the use of a computer software would influence my conversation with the participants. Most of them expressed, however, that they enjoyed the exercise and thought that the graphical charts produced at the end of the exercise (visualising the overall performance of each alternative, see Figure 6 pp. 58), functioned as a tool to stimulate reflection and discussion. Still, I also experienced that some of the participants were primarily concerned with assigning performance scores and weights and did not sufficiently explain the rationales behind the numbers they selected. Hence, in these situations, the most valuable information for further analysis was not satisfactorily communicated to me.

## 8.3 Facilitating Deliberation and Participation

The two studies presented in Paper 1, 2 and 3 illustrate how scientific evaluations are not only based on factual judgements, but also influenced by scientists' subjective judgements. In other words; scientific advice will, in part, depend on who you ask. Based on our findings, we argue that the studies support the involvement of scientists from different disciplinary backgrounds when decisions are sought with regard to a particular technology. This reflects the ideas of a broader scope in risk assessments and facilitating deliberation and participation in decision making, as presented in Chapter 2.

Participation and deliberation in decision making should, however, not be restricted to scientists only, but should involve other impacted parties and the general public. As I briefly discuss in Chapter 2, many challenges arise when trying to facilitate such participation (Delgado et al., 2010). For instance, there are different rationales for promoting participation, some of which are not necessarily in line with the idea of opening up evaluation processes. Rather, they are designed to provide clear policy descriptions (hence they are 'closed' with regard to outcomes) or even to support predefined solutions. The purpose of MCM, on the contrary, is not to provide clear policy recommendations, but simply to map the plurality of scientific and socio-political perspectives on a problem. I applied MCM in the study presented in Paper 4. As already mentioned, the study involved a broad range of participants associated with Norwegian salmon aquaculture. They were asked to assess alternative feed resources for farmed salmon by conducting a MCM exercise. The study showed that different actors within Norwegian salmon aquaculture represent important sources of knowledge about alternative feed resources for farmed salmon. However, no clear conclusions with regard to the suitability of the feed resource alternatives could be drawn from the study. Rather, it showed that the evaluation of the alternatives was influenced by the values and interests of the participants. This was particularly evident with regard to their choice of criteria. A broad range of criteria were identified, concerning (i) health and welfare issues, (ii) economical issues, (iii) environmental issues, and (iv) knowledge and ethical issues. Importantly, some of the criteria identified, e.g., impacts on the local communities where the feed resources originate and the various environmental criteria, exceed what are typically described as the factors driving feed resource substitution, such as price, availability and consumer acceptance (Naylor and Burke, 2005; Tacon and Metian, 2008). Thus, the wide range of criteria identified underlines the value of comprehensive and participatory evaluations, as a means to broaden the scope of and open up evaluation processes, and thereby strengthen the information base upon which future choices about salmon feed are made.

The results of each MCM exercise is presented in graphical charts that visualise the overall performance of each alternative (see Figure 6 pp. 58). These are meant to give the participant a simple overview of the results from the assessment. More importantly, when compared with other charts in the further analysis of the data, they help to visualise the differences in each of the evaluations, and hence, to what extent the assessors' values and interests come into play. Some of the participants expressed, however, that nuances and complexities involved in decision making on future feed strategies for farmed salmon were not satisfactorily described in these graphical charts. Moreover, such graphical expressions could easily be misused/misinterpreted by other users (e.g., policymakers), as each chart clearly describes what are the preferred and not-preferred options of an assessor (or, if results are aggregated in the further analysis, a group of assessors). Misuse or misinterpretation of scientific findings is a common problem that can never be completely prevented. Nevertheless, I would argue that by presenting the data in graphical charts this could perhaps occur more easily than if the results are simply described verbally.

### 8.4 Precaution: When and to What Extent it is to be Practised?

This chapter can easily give the impression that my take on precaution is 'the more the better'. In some ways I defend this position. One obvious reason are the numerous examples from past experience (see for instance, Harremoës et al., 2001) where decisions not based on precaution resulted in serious harm to human health and/or the environment. Another is that the behaviour of complex natural and social systems (of which novel technologies are introduced to and interact with) can never be fully predicted. Still, expert-led risk-based approaches continue to dominate the governance of novel technologies (Millstone, 2007; Stirling, 2006), which effectively limit the opportunities to facilitate truly precautionary and participatory approaches, (as I have described them in Chapter 2). Importantly, at the core of precaution is the recognition that it is not possible to know in advance when precautionary measures are required, due to the uncertainties involved. Hence, in my view, the idea of precaution, and precautionary and participatory approaches in particular, still need to be encouraged, and research is required to further improve the methodologies.

Nevertheless, I also recognise that there is a need to reflect upon when and how to set limits for precaution. This is not only due to practical constraints (e.g., these processes are costly and time consuming), which demand some kind of prioritisation, but serious consideration is also required to determine when and to what extent it should to be practised: E.g., what type of technologies and interventions require precaution? When has the range of uncertainties been sufficiently explored? When has enough follow up research been carried out? When has an issue been satisfactorily reflected upon, or an adequate range of alternatives explored? It boils down to the question commonly raised in discourses over precaution: How safe is safe enough?

For instance, half of the scientists participating in the elicitation of uncertainties associated with DNA vaccination of fish argued that they saw no need for a more thorough risk and uncertainty assessment of DNA vaccines compared to conventional vaccines. Contrary to this, from a precautionary perspective, I would argue that the fact that conventional vaccines have not been subjected to rigorous risk and uncertainty assessments is a manifestation of past negligence, rather than an indication of present-day irrationality or a justification for not assessing novel technologies. This example illustrates that there are different understandings of when to practise precaution. It is not for me to define its limits, but I raise the issue here because I think it is important that these questions become a part of future reflections on how to put precaution into practise.

### 8.5 Further Research

All the studies I have presented and discussed here can be regarded as ‘first steps’. Many of the challenges I experienced when conducting the studies, and the methodological weaknesses identified, could have been dealt with through follow-up research, particularly through in-depth interviews and workshops where the participants met to discuss our interpretation of the findings from the studies. For instance, we could perhaps have overcome some of the language barriers that we faced when trying to communicate the terminology used in the W&H framework (Paper 2), by conducting a second round of in-depth interviews, where we would ask the scientists to explain and justify their opinions in more detail. This would also give the scientists a new chance to reflect about uncertainties and discuss issues they had thought of after participating in the first round of interviews. Another example relates to our study on scientists' perspectives on GM crops (Paper 3). We found that the scientists perspectives were influenced by contextual factors; but based on these findings we could not conclude whether any of the contextual factors played a more central role than the others in shaping opinions (e.g., whether the scientists' opinions were primarily shaped by their disciplinary training, or were a result of socialisation at the work place), or to what extent the different factors influenced each other (e.g., whether scientists from a certain discipline were more likely to work at a certain institute, conduct a certain type of research, or receive a certain type of funding etc.). Follow-up interviews could possibly have provided more insight into these questions. Moreover, new insights could have been revealed by inviting the participants to workshops where they would be given the opportunity to discuss 'face to face' our interpretation of the findings from the first round of interviews. Under these settings the participants would have been encouraged to communicate and argue for their viewpoints more directly. This could particularly have strengthened the level of reflection and the learning experience for the participants.

### 8.6 Maintaining Plurality in Perspectives and Policy Options

The studies conducted for this thesis provide insights about scientists' and other impacted parties' perspectives on, and judgements of, uncertainties, benefits and concerns related to different applications of modern biotechnology in aquaculture and food production. It is, however, not the specific findings from the studies that are most interesting to me. Rather, I consider the plurality of the perspectives identified as the most valuable insights from my research. The studies presented in Paper 3 and 4 underline, in particular, how complex problems are open to multiple interpretations. The studies illustrate that a single 'best' solution can never be identified when addressing complex problems, such as whether or not to release GM crops, or how to feed farmed salmon.

Acknowledging complexity and uncertainty implies to provide plural and conditional policy recommendations (Stirling, 2006, 2008a, 2009). As always, policymakers are faced with the challenge to make a final decision. Left with a range of plural and conditional recommendations, rather than clearly defined advice, this task could easily become even more challenging. In turn, it would leave policymakers better able to make decisions that themselves are differentiated and conditional, e.g., specific requirements can be set as to when, where and how a given technology is to be applied. Moreover, as advocated by Stirling (2006, 2008a, 2009) policymakers should strive to maintain plurality in policy options and their final decisions. In this way more options will be available in case of future changes in conditions (e.g., resource availability) or societal values. Hence, maintaining plurality (both in terms of perspectives, policy recommendations and decisions) is important as a means to enhance reversibility, adaptability and resilience in relation to the governance of novel technologies, which may ultimately lead to more sustainable pathways.

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# Paper 1

# Paper 2

# Paper 3

# Paper 4

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