CASE STUDY 6.3

RISK ANALYSIS OF THE POTENTIAL INTERBREEDING OF WILD AND ESCAPED FARMED COD (*Gadus morhua* Linnaeus)

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6.3.1 Introduction

Cod (*Gadus morhua* Linnaeus) is a predominantly benthic species found on both the eastern and western sides of the North Atlantic from Greenland and south from the Barents Sea to Cape Hatteras and the Bay of Biscay. It feeds on both invertebrates and small fish. Age at first maturity is reported as 3.1 years and the maximum reported age is around 25 years, with males reaching 200 cm and 96 kg, although large specimens are now rare. Cod has a long tradition as an important commercial species, enormous stocks having existed in the past in areas such as the Grand Banks. Stocks in the North East Atlantic have recently declined to a low level, and measures are being taken to attempt to restore them. The traditional popular demand for cod for human consumption, low stock levels, and high growth rate makes the species an attractive target for aquaculture development.

The concern being addressed in this document is that farmed cod in Scotland may escape from cultivation units and genetically interact with wild cod, and that the consequence of this interaction is reduced survival in the wild population at local or larger scales. This concern is addressed through a risk analysis framework that includes: hazard identification, risk assessment (release assessment, exposure assessment and consequence assessment), and risk estimation and management. The analysis is structured around a logic model to clarify the pathway leading from the hazard (escaped cod) to the endpoint (reduced survival in wild populations).

The series of steps and processes leading from the establishment of cod farms in coastal waters to significant decreases in wild cod stocks as a result of genetic interactions between the two groups of cod can be summarized in a logic model, as below:

Process of concern : Changes in fitness of wild populations of cod due to genetic introgression
End Point of concern : Significant decline in survival in wild cod populations due to interbreeding with escaped cultured cod.
Logic model steps :

1. Cod farms are established in coastal waters.
2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
3. Cultured cod interbreed with wild cod.
4. The progeny of this interbreeding (hybrids) show reduced fitness. This is dependent on there being phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons.
5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.
6. Genetic interaction causes declines in endemic, evolutionarily significant units (populations), for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.
7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild cod stocks.

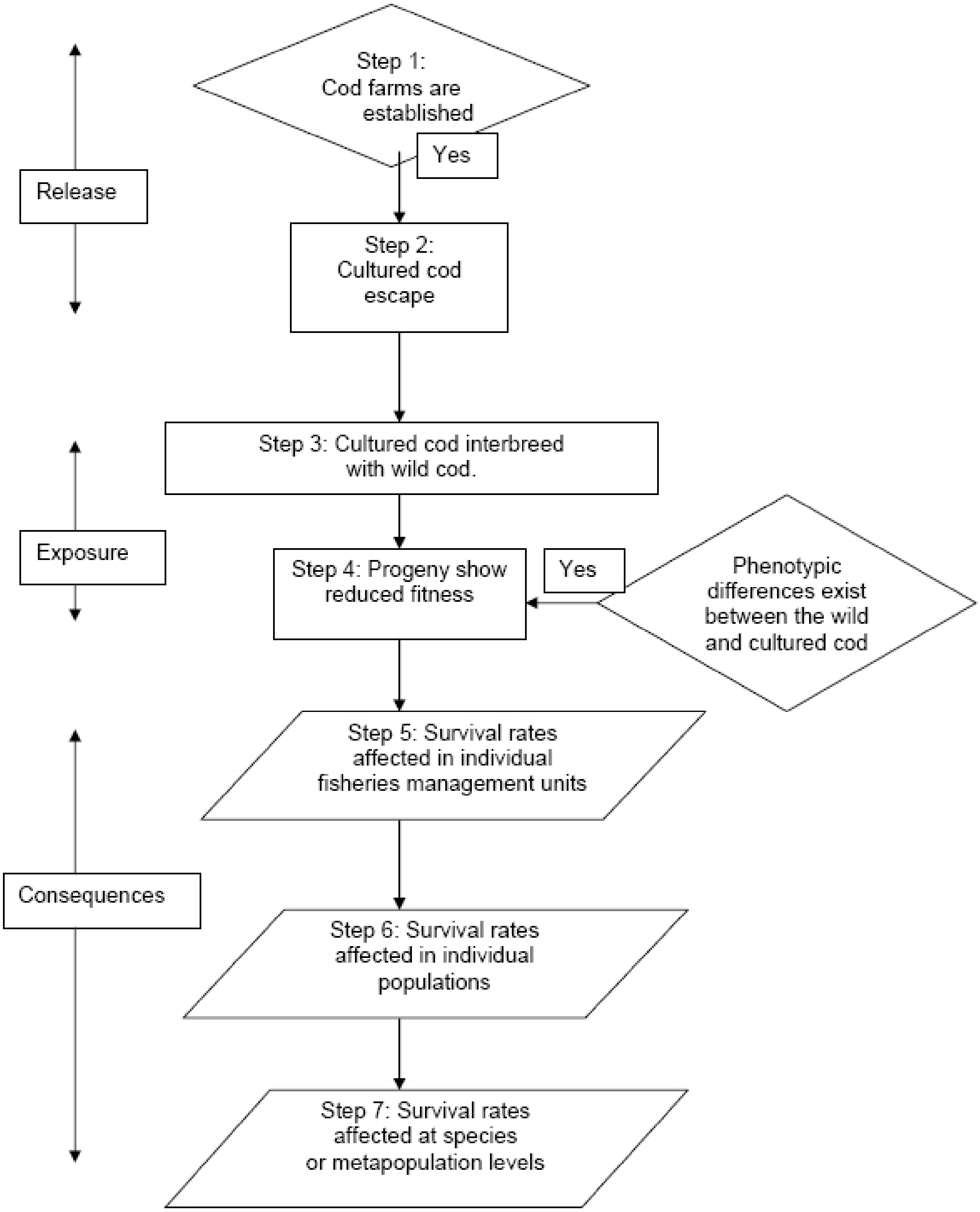
This logic model can be illustrated diagrammatically in Figure 6.3.1. The steps are classified into aspects related to the release of cultured cod into the environment, the exposure of the wild population to the genetic composition of the cultured fish, and the consequences for the wild populations at difference scales from local to the range of the species.

6.3.2 Hazard Identification

The hazard being assessed is the escape of cultured cod, in the form of fish (juvenile or mature), fertilised eggs, or gametes. The authors have not found any published accounts of the effects on wild populations of such escapes. However, cod stock enhancement programmes (for example, intentional releases of large numbers of hatchery-produced cod juveniles to the wild with the purpose of enhancing wild cod stocks) have occurred in several areas, and observations made in these programmes can provide some guidance on the likely interactions of unintentional escapes of farmed cod.

An overview of cod stock enhancement activities along the coast of North America has been compiled by Richards and Edwards (1986). No consideration was given in this review to the potential impact of these releases on natural ecosystems. Further references

Figure 6.3.1 : Diagrammatic representation of the logic model used for the genetic interactions of farmed and wild cod. (Standard flow chart symbols from http://www.patton-patton.com/basic_flow_chart_symbols.htm)



relating to cultured and wild cod interactions include Jørstad *et al.* (1994) and Kitada *et al.* (1992).

Historically, cod stock enhancement has occurred in Norway, Sweden, Denmark, Faroe Islands and North America. Svåsand *et al.* (2000) reviewed the effects of these attempts to supplement wild stocks with cultured cod. Releases involved fish between 8 and 41 cm in length (wild cod in Scotland are ~20 cm long at year 1 and ~50 cm at year 2). The numbers of fish released were relatively small, and varied between 500 and approximately 400 000 fish. Survivability of released cod was highly dependent on the age and size at release. The average rate of mortality of released yolk-sac larvae in Norway was 23% per day during the first 10 days, with only 0.15 % surviving the first 40 days after release. The optimal timing for release is generally after the juveniles have reached the size at which they settle to the benthos.

The occurrence and migratory habits of Baltic cod, together with the changes in their allele frequency, haemoglobin types, meristic characters and otolith types, based on results of extensive tagging trials since the 1950s, were reviewed by Otterlind (1985). About 15 transplantation experiments with tagged cod were conducted to assess the potential homing ability of the fish. The waters along the west of Bornholm constitute an area of hydrographic instability with varying cod migrations and passive transport of fry by currents. Except for local stocks, cod raised in the central and northern Baltic areas migrate mainly to the east of Bornholm, with a varying contribution of the cod from the west of the Baltic Sea. Fish in the latter group migrate primarily southward within the Baltic Sea to spawn, and as adults they usually stay east and north of Bornholm. Results of the transplantation experiments support a strong linkage between cod migration and hydrographic factors. Cod tagged and transplanted to a new area behaved and moved in the same way as the local stock. Indications of 'homing' can be found in areas with suitable hydrographic gradients, such as changes in salinity (*for example*, in Oresund).

Studies from Norway suggest that released reared cod have a variable fidelity to an area. Fish from one resident southern coastal population were fairly stationary when released, with more than 80% of fish recaptured within 5 km of the release site, and no more than 5% dispersing more than 10 km. Reared fish from another northern population had only 45% recaptured within 10 km of the release site. In Denmark, 72% of recaptures were taken within 40 km of the site of release. In the Faroes, more than 50% of the recaptures occurred within 10 km of the release site. On this scale of dispersal (for example, within 50 km of release) Svåsand *et al.* (2000) stressed that results obtained in one area cannot be generalised to other area.

Svåsand (1993) also examined behavioural differences between reared, released and wild juvenile cod, using Floy anchor tags and oxytetracycline markers. While differences in individual behaviour patterns occurred, no differences in migration patterns between wild and reared specimens were demonstrated.

Nordeide and Salvanes (1991) compared the stomach contents and liver weights of reared, newly released cod and wild cod; the stomach contents and abundance of potential predators were also described. During the first three days after release, the reared cod fed mainly on non-evasive prey such as gastropoda, bivalves, and actinaria. This is in contrast to wild juvenile cod, which mainly fed on gobidae, brachyura, and mysidacea. Large cod, pollock, and ling preyed upon the released cod immediately after their release, whereas, during the months following release, the stomach contents of large predators were dominated by labridae and salmonidae, which are also the typical prey of wild cod. The abundance of predators did not seem to increase in the area of release. However, a study by Svåsand and Kristiansen (1985) found no difference in dietary composition of cod five months after release. This suggests that although the foraging behaviour of newly released cod is poorer than wild conspecifics, they adopt similar feeding behaviour to wild fish within five months of release.

Jørstad and Nævdal (1992) and Jørstad (1994) reported an extensive series of investigations of the effects of mass rearing and release of 0-group cod in fjords and coastal areas of Norway. Each year since 1987, pond produced cod have been liberated in Masfjorden, a small fjord north of Bergen. The released cod, as well as the wild fish and those recaptured in the fjord system, have been genetically characterised by electrophoretic analyses of haemoglobin and several enzymes. In 1990 and 1991, about half of the released cod consisted of offspring of broodstock homozygous for a rare allele (Pgi^{-1}(30)). This broodstock was produced by crossing pre-selected heterozygotes for this allele, the homozygotes among the offspring were sorted out on the basis of biopsy sampling of muscle tissue, and when matured, used as parents (Jørstad, 1994). Extensive genetic studies and monitoring were carried out in Masfjorden and Øygarden for both the released and wild cod. Except for the enzyme GPI, the groups of fish did not differ and the patterns of change associated with the GPI frequencies were attributed to genetic drift rather than local adaptation, for example, there was no evidence that the relative survival of the released and wild fish was affected by local conditions.

Svåsand *et al.* (2000) reviewed studies of the ecosystem level effects of large scale releases of reared cod in the Masfjorden and Troms areas of Norway. The Masfjorden studies involved a control fjord and an experimental fjord into which large numbers of reared cod were released. Both sites were monitored before and after the release to detect potential interactions between released cod, its predators (large cod, pollock) and competitors (poor cod, *Trisopterus minutus*), and population characteristics (abundance, growth, condition factor, liver index). The abundance of selected prey species was also monitored. Only minor effects could be ascribed to the releases of cod (Fossâ et al., 1994). Recent unpublished data on the poor cod suggests a reduction in size in the experimental area, but not in the control area. For wild cod, however, there was a slight reduction in condition factor and liver index. Higher densities in the experimental fjord became undetectable within 1.5 years. The data suggest that reared cod suffered higher mortality than the wild cod.

In the Troms area experiment, releases did not increase the biomass of cod in the fjord, nor did they reduce prey abundance. A strong year class at that time was believed to have lowered growth rates and may have had an effect on the ecosystem similar to that of an average year class enhanced by released fish.

6.3.3 Risk assessment

The following analysis of the risks of genetic interactions between wild and cultured cod in N.W. Scotland is predicated on the assumption that carrying capacity is not a limiting factor for the abundance of wild cod. Given the historical fishing pressure, low abundance of stocks over more than a decade and the nature of the meta-population structure of cod populations, it is likely to be very difficult to detect carrying capacity effects at the meta-population level. With the potential movement of individuals between sub-populations, it may also be difficult to detect carrying capacity constraints at the sub-population level; but if constraints were occurring they are most likely to be evident at this level.

Our understanding of long term effects of introgression in fishes is limited and has been best studied in salmonid populations. Studies of introgression in marine fishes are almost non-existent. Discussion of the potential effects of introgression between wild and cultured cod must therefore be made in relation to theory and knowledge of the interactions between wild and cultured salmonids.

The concern being addressed herein is that escaped cultured cod may interbreed with wild populations of cod and negate the effects of selection in the formation of locally adapted populations. The consequence of this introgression would be reduced survival in the wild fish population.

Determining what constitutes the size of a managed population is predominantly a governance issue of policy. However, from a scientific point of view it is possible to make some *a priori* estimates of the minimum population size required for the allelic frequency in a population to be effectively determined by selection.

During a protracted period of decline in the size of a populations, there is the possibility that the numbers will become so small that the effects of natural selection will become diluted or nullified by inbreeding and stochastic changes in allele frequencies (genetic drift). Published numbers used for this critical population size vary between effective population sizes (N^e) of 500 and 5 000 individuals (Lande 1995; Franklin 1980 and Dennewitz 2003). In the following analysis, it will be assumed that, if the population has been in decline for a number of generations and the N^e is below 500, then any long term stability in genetic frequencies is not determined by local adaptation. The genetic risk analysis should therefore be performed on the next level, for example, the lowest component level of population structure that exceeds the minimum effective population size for natural selection to be effective.

6.3.3.1 Release assessment

The hazard being assessed is the escape of farmed cod (as fish or gametes) from cultivation sites. Cod gametes may be released by caged cod, and cod have been known to breed during their culture in cages. Further, farms that choose to specialise in the market for larger cod or to maintain fish as a potential brood stock would have large, mature fish in their systems thereby increasing the opportunity for spawning in cages. However, the reductions in growth rate associated with redirection of energy into making gametes has resulted in the development of photoperiod manipulation protocols to delay or suppress maturation (Taranger *et al.* 2006). It is likely that, in the future, farmers will manage their stocks so that very few fish spawn in the cages, thereby reducing the probability of gametes or fertilised eggs escaping from the cages.

While techniques are rapidly developing to control reproduction in cod culture, there is still some potential for cod to spawn in cages. Cod milt and eggs are known to survive for a relatively long time after release, and fertilization of eggs can occur upwards of 60 minutes after release. If present, gametes from wild cod outside net pens could therefore potentially interact with gametes produced by farmed fish inside the cages, although the main spawning areas for wild cod are in more offshore areas.

A similar problem of dispersion of a time-limited viable agent is dealt with in management of diseases on fish farms in Scotland. There the criterion used is the predicted dispersion of an agent over a tidal cycle (12 hrs). That has been translated to a ‘rule of thumb’ of a 5 km separation distance between groups of farms in a disease management unit. If thought necessary, a similar approach might be applied to review the existing locations of cod farms and be part of future planning to separate farms from cod breeding areas. At present, the depth and location of wild cod spawning grounds suggest that the dominate route of interaction between wild and cultured cod will be via escapes of cod from cages rather than via dispersal of gametes.

The inability to reliably produce cod fry for aquaculture has been a significant historical constraint on the development of the industry. In 2002, a breakthrough in the production of cod fry occurred in Norway, when approximately 3 million fry were produced. In addition, survival rates of 87% from hatching to 0.2 g were reported in one hatchery in Scotland. These recent success stories are due to improved knowledge and an increased number of enterprises. A production target of 10 million fry in Norway is expected in the next few years, which will be followed by a subsequent substantial increase in production. As can be seen from Figure 2, intensive fry production is the dominant production method.

Fry production in other countries is less developed. In Scotland, around 50 000 juveniles were stocked in 2002, with 15 tons of cod produced in 2000 and 2001.

Figure 6.3.2 : Total production of cod fry in Norway 1983 - 2002 (Karlsen and Adoff 2003)

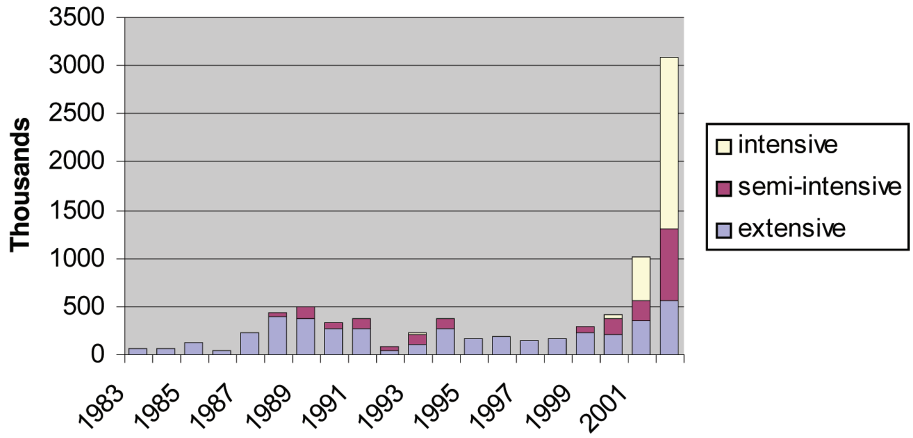
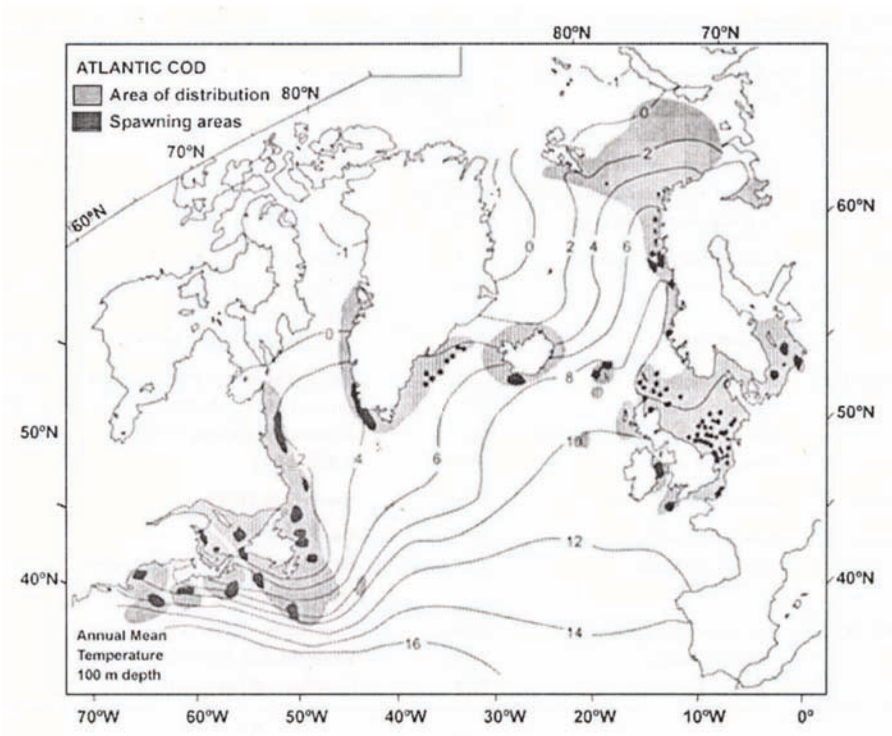


Figure 6.3.3 : Cod distribution and spawning areas (after Imsland and Jonsdottir 2003)



More than 350 tons of production is predicted in 2005. In Ireland, a research fellowship is in place to identify and harness potentially exploitable research and technology so as to enable the establishment of a commercially viable cod hatchery as a preliminary step to developing an industry.

Cod culture in sea cages is currently confined to relatively sheltered inshore areas, compared to salmon culture. The siting, distribution and position of farms 'licensed' to hold cod will be determined by national regulatory bodies (for example, Local Authorities, the Crown Estate Commission and the Scottish Environment Protection Agency in Scotland, and the Ministry of Fisheries in Norway). From the FRS (Scotland) database, 20 out of 483 registered farms have multi-species licences and therefore have the potential to stock and produce cod. No aquaculture licences for cod have yet been issued in Ireland, although several applications are being evaluated. Cod reared in pump ashore facilities, particularly those employing treatment of discharge water (filtration and sterilisation), pose a negligible risk in terms of fish escapes.

FAO data show that the production of farmed cod in 2001 occurred in Norway (608 tons), UK (15 tons), and Iceland (140 tons). More recently, it was predicted (Goodlad, 2003) that cod production may increase from 6000 tons in 2003, to 200 000 tons in 2010, and 400 000 tons in 2020, mostly in Norway. Predictions for Scotland suggest 25 000 tons will be produced by 2012-14. This dramatic increase in cod farming will inevitably lead to an increased risk of escapes.

Rearing trials suggest that sites with water currents in excess of 1m per second are unsuitable for growing cod. Consequently, cod farms will tend to continue to be located in less exposed locations, in terms of both tidal currents and wave action, and thus the risks associated with storm damage will be less than those for salmon (assuming engineering comparability of equipment). Measures such as double netting will further reduce the likelihood of escapes.

There have been no reported escapes of large numbers of farmed cod in Scotland to date (2006), although the industry is still in its infancy. Therefore, there is no specific information available on the rates of escapes of farmed cod under Scottish conditions. However, extensive information is available on rate of escapes from Scottish salmon farms, due to compulsory notification of escapes (Registration of Shellfish and Fish Farming Business and Registration Order 1985). Reporting of escapes is also compulsory in Ireland and Norway. Over the last 5 years, there have been 20-25 escape events per year from Scottish fish farms, mostly from Atlantic salmon farms. The numbers of escapes of salmon from saltwater sites in Scotland have been between 76 000 and 411 000 growing fish (1-4 kg) per year (Table 6.3.I).

This table suggests that the rate of escape is typically around 0.1 – 0.5% of the total number of individuals in cultivation. If this rate is applicable to cod culture, this suggests an escape rate of between 20 000 and 150 000 cod per annum at an annual input to on-growing of around 10 000 000 juveniles per annum.

As a consequence of the fidelity of cultured cod to the area of release, it is likely that cod escaping from the Norwegian industry would mainly join local wild cod in a northern migration to breeding areas, rather than join the fish in the North Sea. As such, it is anticipated that any farmed fish breeding with North Sea cod would mainly be those originating from Scottish farms.

The main causes of escapes from salmon farms have been: human error, equipment failure, bad weather and predator attacks. Cod are currently cultivated using similar equipment (square or circular netting cages with steel of plastic flotation collars in sheltered coastal waters), and therefore these factors could also be considered the main areas of risk with regard to cod farming, with some modifications:

- The generally more sheltered locations of the cod farms at present would lessen the risks of storm damage, but shelter could increase the risk of predator (for example, seal) attacks.
- Human error and equipment failure could probably be regarded has having similar levels of risk as salmon farming.
- Evidence regarding 'nibbling' of nets is currently unclear. It has been reported not to appear to be a significant factor with cod (Scottish Executive Working Group on Escapes), particularly with the use of double nets, but on the other hand observations of 'determined attempts' to escape through netting has been reported in Norway (www.sintef.no).
- Cod can be transferred to sea pens at weights above 5 g, whereas the minimum weight at transfer of salmon smolts to sea is typically 35 g. The risk of escape through minor holes in the net is consequently greater for juvenile cod.
- Unlike salmon, cod shoal rather than school, so the motivation for a contained cod to follow an escaping cod may be less than it would be for salmon in similar circumstances. However, further work is required in this area.

Although outside the scope of this risk analysis, it may be noted that accidentally released fish from culture sites may interact with local wild cod populations at a number of life-cycles through feed competition and behavioural stresses. Behavioural stress will be particularly intense when territorial competition is a key component controlling population density in a given habitat. If a decline in abundance of cod during the 1900s is primarily a consequence of fisheries pressure, it would seem likely that food and habitat resources do not currently limit the survival of cod. This conclusion has been reiterated by Baxter (2000) who states that "unless a small wild population is swamped by large-scale releases (or stocking) of reared fish, it seems unlikely that the reared fish will out-compete the wild fish".

Table 6.3.I : Numbers of salmon smolts put into salt water on-growing units, and numbers of escapes for 1999 – 2004. The percentages are calculated from the smolt inputs in single years. As the production cycle is approximately 2 years, the escape rates expressed against the total fish numbers in cultivation will be approximately one half of the percentages in this table.

	Number (millions) of salmon smolts put to sea	Numbers escaped in salt water (thousands)	% Escapes
1999	41.1	257	0.63
2000	45.2	411	0.91
2001	48.6	76	0.16
2002	50.1	376	0.75
2003	43.8	104	0.24
2004	38.1	83	0.22

6.3.3.2 Exposure Assessment

6.3.3.2.1 Distribution and movements

Studies suggest that, in the North Sea and off the coasts of Canada, Iceland and Norway, cod have differentiated in to a number of subpopulations (Imsland and Jonsdottir 2003; Jorstad *et al.* 2007). Ruzzante *et al*. (1996) have demonstrated that there is genetic differentiation between onshore and offshore populations of cod in Canadian waters off the coast of Newfoundland. Later work by Ruzzante *et al.* (1998) suggested as many as 14 subpopulations may exist if both inshore and offshore populations are considered.

In the Eastern North Atlantic, Neilsen *et al.* (2001) identified three distinct subpopulations (North East Arctic Ocean, North Sea and Baltic). In the North Sea, recent microsatellite DNA studies (Hutchinson *et al.* 2001) suggest that there may be four distinct subpopulations. The amount of information supporting four rather than the traditional three subpopulations is limited and but an EU FP5 project (METACOD 2005) is investigating this issue.

This constitutes a major difference from the structure of salmonid populations, where substantial genetic differentiation can be found over relatively small geographical scales (reviewed by Altukhov *et al.* 2000). This is not unexpected, as salmonids breed in very discrete sites within lakes, rivers and streams and show high fidelity to a spawning site. Those sites exhibit considerable habitat heterogeneity and physical isolation.

Clearly the precise number of genetically differentiated cod populations is an ongoing discussion. Smedbole and Wroblewski (2002) have framed the discussion of cod population differentiation in terms of metapopulations, each composed of a set of local subpopulations. The degree of genetic differentiation among subpopulations may range from slight to almost complete isolation. The spatial patterning of subpopulations within a meta-population is temporally dynamic; subpopulations may undergo extinction and recolonisation, and new subpopulations may develop. Extinction, recolonisation and differentiation of subpopulations will be affected by abundance in the meta-population and recent studies (Beamish 2004a,b,c) suggests that oceanic regime shifts may, on a time scale of decades, have as large an effect on population abundance of marine fishes as fishing pressure.

If, in the course of time, a subpopulation number declines there is the possibility that the numbers will become so small that the effects of natural selection will become diluted by stochastic changes in allele frequencies over time (genetic drift). Under these circumstances, outbreeding to other components of a meta-population provides a degree of stability to the allelic frequencies in the subpopulation. Abundance of cod in NW Scotland is currently so low that the influence of genetic drift and the importance of other subpopulations in stabilising allelic frequencies must be considered.

Given the above complexity, some simplifying assumptions must be made about the structure of cod populations. Currently, the main areas where the aquaculture industry is actively engaged in seeking to develop cod farming are Canada, Scotland, Norway and Ireland. Imsland and Jonsdottir (2003) identify groupings of spawning areas off the east coast of Atlantic Canada, Scotland and Ireland, as well as off the north coast of Scotland. Gene flow between populations is generally expected to be highest between populations whose spawning areas are closer together. These aggregations of spawning areas may therefore form the basis for meta-populations with subpopulations derived and maintained by individual spawning areas within an aggregation of spawning areas. On this basis, for the purposes of this analysis, the cod population structure in the North Atlantic will be assumed to be composed of separate meta-populations in the North West Atlantic, Iceland, Scotland- North Sea (North Sea, NW Scotland, Skaggerak, and English Channel) and Norway (North of Stavanger).

Cod eggs and larvae were found through out the west and north coasts of Scotland during the spawning season (January-April) in the 1970s. By the 1990s, this area had diminished to areas off the west coast off the Western Isles and the northern North Sea (Heath *et al.* 1994). In this area, juvenile cod during their first year are found close inshore or around the mouths of sea lochs and fjords. Recruits to the adult cod population are widely distributed on the west coast of Scotland, mainly in offshore areas where they can occur in large shoals.

East of the UK, after hatching at a length of about 0.4 cm, young fish grow to between 2 and 8 cm by June, and are concentrated mainly in the eastern and northern parts of the North Sea. By the following winter, the young fish are between 13 cm and 26 cm in length and are concentrated in the shallow coastal waters of the eastern North Sea. One and two year old cod can be found all over the North Sea, although by age three they are distributed mainly towards the northern part of the North Sea (The Centre for Environment, Fisheries and Aquaculture Science, pers. comm.).

At the moment there is very little conclusive information on cod nursery areas. The general feeling at the moment is that juvenile cod prefer exposed rocky inshore areas. However, they have also been found on offshore gravel banks in the southern North Sea and sand banks off the west coast of Scotland (EU project METACOD, 2005; and current METAGADOID project). These projects have identified regional populations of cod in the Moray Firth, off Flamborough Head, in the German Bight, in the Southern Bight of the North Sea and in the English Channel that separate during the spawning season and, in some cases, inter-mix during the feeding season. The Clyde Sea has also been identified as a preferred area for juvenile cod. From the evidence of NW Atlantic stocks, we might expect that the different reproductive units might intermix to some extent during the summer.

There is some understanding of the movements of cod to the west of Scotland. As elsewhere, eggs and larvae are dispersed by currents until the young cod move onshore in the spring where they feed and grow in shallow waters for the first year. In late summer, cod move from west of the Hebrides to the north coast of Scotland. In late winter and early spring, they reverse this movement. There is information to indicate that, in the NW Atlantic, cod migrate along clines of preferred ambient temperatures (Rose 1993). Some coastal aggregations of cod appear to show very limited migration and these are most likely to be the most sensitive to interactions with farmed stocks. Cod reach maturity at 2 - 3 years and on the west coast can also spawn at this age. Although maturity at age varies by region, all cod are spawning by six years of age. Non-spawning adult populations can be either migratory or resident.

Results from tagging experiments show that there is a little interchange of cod between the North Sea and areas to the west of Scotland. Tagging studies carried out over several decades have also shown that generally the maximum distance travelled from the release point is about 200 miles, although a few long-distance migrations have been recorded. In one experiment in June 1957, when cod were released in the central North Sea, two fish were recaptured off the Faroe Islands in September 1957 and one fish was recaptured off Newfoundland in December 1961. The available information indicates a degree of uncertainty in understanding of the migratory and other behaviour of cod, and the existence of structure within the overall population to the east of the UK.

Tagging data from Scotland show that there is little exchange of fish between the Firth of Clyde population and those in the Minch, particularly in the North Minch, north of Skye. Cod from the Minch have been caught north of Scotland but there is little apparent exchange between Minch cod and cod in the Moray Firth (NW North Sea).

The above discussion has mainly concentrated on cod stocks round the United Kingdom. Although the appropriate information is not presented, it is considered that the principles and patterns established in this limited area are broadly applicable to cod in other areas, for example, off the Norwegian or Canadian coasts.

6.3.3.2.2 Growth and mortality

Under typical growth rates in Scottish waters, wild cod will reach 20 cm (90 g) after 1 year, 50 cm (1300 g) after 2 years, and 80 cm (5200 g) after 4 years. Data on growth rates of farmed cod transferred to net pens in Scotland at an average weight of 5 g in July are summarised below:

Date	Average weight (g)
July – 1st year	5
October – 1st year	40
December – 1st year	120
February – 2nd year	230
April – 2nd year	350
December – 2nd year	2000
December – 3rd year	3500

A growth trial in net pens carried out on wild cod captured from Bay Bulls in Newfoundland, showed that, when cod were fed on either capelin or two different types of formulated wet diets, they grew on average between 33-34% over a three-month period of the trial (Clark *et al.* 1995).

Predation mortality of cod eggs is predominantly from sprat and herring, as well as juvenile and adult cod cannibalism. The survivability of settling larvae has been linked in many studies to the complexity of the seabed, and is one of the targets of the METACOD project.

Most mortality occurs during the juvenile stages. A significant proportion of the mortality can be due to starvation and cannibalism by older cod, as well as predation by other piscivores. Not surprisingly therefore, different age classes of cod do not aggregate together. After about one year's growth, young cod (in Scotland, at ~20cm length) generally move offshore to feed where they become susceptible to increased fishing pressure prior to recruiting to the spawning stock.

Most cod stocks in the North Atlantic are below the ICES precautionary levels, and in some ICES areas there is a moratorium on cod fisheries. Many of these populations have been in decline for more than a decade, and as the meta-population shrinks and can no longer support all its subpopulations, fisheries have witnessed the disappearance of some local cod populations. Since 1980, the fishing mortality on North Sea stocks has been around 1.0, although it has varied rather more since 2000 (0.5 – 1.2) at a time when stocks have been reduced to such a level that productivity is impaired, and a formal stock recovery plan has been introduced at EU level (ICES 2005).

6.3.3.2.3 Diet

In a study off the west coast of Sweden, Mattson (1990) reported that cod ranging in size from 6 to 97 cm fed at 40-90 m depths. Diets consisted mostly of benthic and epibenthic species (Mattson 1990), with 75% crustaceans and fish. At larger sizes, the proportions of benthic species to copepods increase with size. Young cod up to 1-3 cm size feed exclusively in the water column on copepods, then at 4-6 cm size add benthic prey species such as mysids and amphipods, but copepods remain an important food item. Large cod also consume molluscs, worms and smaller fish.

Juvenile cod are preyed upon by larger piscivorous fish (including larger cod), seals, cetaceans and birds. The proportion of each of the predator types has been shown to vary from year to year. Cannibalism is a large part of predator-prey relations, with larger 0-group cod and older cod consuming smaller ones. Stomach content surveys seem to be most comprehensive in the Baltic Sea. Studies from Newfoundland corroborate these findings. Seals are a significant predator of adult cod; 82% of seal diet in Northern Scotland made up of fish, with 50% sandeel and cod also important prey items. A Canadian study also found that grey seal predation caused 10-20% of mortality in cod stocks.

6.3.3.2.4 Abundance

Cod stocks around Scotland are under severe fishing pressure. Spawning stock levels for both the North Sea and west coast stocks are below safe biological limits. Stocks have been below ICES precautionary levels since 1988. ICES advised the European Commission and national governments that all fisheries which target cod, even as a bycatch, in the North Sea, Skagerrak, Irish Sea and waters west of Scotland should be closed (ACFM 2002).

The ICES ACFM report for 2003 (ACFM 2003) estimates that the spawning stock biomass of cod to the west of Scotland in 2002 was 2,230 tons, with 3 000 000 individuals recruiting at age one. In 2005, the biomass of these stocks was estimated at only 350 tonnes (ACFM 2005). The spawning stock biomass in the North Sea, English Channel and Skagerrak combined was 54,400 tons, with 168 000 000 recruits at age one. The most recent complete data on numbers of individuals present in the North Sea/Skaggerak/English Channel stock assessment area are for January 1, 2003 (Table 6.3.II).

Table 6.3.II : ICES estimates of numbers of cod at age in the North Sea, Skaggerak and English Channel combined, January 1, 2003.

Age	Number of individuals
1	50 037 000
2	63 059 000
3	14 034 000
4	13 234 000
5	1 542 000
6	260 000
7	122 000

The combined average landings of wild cod in the waters off Ireland and UK have plummeted from 75 000 tons per annum to less than 25 000 tons since the mid-1990s (Marine Institute, Stock Book 2001). Around Iceland, there has been low spawning stock biomass and weak recruitment since the mid-1980s.

6.3.3.2.5 Reproduction and spawning

Adult male and female cod form pair bonds, but egg fertilization is external. Females are batch spawners, often producing 15 egg batches over a period of six weeks. One adult female can produce around 4 million eggs (depending on size) per season. Around Scotland, cod may reach maturity at two years of age, but do not spawn until four years old. At age six, all fish are mature. However, most fish are caught in the fishery by the time they are age two.

Data taken from the ICES International Bottom Trawl Surveys, two EU funded projects (Heath *et al*. 2003; METACOD 2005), ichthyoplankton surveys and responses to questionnaires taken from fishermen have found that cod spawn throughout much of the North Sea, although some spawning aggregations do occur. The main spawning areas in the North Sea are in the central North Sea around the Dogger Bank, the southern North Sea, and the German Bight. There is also a center of spawning in the NW North Sea in the Moray Firth (CEFAS). The EU projects are producing much useful information, and FRS has produced a report on North Sea spawning grounds. Spawning aggregations also appear to occur in the Irish Sea and off the NW coast of Scotland. Spawning on the West Coast takes place between January and April, mainly in offshore areas.

The time of spawning is well documented as being between January and April, with the more northern areas spawning later than the more southern areas. Eggs, which are about 1.4 mm in diameter, are found floating in the surface layers over large areas of the North Sea. They typically hatch over a period of 11-30 days, depending on water temperature. *C. finmarchicus* is the staple prey of first feeding larvae of Atlantic cod. Cod juveniles live in the upper water column until around August before settling to a demersal life style, driven mainly by changes in food requirements from predominantly copepods to benthic species.

In Iceland, mature cod in the spawning period were typically found in waters over 300 m in depth, indicating that spawning normally occurs offshore (Begg and Marteinsdottir 2002a, b).

A Canadian study on variation in size-specific fecundity of cod sampled from the Gulf of St. Lawrence and the Georges Bank indicated significant variation that could not be attributed to physiological conditions (McIntyre and Hutchings 2003).

6.3.3.2.6 Genetic structure of wild populations

As discussed above, there is an ongoing debate about the large scale and small scale structure of cod populations. However, to evaluate the potential effects of cultured cod on wild populations, some attempt must be made to outline the likely structure and variability of wild cod populations. Smedbol and Wroblewski (2002) have described cod population genetics as 'meta-populations'. The meta-population structure incorporates concepts of discrete local breeding populations connected by immigration and emigration. Depending on factors such as the distance between areas occupied, geographic or oceanic barriers, and the dispersive ability of the species, the degree of segregation between subpopulations can range from slight to almost complete isolation. However, exchange between subpopulations of the meta-population prevents the development of separate autonomous populations. Begg and Marteindottir (2002a, b) typify a cod meta-population as a composite of local populations (*for example,* spawning components) between which individuals move, and where 'source' populations provide immigrants to less productive 'sink' populations.

No information was found that would allow comment on the rate of straying (and presumably introgression) between subpopulations within a meta-population.

6.3.3.2.7 Synthesis

Genetic interactions between farmed and wild cod depend on escapes of fish from holding facilities. Wild cod can have a protracted spawning period (usually January to June, depending on the area) thus presenting opportunities for a temporal coincidence in the occurrence of wild and cultured cod gametes released from cages. Further, studies have shown that cage reared cod will spawn concurrently with wild cod in the same region. However, wild cod appear to spawn in offshore areas at considerable depth some distance from the present location of cage culture, and therefore it is unlikely that gametes from cages will encounter gametes from wild stocks.

Most adult cod stocks do not frequent the shallow, coastal waters typically used by the salmon industry today, and which will be the location for a developing cod farming industry. As such, direct interaction between caged and wild mature adults will be limited.

Wild, juvenile cod are known to occupy near shore areas where cobbles and kelp can be used for predator evasion and offer diverse feeding opportunities. Eelgrass beds are also known to be important nursery areas where they occur. Escapes in these habitats would probably interact with wild juvenile cod, and give opportunity for escapes to mix into wild stocks, but clearly would not immediately interbreed.

In the event of escapes, the age of the released cod may determine how they adapt to the marine ecosystem. For instance, wild juveniles typically establish schools in inshore, shallow water areas. Escaped juvenile fish may therefore join conspecifics of similar size in inshore waters. On the other hand, adults are found in deeper, more oceanic areas and escaped cod may also follow this migration pattern. Where mature fish escape at the appropriate time of year, they would need to migrate to offshore spawning areas before they could potentially interbreed with wild populations.

Conversely, small juvenile wild cod may enter cages and be exposed to predation during their first year when they have a pelagic life style, but after that it is unlikely that they will be exposed to predation by caged fish. However, the numbers of juveniles lost in this way may not be significant, as juveniles are known not to inhabit the same area as older cod (perhaps to avoid cannibalism) and may therefore actively avoid older cod in cages.

It is not known if adaptation to local environments exists in marine fishes like cod, but if it does, such adaptation will depend on the degree of isolation from other conspecifics. The Danish Institute of Fisheries Research is studying the possible occurrence of local adaptations in marine fishes, and this work should provide useful information relevant to the consequences of escapes of cod.

At least in the first instance, cod farming is likely to occupy the same general areas of coastal waters as salmon farming. Some competition for space may occur, but as farmers seek to grow cod experimentally at established salmon farms, relatively little additional capital will initially be required to establish cod farming on a small scale.

6.3.3.3 Consequence Assessment

The genetic effect of escapes is likely to be minimal if the farmed stock is made up of wild-caught juveniles from a widespread and abundant local stock, which has a regional rather than local population structure. On the other hand, there is a significant potential for change if farmed fish are of non-local origin with low genetic diversity (*for example*, from small populations with a high degree of inbreeding), and subsequently mix with a population that is not differentiated into a series of distinct local populations. Since cod populations are now rather small in many inshore waters, the impacts on wild cod populations may be noticeable if unusually high numbers of non-native farmed stocks repeatedly escaped into depleted local stocks.

Whether cultured for all of their life cycle or only part of it, cultured fish face different selective pressures and a different 'learning environment' than wild populations. Consequently, cultured cod will ultimately express different genetic, phenotypic and behavioural traits than wild cod. A critical question is how significant these differences will be, and to what degree will they impact wild populations when cultured and wild populations interact. Experience with cod culture (as an enhancement activity) dates back to the middle of 1800s. However, actual investigations of the differences between wild and cultured cod are primarily from studies in the 1980s and 1990s. Our knowledge of the differences is further limited by a number of factors including the short time cod have been under continuous selection for culture, the incomplete knowledge of the genetic structure of wild and cultured cod populations, and the fact that, both in culture and in the wild, the selective pressures on the cod genome are constantly changing.

The potential for inter-species hybridisation involving escaped farmed cod is not thought to be a problem (FRS pers. comm.). An extensive e-journals literature search found no reference to any literature on cod hybridization. However, experiences with salmon suggest that further research may be required. Youngson *et al.* (1993) have identified what is likely a behavioural deficiency in escaped farmed salmon that has led to increased levels of hybridization with brown trout. Such hybridization was found to be ten times more frequent among escaped farmed than wild Atlantic salmon females.

Recent studies on NE Atlantic cod conducted by Dr T Svåsand, from the Institute of Marine Research in Norway, included comparisons of wild and cultured cod in regards to behaviour, migration patterns, stomach contents, and growth. Feeding methods, and the efficiency of feeding methods, have been shown to be different in wild and reared cod, with the wild cod generally outcompeting reared cod. Therefore, if feed limits survival, escaped fish are likely to have lower survival rates than wild conspecifics.

The current trend among start-up cod hatcheries in EU countries is to source either eggs or broodstock from established farms that are certified as disease free, thereby minimising risks associated with the use of wild cod of indeterminate health status. Consequently, the practice of introducing non-indigenous cod may increase and accelerate the rate of genetic divergence between farmed and wild cod stocks.

Wild populations can re-adapt following introgression. They do this when individuals from other genetically distinct cod populations (strays who fail to home to the breeding grounds of their parents) interbreed, and presumably can do so when the introgression is with farmed fish. The rate at which the maladapted genes are removed from the population depend on the magnitude of the fitness reductions, the effective population size (Ne) of the wild fish population (a low Ne will reduce the rate of removal of maladapted genes), and the rate of gene flow between the cultured and wild population.

Studies of the magnitude of the reduction of fitness in hybrid cultured and wild cod have yet to be undertaken. Cod, however, have been in culture for a relatively short period and have had little time to genetically differentiate themselves from the wild populations. Cultured salmonids, in contrast, have been raised and selected for culture for many generations. Studies by Skaala *et al.* (1990) and McGinty *et al.* (2003) have shown that maladapted traits in hybrid salmonid populations are removed rapidly over a few generations. It would seem reasonable therefore to expect the same maladapted traits in cod.

Effective population sizes large enough to be free of genetic drift and inbreeding should not experience a reduction in the rate of removal of maladapted genes from the population. Published effective population sizes (Ne) required to avoid the long term effects of interbreeding and genetic drift range from 500 to 5000 (Franklin 1980; Lande 1995). These are only crude approximations but give a starting point for evaluation of the status of wild populations. Hutchinson et al. (2003) calculated the ratio of effective population size to census population size in cod as 0.00004. As noted earlier, estimates of the number of fish recruiting to wild populations that cultured Scottish cod are likely interbreed with (North Sea – Skaggerak – English Channel Metapopulation) is in the order of 100s of millions of fish. One hundred million fish would constitute an effective population size of approximately 4000 fish so it is currently unlikely that the effective population size would limit the rate at which maladapted genes would be removed from the wild population.

The rate of gene flow between wild and cultured populations will, to a large degree, be determined by the proportion of the breeding population which is of cultured origin. Allowing for growth in production to the level of 30-40 000 tonnes per annum in the next 15 years, there would be approximately 10 000 000 fish in cages. Based on earlier discussions of a likely rate of escapes of 0.1 - 1% of the confined population, and all survived to breed, that would suggest that there could be 10 000 – 100 000 escaped cultured fish available for inter breeding. The actual level is likely to be much smaller due to mortalities after escape and before maturity, and there may also be a reduced success of effective breeding by cultured fish due to behavioral or other failures on the breeding ground. If there were 10 000 000 breeding age individuals in the wild, a generous estimate of the gene flow rate would be 1%. Through modeling the effects of gene flow, Theodorou and Couvet (2004) estimated that a gene flow rate of 5% annually each year for 20 years should have only a minor effect on the fitness of the affected population, provided that its effective population size was adequate.

It seems likely then that any introgression between wild and cultured fish at the projected growth of the Scottish farmed cod industry is unlikely to result in a major change in the fitness of nearby wild cod stocks in the next 15 years or so.

6.3.3.3.1 Logic model

The series of steps and processes leading from the establishment of cod farms in coastal waters to significant decreases in wild cod stocks as a result of genetic interactions between the two groups of cod was outlined at the beginning of this document in the form of a logic model as below:

Process of concern: Changes in fitness of wild populations of cod due to genetic introgression

End Point of Concern: Significant decline in survival in wild cod populations due to interbreeding with escaped cultured cod.

Logic model steps:

1. Cod farms are established in coastal waters.
2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
3. Cultured cod interbreed with wild cod.
4. The progeny of this interbreeding (hybrids) show reduced fitness. This is dependent on there being phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons.
5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.
6. Genetic interaction causes declines in endemic, evolutionarily significant units (populations), for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.
7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild cod stocks.

The information presented in the preceding sections of this risk analysis allows annotation of each step in the logic model to indicate the likelihood that each step has been, or will be, completed. This exercise has been carried out for the cod farming industry as it is in Scotland in 2005, and how it might be in 15 – 20 years time, when production is forecast to reach 25 000 – 40 000 tonnes.

1. Cod farms are established in coastal waters.
   Highly probable - Cod farms are already established in Norway and Scotland. The current intensity and geographical range of the small number of farms are low. Considerable growth in production is planned for the coming years. Where active cod farms will tend to aggregate, as salmon farming has done, it is likely that the density of the farms will, over time, increase, but will still occupy only part of the wild cod's coastal habitat. Intensity of development and geographic extent are therefore considered to develop to moderate at the end of the period under consideration. Once in place, the farms tend to become a long term feature of the coastal environment, although they can be moved or removed. (duration - low). For this evaluation, the **severity** of this step is considered to be currently **low**, but may increase to **moderate** with time. Given the market demand for cod and the current limitations on wild fisheries, the probability of this step in the logic model occuring is **high** at present and over the time frame of the assessment.The **uncertainty** associated with this prediction is **low**, as development has already been initiated.

2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
   With the present equipment and husbandry practices used in the industry, it is highly likely (**Probability** is **high**) that some cod will escape from cages. Experience with other species indicates that accidents happen. Data for the period 1999 – 2004 suggest an escape rate of 0.1 – 1.0% of salmon from cages in Scotland. Loss of fish from the cage will be strongly avoided so escape rates are likely to remain at least as low as that of salmon farming (< 1.0%). Currently, this will be of **low intensity**, and limited (**low**) **geographical distribution**. If the farms were totally removed, then, no further escapes of fish or gametes could occur (**Duration - Low**). The resultant **severity** of the interaction of the present scale of production will be limited (**low**), and there is a high probability that this prediction will be realised.

   As the industry grows, numbers of escapes will increase (**Probability - High**), and be spread over a larger area, but will still be small relative to the abundance and distribution of wild cod. The **intensity** and **geographical** spread of this are considered to be **moderate**. As in the previous paragraph, the **duration** will be **low** if cultivation ceases. **Severity** of this effect will therefore move towards **moderate**, and there is **moderate uncertainty** in this assessment.

3. Cultured cod interbreed with wild cod.
   Studies of released juvenile cod in fjord environments in Norway have detected no differences in behaviour (migration patterns) between released and wild cod, and have shown that interbreeding does occur. It is therefore highly likely that escaped fish will interbreed with wild fish (**Probability - High**). There is **low uncertainty** associated with this prediction. As the cultured fish genetically differentiate from wild stock, this may result in reduced competence to follow the wild fish to the breeding ground or to maintain the necessary spawning behavior. The intensity of interbreeding is currently assessed as extremely low, and of low geographical extent. The current Severity level of interbreeding is considered Low.

   As the industry expends, the **intensity** and **spread** will increase, although it is considered that it will remain no more than **moderate**. If farms were removed, no further interbreeding between escaped and wild cod could occur (**duration** - **low**). The **severity** of interbreeding in the future is therefore evaluated as **moderate**. The **Probability** of interbreeding in the future is reduced to **moderate** as domestication generally reduces the ability of wild and cultured stock to breed successfully together. **Uncertainty** associated with these predictions is **Low**.

4. The progeny of this interbreeding (hybrids) show reduced fitness.

   There is no evidence to support this contention for cod. For this to occur, it will be necessary for the cultivated fish to show phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons. There is evidence from restocking experiements that cultured juveniles can be selected to show phenotypic differences from the wild stocks. Currently, the industry uses a mixture of captive and wild caught mature adults as broodstock and this will mitigate against genetic differences between wild and farmed fish (**intensity** is **low**). The cod farming industry has a limited distribution in Scottish coastal waters (**geographical extent** has a **low** value). However, as it may take a few years for nature to remove hybrids from the population after removal of the farms, the **duration** of this is considered **moderate**. Therefore the current **probability** of the development of phenotypic differences (and subsequent reduction in fitness) for genetic reasons is **extremely low**.

   It is likely that as cod cultivation systems develop, cod will progressively become more independent of input of genetic material from wild populations. This will make it easier to select broodstock for genetically determined phenotypic traits (intentional or otherwise) desirable for cultured fishes (for example, late maturation). Therefore, the **intensity** of reduced fitness for hybrids will rise to a **moderate** level. Experience with salmonids suggests that as the differences between farmed and wild stocks become more pronounced, the genome of the escaped fish will lilkely be more heavily selected against. The geographical extent of this will probably be linked to the distribution of the farms. Even with suggested expansion of the industry, it is unlikely the industry will be close to most of the Scottish areas occupied by cod, and so the value of **geographical extent** is **moderate**. It is anticipated that if cod farming ceased, the **duration** of the effect of interbreeding now, and in the future, would last as little as a couple of generations and therefore the duration of this step in the logic model is expected to be **moderate**. As a result, the **severity** of this step will also increase to **moderate**. Over time, it is **highly probable** that greater differences will develope between farmed and wild stocks and there will be a reduction in the fitness of hybrids. The **uncertainty** about the fitness of current and future hybrids is considered to be **high** as no studies of hybrid fitness in cod have been undertaken.

5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, (for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at managed stock level.)

   Under the current industry conditions in Scotland, it is unlikely (**extremely low probability**) that even localised stocks will be adversely affected. This prediction is **highly uncertain** as it depends on the details of the presently limited distribution (**low** score for **geographical extent**) of cod farms within small areas of largely unknown stock structure. It also depends on the **intensity** of interaction between wild and cultured stock, which is likely to be limited (a **low** score). The uncertainty will decrease as the abundance and distribution of the target population increases. As in the previous step, if farms were removed from Scottish waters, the effects of interbreeding would quickly decline but might last a generation or two. Therefore, the duration of effect is considered to be **moderate**.

   As the industry expands, the probability of change will increase. However, knowledge of the detailed population structure of cod in the Atlantic is incomplete. Currently, stock management is based on large geographical areas (for example, North Sea, Skaggerak and Channel combined). However, there are suggestions that inshore populations in some fjords or sealochs may be to some degree distinct from the more open sea populations. If this is true, the small size of individual inshore populations may mean that sufficient escapees may be available from an expanded industry to significantly change the local wild population genome. At present, the distribution of farms is such that gene flow into these populations is likely to be intermittent, quantitatively small and the genetic differences small, so the **interaction** will be of **very low** intensity. With an increased number of farms in an area this would increase, as has been shown to occur for salmon (McGinnity *et al.* 2003) and brown trout (Skaala 1990) but it will remain confined to a small portion of the range of cod (**Intensity** - **Moderate**, **Geographical Extent** - **Low**). As a consequence, the future **severity** of change will increase to **moderate**. Hybrids will occur for a limited amount of time and so the **duration** involved in this step is seen as **moderate**.

6. Genetic interaction caused declines in endemic, evolutionarily significant units (populations), (for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.)

   The scale of impact required to affect survival in wild cod at population level is greater than that required (in step 5) to affect more localised management units. The present **intensity** of interactions at the population level will be small (**low**), and the **geographic extent** will be very limited (**low**), although, as in previous steps, the duration may be **moderate**. Consequently, **severity** is **low**. The current **probability** that this happen is **extremely low**, and the **uncertainty** is this prediction is also **low.**

   Any escapes from the industry in the future will be interbreeding a population large enough so that the **intensity** of the interaction will remain **low** in spite of the increase in the absolute number of fish interbreeding. A larger industry will likely be more dispersed, and so there will be a **moderate geographic extent** of the interaction in reaction to the geogrphic extent of evolutionary unit. As in previous steps, the cessation of effect of interbreeding will lag behind cessation of the culture activities. from that reason, the **duration** of the effect is considered **moderate** and the consequent **severity** of occurrence will be **moderate**. With increases in the size of the industry, the probability and **uncertainty** of this effect will increase, but is considered to be **low** as the effect of the escapes is spread over a larger wild population.

7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild/feral cod stocks.

   The current probability of effect on such a large scale is extremely low. The **geographical extent** of the industry is small (**low** score). The **intensity** of the interaction with Scottish farmed fish over the entire meta-population is small (**low** score) through the **duration** of any effect is likely to extend to a **moderate** period of time after cessation of cod farming. The consequent **severity** of interaction is rated as **low**. **Probability** of effects at the level of meta-population is judged to be **extremely low**, with a low level of uncertainty associated with this predication.

   Even the suggested increase in production is not considered to increase the probability of effect above the extremely low level. However, the **geographic extent** of the industry will increase (**medium** score). The **intensity** of the interaction with Scottish farmed fish over the entire meta-population is likely to remain small (**low** score) through the **duration** of any effect is likely to extend to a **moderate** period of time after cessation of cod farming. The consequent **severity** of interaction is rated as **moderate**, and the **uncertainty** associated with this prediction is **low**.

   The outcomes of the risk analyses for the current scale of cod farming in Scotland, and the predicted scale in 15 – 20 years time, are shown in Tables 6.3.III and 6.3.IV.

6.3.3.4 Risk estimation

Without regulations or farm management practices specific to cod farms, there is unlikely to be any difference between the outcome of the Consequence Assessment and that of the Risk Estimation. Risk management may be able to alter the values in Tables 6.3.III and 6.3.IV.

6.3.4 Risk management

Option evaluation in risk management addresses what might be done to reduce the probability of a risk being expresses, or to reduce the uncertainty in the predicted expression of a risk. The process identifies, for each step in the logic model discussed above, what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty in the predicted probability that the step will happen. Usually this involves further research or development.

An initial consideration must be whether any action is necessary, for example, whether the risk is large enough that some mitigation is appropriate. In the case of the Scottish cod industry as it is today, the wild stocks are protected from the endpoints (undesirable consequences of interactions with escapes from cultivation) by the extremely low probability that there are phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons. Furthermore, the small size of the industry and its patchy distribution lead to an extremely low probability that there could be sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is not sufficient to affect population fitness, at the population or meta-population levels. However, there is high uncertainty in the latter assessment.

The need and opportunity for mitigation is therefore considered in relation to the Scottish industry as it might be 15 years time. By that time, it is anticipated that the expansion in the industry will mean that there will be less protection for wild stocks from adverse consequences of interactions with escapes, although technical developments such as improved containment may mitigate against this. Table V identifies both mitigation and research or development steps that could be in addressing risks associated with genetic interactions arising from cod culture.

Whether there will be an impact from escapes from cod farms will depend on the exact nature of the population structure in the wild stock and the genetic nature of the farmed stock. For instance, it could be the impact of escapes would be minimal if the expanded Scottish cod industry reared wild-caught juveniles from local stocks that were widespread and abundant, and showed a regional rather than local population structure. This would be true even if escapes involved relatively large numbers of fish. On the other hand, a significant local impact could occur if the farmed stock were a variety of non-local origin with a narrow genetic base (for example, a high degree of inbreeding), and escapes mixed with a highly structured stock with low numbers in the local population.

The release of genetic material from cod farms (either as gametes or as escaped fish) could be minimised by harvesting fish before they reach maturity; using sterile fish; or using pump-ashore sites where the effluent water can be filtered or sterilised. Use of sterile fish on cod farms would eliminate any possibility of genetic interaction with wild stocks. The use of triploid fish has been investigated in salmon culture; however the cost, relatively poor growth and market acceptability could be problems. More research into other methods of producing sterile fish is required. Studies at the University of St Andrews, Memorial University of Newfoundland, The

Table 6.3.III : Analysis of the cod industry in Scotland as it is today, producing a few hundred tonnes per year.

Steps in the logic model	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity (C,H,M,L, or N) [1]**	**Probability (H,M,L,EL, or N)[2]**	**Uncertainty (H,M, or L)**	Stage of assessment
Cod farms are established in coastal waters.	L	L	L	L	H	L	Release
Cultured cod, as gametes, eggs or fish, escape from cages.	L	L	L	L	H	M	Release
Cultured cod interbreed with wild cod.	L	L	L	L	H	L	Exposure
The progeny of this interbreeding (hybrids) show reduced fitness.	EL	L	M	L	EL	H	Exposure
Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	L	L	M	L	EL	H	Consequence
Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L	L	M	L	EL	L	Consequence
Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population , i.e Escapes of cultured cod cause significant decreases in wild/feral cod stocks.	L	L	M	L	EL	L	Consequence

Table 6.3.IV : Analysis of the cod industry in Scotland as it may be in 15 years time, producing 25 000 - 40 000 tonnes per year.

Steps in the logic model	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity (C,H,M,L, or N)** [1]	**Probability (H,M,L,EL, or N)** [2]	**Uncertainty (H,M, or L)**	Stage of assessment
Cod farms are established in coastal waters.	M	M	L:	M	H	L	Release
Cultured cod, as gametes, eggs or fish, escape from cages.	M	M	L	M	M	M	Release
Cultured cod inter-breed with wild cod.	M	M	M	M	M	L	Exposure
The progeny of this interbreed-ing (hybrids) show reduced fitness.	M	M	M	M	H	H	Exposure
Sufficient gene flow to affect sur-vival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	L	M	M	M	H	Consequence
Genetic interaction caused declines in endemic, evolu-tionarily significant units (populations), i.e. Genetic interac-tion between wild and populations of escaped cultured cod causes sig-nificant declines in survival in wild cod populations.	L	M	M	M	L	L	Consequence
Gene flow is perva-sive and persistent enough to affect fitness at the level of species or meta-population , i.e Escapes of cultured cod cause sig-nificant decreases in wild/feral cod stocks.	L	M	M	M	EL	L	Consequence

Table 6.3.V : Possible mitigation and research activities to reduce the probability of steps in the logic model occurring, or reduce the uncertainty in the estimate of that probability.

	Logic Model Step	**Probability**	**Mitigation** (regulate/design/ modified practices)	**Uncertainty**	**Research/Development**
1	Cod farms are established in coastal waters	H	• Where feasible move to land- based production	L	• Develop economically competitive land-based technologies.
2	Cultured cod, as gametes, eggs or fish, escape from cages.	H	• Improve containment design and/or build in fail-safe measures • Recovery plan for escaped fish	M	• Improve contingency plans for recapture, possibly including prior imprinting, e.g. of prey (pellets)
3	Cultured cod interbreed with wild cod	M	• Use of sterile fish • Harvest fish before maturity	L	• Improve methods of producing sterile fish
4	The progeny of this interbreeding (hybrids) show reduced fitness	H	• For each generation recruit all grow-out stock from juveniles captured in the wild • Retain the wild genome as far as possible	H	• Develop models of the impact of interbreeding on fitness. • Determine if differences are primarily genetic rather than environmental in origin. • Determine if differences are associated with differential survival.
5	Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	• Limit the distribution of cod farming to either proximity to small value stocks or very large stocks.	H	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between stocks
6	Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L		L	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between populations
7	Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population , i.e. Escapes of cultured cod cause significant decreases in wild/feral cod stocks	EL	• Limit the distribution of cod farming in relation to the distribution of the species or meta population	L	• Identify dynamics of genome at the meta population or species level.

Institute of Aquaculture at Stirling University, and the Institute of Marine Research in Sweden are investigating photoperiod control of maturation in cod. The British Marine Finfish Association website reports that "*Recent research has shown that continuous light can delay sexual maturation and improve growth, making the utilization of photoperiod manipulation a viable option*". This suggests that husbandry practices could significantly reduce the risk of release of viable gametes.

Recently, there has been considerable interest and action concerning the possibility of recapture of escaped salmon, since escaped salmon tend to remain in the area of the cages for some time after escapement. This is thought to be due to their tendency for schooling behaviour, and imprinting on artificial 'prey' (for example, feed pellets). The potential to recapture escaped cod has not been analysed; but is an important area for research. It is also important to discuss this with the public early in a development programme, and to derive the risk management triggers and contingency plans in an open and transparent manner, for each area where a wild cod sub-population can be identified.

6.3.4.1 Risk Mitigation

As indicated in the risk management table above, two broad approaches can be taken to manage these risks. The first is direct mitigation, which generally reduces the likelihood of a step in the logic model being fully realised. These mitigation measures usually take the form of regulatory strictures such as moving culture to land based facilities, or codes of practice used by industry. As can be seen under the column headed mitigation, most of these options can be put in place using regulatory or code of practice mechanisms. Some, such as the requirement for geographic limits to the culture of cod (mitigation for logic model step 5) may necessitate a wider planning process.

Where a regulatory approach is taken, care must be given to ensure that only those regulatory measures are taken that are necessary to reduce the level of risk to give an acceptable level of protection. Regulation for an extreme level of protection, where not required, is contrary to the concept of sustainable development. Suggestions such as moving marine culture to land based facilities (mitigation for logic model step 1) should be considered carefully in this context.

The other approach to managing risk is to reduce sources of high or moderate uncertainty in the risk analysis. In this context, one of the advantages of risk analysis is that it can assist in identifying priorities for research and development work. For example, step 5 in the logic model is associated with a high degree of uncertainty. That uncertainty in the decision making process could be reduced by research that defines gene flow rates between wild populations, and which could do much to clarify where specific populations may be at risk due to a low rate of gene flow with other components of the meta-population.

Testable models can be useful in the development of knowledge as well as being of immediate assistance to decision makers faced with uncertainty. A clear weakness in the confidence of the assessment is the lack of information on the likely fitness of hybrids formed by the interbreeding of wild and farmed fish (Step 4, **High uncertainty**), and of the consequences of any reductions in fitness for local and more widespread populations. Lacroix *et al.* (1998) show modelling approaches to estimate genetic introgression into the genome of wild stocks for salmonids, and such approaches should be considered for application in studies of non-salmonids as well. While it is too early to undertake such research on cod in Scotland (because genetic differences between farmed and wild stocks are currently small) it may be possible to consider the design of appropriate experiments when cod cultivation becomes closed (ie the complete life cycle occurs in cultivation and does not require inputs from wild populations) and selection for desirable traits is established.

It is important to be as inclusive as possible in considering how to control risk. Some control of risk may not directly involve the hazard under consideration (for example, cod farming). For example step 5 talks of sufficient gene flow. That will in part be determined by the relative size of the populations of wild and cultured fishes. The maintenance of sufficiently large wild cod populations (for example, through managing fisheries pressure, stock enhancement schemes, etc.) may be an efficient tool to mitigate the effects of increasing numbers of individuals escaping from aquaculture. That is no mean feat. Even so, there is evidence (Rice and Cooper 2003) that strict adherence to advice from fisheries scientists increases the likelihood of success in this objective. So, healthy wild stocks in and of themselves help to limit the effect of interbreeding with farmed escapes.

The potential impact of escapees will be greater if the local population with which they mix is small. The recent decline in North Sea cod stocks has arisen from a range of pressures, including fishing, but also because of declining recruitment in the area. Proposals have been made to support the natural recruitment of cod through ranching, not to enhance the fishery but to bring the stock back to the size that can be naturally supported in the area while supporting a substantial fishery.

Culture-supported stock support for stock stabilisation (covering the full gene pool in the broodstock to avoid inbreeding or outbreeding depression) could be used to avoid some critically small stock size, i.e. not using aquaculture to produce market size fish, but to produce fish fit for survival in the wild. Such culture-based fisheries could also be considered as a mitigation strategy against the potential effects of escapes.

The assessments of high probability and/or high uncertainty can be used to guide allocation of resources to those areas where they should be most effective. For example, Step 2 has high probability but, if this can be reduced, the overall risk of adverse effects would be reduced. Actions could be directed at measures to reduce the rate of escape of cultured fish. Combinations of regulatory and developmental research can be very powerful approach to mitigation. The critical event of cod escaping containment (Step 2) is very responsive to such an approach. This applies to both floating cages (mooring, net quality, resistance of the raft to waves, avoidance of predators damaging the nets, choice of locations, etc), and to land-based facilities (screening and treatment of effluents). Development of closed systems, on land or floating, could be encouraged and, when economically feasible, their use can be encouraged by codes of practice or regulatory tools.

6.3.5 Literature cited

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