Highly probable - Kelp beds are within 40 m of the salmon farm, and therefore close enough to receive some nutrients. Fish biomass is sufficient to produce sufficient nutrients bi-yearly in the summer when background levels are low. The intensity and geographic extent is medium because it is likely that only the section of the kelp bed nearest the farm would receive nutrients. Increases in epiphytic algae occurs when background nutrient levels increase by 80% for extended periods of time during periods of high light, and this is 4.5 µM at this site (summertime). For one quarter of the production cycle of this value is exceeded when fish biomass peaks (approximately 4 months). Uncertainty is low, because this has already been shown to occur on seaweeds in proximity to the salmon farms.

5.1.1 Epiphytic algae promote light limitation.
Highly probable - Once laminae are covered with organisms, photosynthesis is impaired. Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. Researchers have only found an increase in epiphyte abundance and a decrease in photosynthesis in the host with nutrient pulses. In addition, the high nutrient pulse occurs only four months every second year. Uncertainty is low, because scientific evidence supports a decrease in photosynthesis with shading.

5.1.2 Lamina production changes due to light limitation caused by epiphytic algae.
Medium probability - Late spring and early summer is the rapid growth period for *L. saccharina*. When the nutrient pulses are highest at summer end, it is, therefore, likely laminae have already grown to their maximal extent. Therefore, a reduction in photosysthesis would not greatly affect kelp production. Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire kelp bed is not affected. The cycle of high nutrient pulses from fish farms repeats bi-yearly. Uncertainity is medium, as researchers have examined both nutrient pulses, epiphytic algae and seaweed growth, but not at the time of maximal fish farming dissolved nutrient releases.

5.1.3 Kelp productivity changes as a result of changes in lamina production from epiphytic algae.
Low probability - Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. Researchers have only found an increase in epiphyte abundance and a decrease in photosynthesis in the host with nutrient pulses. In addition, the high nutrient pulse occurs only four months every second year. Furthermore, a decrease in lamina biomass in the upper story would open light up to lower story younger individuals thus promoting growth of younger kelp in the lower story. Uncertainty is high, as population decline due to epiphytic algae has not been actually studied.

5.2.0 Blade erosion increases due to epiphytic algae increases.
Highly probable - This has been documented in previous research investigations. Researchers have only found an increase in epiphyte abundance and host erosion due to an increase in dissolved nutrients (not total lamina coverage). Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. The cycle of high nutrient pulses from fish farms repeats bi-yearly. Uncertainity is low as this has been documented in previous investigations.

5.2.1 Sori production changes due to blade erosion
Highly probable - At the time of the nutrient pulse from the salmon farm, *L. saccharina* is producing sori. Intensity of impact is medium. Researchers have only found an increase in epiphyte abundance and host erosion due to an increase in dissolved nutrients (not total lamina coverage). If the epiphytic algae grow over sori tissue or areas where sori would have been produced, and this tissue is consumed, then, sori production would be restricted. Impact is not high, as the kelp can live three to four years and the pulse occurs twice in four years. Uncertainity is high, because no one has correlated epiphytic algae with host sori production.

5.2.3 Kelp productivity changes as a result of changes in sori production.
Highly probable - Intensity of impact is low because most likely only the section of the kelp bed nearest the salmon farm would be impacted by dissolved nutrients. The nutrients would be taken up by the kelp and epiphytes at the front of the bed leaving few nutrients for the kelp in the reminder of the bed. As well, the high nutrient load during adequate lighting occurs only four months every second year, whereas kelp live three to four years. Gametophytes have a wide dispersal range (possibly greater than 200 m), so if the affected kelp did not produce sori, it is likely that new recruits would be obtained from the unaffected kelp outside of the range of the fish farm. This would be the case in a healthy population. In a population affected by sea urchin limited sori production could set back attempts to maintain or restore kelp populations. Uncertainty is high, as the effect of epiphytes and dissolved nutrients on kelp population decline due to limited sori production has not been examined in the field.

5.3.0 Dissolved nutrients affect C and N storage

Medium probability - Under normal circumstances in the region, *L. saccharina* grows during the high light period until nitrogen stores are depleted. At the same time, carbon is stored so that dissolved nitrate can be stored during the dark period that occurs the following winter and early spring. Biyearly on the salmon farm, the kelp receives farm derived nutrients. Then it can grow without the need to consume its nitrogen stores. It continues to grow until the end of its growth period when sori are produced. Some evidence exists that indicates that carbon is not stored when kelp is fertilized in this way. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed to leave few nutrients for the rest of the bed. This pattern will occur as long as the fish farm is in the area. Uncertainty is high, as little field work as been done in this area.

5.3.1 Lamina production changes due to changes in C and N storage.

Low probability - Carbon that is stored in Laminaria in the summer is used for nutrient uptake in the spring and for growth under low light conditions. If carbon is not stored, the production of the new laminae may be decreased. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed to leave few nutrients for the rest of the bed. Therefore, most of the bed would not be affected by the nutrients. This pattern will occur bi-yearly as long as the fish farm is in the area. Uncertainty is high, because researchers have not investigated the effect of low C stores on regeneration in perennial kelp.

5.3.2 Kelp productivity changes as a result of changes in lamina production.

Low probability - Little information exists relating to the fitness of *Laminaria* without suitable carbon stores at the time of nitrate availability due to upwelling. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed leaving few nutrients for the kelp in the rest of the bed. In addition, the effect is expected only once every two years, but it will endure as long as the fish farm is present. Uncertainty is high due to the general lack of information in this area of research.

5.4.0 Dissolved nutrients affect lamina growth.

Highly probable - In the area of interest, *L. hyperborea* are the largest in Norway. We can also expect that *L. saccharina* would also be the largest, as temperature and lighting is favorable for them too. Growth is expected to be good in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Due to the optimal environmental conditions, in this area, severity of this effect on kelp would be marginal. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

5.4.1 Increase in lamina growth causes light limitation.

High probability - Previous research investigations have clearly shown that increases in lamina production can cause self shading of upper story individuals and shading of lower and younger story individuals. Intensity is expected to be low, because the size of the kelp in the bed in this area is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the level of understanding and available information.

5.4.2 Lamina production changes due to light limitation.

Highly probable - It is well known that light limitation negatively affects kelp growth unless carbon stores are adequate. Intensity is expected to be low, because the size of the kelp in the bed is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the high level of understanding in this area.

5.4.3 Kelp productivity changes as a result of changes in lamina production.

Low probability - In the area of interest, kelp are already the largest in Norway. Lamina production is expected to be optimal in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Hence, dissolved nutrients from the fish farm would not greatly affect the kelp. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

5.5.0 Sori production changes as a result of changes in lamina production

Highly probable - Sori are produced on lamina, so it is logical to assume that sori production will change if lamina production changes. Intensity is expected to be low, because the size of the kelp in the bed is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the high level of understanding in this area.

5.5.1 Kelp productivity changes as a result of changes in sori production.

Low probability - In the area of interest, kelps

Table 6.4.III : Table summarizing risk estimation for logic model 2.

Steps in logic model 2 (Sites A and B)	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity**	**Probability**	**Uncertainty**	Stage of assessment
1. Suitable kelp habitat is in the area of interest	M^A H^B	H^A H^B	H^A H^B	M^A H^B	H	L	
2. A salmon farm is within or close to kelp habitat	M^A H^B	H^A M^B	H^A H^B	H^A H^B	H H	L L	
3. Kelp are growing in the area of interest	$M^{A,B}$	$M^{A,B}$	$H^{A,B}$	$M^{A,B}$	M	L	
4. Particulate matter from the fish farm accumulates in benthos	H^A M^B	H^A M^B	H^A H^B	H^A M^B	H H	L L	Release
Release summary (Logic model steps 1-4)				$M^{A,B}$	M	L	
5.1 Gametophytes are affected by sulfide toxicity	M^A L^B	M^A L^B	H^A H^B	M^A M^B	H	H	Exposure
Exposure summary				M^A M^B	H	H	
Decrease in kelp productivity	M^A L^B	M^A L^B	H^A H^B	M^A M^B	M	H	Consequence
Consequence summary				M^A M^B	M	H	
5.2 Particulate matter affects gametophyte via burial	M^A L^B	M^A L^B	H^A H^B	M^A M^B	M	M	Exposure
Exposure Assessment							
Decrease in kelp productivity	M^A L^B	M^A L^B	H^A H^B	M^A M^B	M^A L^B	H	Consequence
Consequence Assessment				M^A M^B			
5.3 Heavy metals reach toxic concentration	L^A	L^A	L^A	L^A	L^A	H	Exposure
Decrease in kelp productivity due to heavy metal toxicity	L^A	L^A	L^A	L^A	L^A	H	Consequence
Overall risk of a drop in local kelp population (highest severity and probability)				M	M	H	

Explanatory notes:

1. **Probability = H** – High, **M** – moderate, **L** – Low, **EL –** Extremely Low, **N –** Negligible.
2. **Severity = C** – very intense, **H** – high, **M** – Moderate, **L –** Low, **N** – Negligible. There are three components of severity that should be considered: the duration of the activity, the degree of change, and the geographic extent of the change.
3. **Uncertainty = H-** Highly uncertain, **M** – Moderately certain, **L** – Low Uncertainty.
4. The final rating for the **Probability** is assigned the value of the element with the **lowest** level of probability.
5. The final rating for the **Severity** (intensity of interaction) is assigned the value of the step with the **lowest** risk rating (e.g., **Medium** and **Low** estimates for the logic model steps would result in an overall **Low** rating). The final value for severity for each specific risk is assigned the value of the lowest individual logic model estimate.
6. The final rating for the **Uncertainty** is assigned the value of the element with the **highest uncertainty** level (i.e. the least certainty).

A: Site A B: Site B

are already the largest in Norway. Sori and lamina productions are expected to be optimal in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Hence, dissolved nutrients from the fish farm would not greatly affect the kelp. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

Logic Model 2.

The following material is summarised in Table 6.4.III.

4. Particulate matter from the salmon farm accumulates in benthos.
Highly probable - Benthic change in Norway due to salmon farming has been shown to occur in over 80 salmon farms that were monitored in a study. Benthic impact occurs within two months of the introduction of fish. The site depth and current speed are not correlated to biological change in benthic conditions right under the farm. That is, the benthos are expected to change at both sites A and B. The zone of benthic change extends to at least 100 m from the farms. The magnitude of benthic changes decreases with distance from the farm. Benthic faunal change toward more sulphide resistant species persists as long as the site is farmed, and beyond five years post farming in sheltered sites. Severity is moderate, as the zone of major benthic change is generally localised. Uncertainty is low, because much data exists on benthic impact.

5.1.0 Hydrogen sulphide kills gametophytes.
Highly probable - As documented in research investigations, sulphide after the start of farming operations quickly reaches toxic levels for aquatic plants (2.5 µM) below and at a distance exceeding 100 m from a salmon farm. This low tolerance to sulphide has been suggested as the reason that kelps are not commonly found in muddy anaerobic substratum. The potential particulate fallout zone covers the kelp bed on both farms (Sites A and B). Intensity is expected to be low to high because the geographical distribution of the waste, sulphides, kelp and gametophytes are not uniform. Kelps that are furthest away would receive fewer waste particulates and depending on the kelp density, the kelp closest to the farm would intercept most of them. Following these trends, initially waste accumulation followed by sulphide production would start at the front of the kelp bed, and over time proceed to the back of the bed. The latter statement would depend on the density of the kelp bed. At Site A due to the lower current velocity, the effect would be more pronounced. Duration of the effect lasts as long as the farm remains in the area. Uncertainty is high; because researchers have studied the ability of kelp to settle particles but not the associated formation of sulphides, and no research on this topic has been carried out on fish farms.

5.1.1 Kelp population decreases.
Medium probability - In the area of the salmon farm at Site A, *Laminaria* are heavily preyed upon by sea urchins so survival depends on recruitment. Recruits would be killed if they fell upon sediments containing low concentrations of sulphide (2.4 µM). As deposition is heaviest in that part of kelp bed closest to the farm, gametophytes would not survive there. Over time, kelps would die off in the frontal zone. As the kelps are continuously devoured by sea urchins, and not replaced due to gametophytes lost to sulphide, kelp further back in the bed could trap more of the organic waste, accumulation of which would lead to formation of sulphide and so on until the kelp bed is gone, or insufficient particles are trapped, and the remaining bed is left unaffected. The latter event depends on the distance from the farm. Intensity is low to medium depending on the site. Intensity is limited to the zone of influence of the farm and would be highest in the sheltered site, Site A, as there the zone of influence over the kelp bed is greater than at the more exposed site, Site B. The effect would occur as long as the fish farm is in the area, and several years after closure at Site A. Uncertainty is high. It is known that only a low level of sulphide is required to kill the gametophytes but research has not been conducted on this scenario (for example, particulate waste and salmon farming).

5.2.0 Organic waste particles bury gametophytes.
Medium probability - Kelp are known to have the ability to trap particulate matter, which then settles within the bed. Only a small cover of debris is known to kill gametophytes. Intensity is expected to be low to medium depending on the site because the geographical distributions of the waste, kelp and gametophytes are not uniform. As well, burial is expected to be most intense at the edges of the kelp bed where most of the particles are trapped. The latter statement would depend on the density of the kelp bed. Uncertainty is medium; because researchers have studied the ability of kelp to settle particles, but they have not done so near salmon farms.

5.2.1 *Laminaria* population decreases.
Low to highly probable depending on the distance from the salmon farm. In the area of the salmon farms, *Laminaria* are heavily preyed upon by sea urchins. Therefore, their survival depends on new recruitment. New recruits would be buried at the front of the kelp bed closest to the farm, but as the kelp are devoured by sea urchins and not replaced due to gametophytes, kelp in the interior of the

bed would trap particles with associated burial of gametophytes and so on until the kelp bed is gone, or insufficient particles are trapped, and the remaining bed is left unaffected. The latter event depends on the distance from the farm. Intensity is low to medium. Intensity is limited to the zone of influence of the farm and would be highest in the sheltered site, Site A, where the zone of influence over the kelp bed is greater than at the more exposed site, Site B. The effect will persist while the farm is in operation, and several years after closure. Uncertainty is medium. It is known that only a small amount of sediment over gametophytes is needed to kill them, but research has not been conducted on this scenario (for example, particulate waste and salmon farming).

5.3.0 Heavy metals in the sediments reach toxic levels for gametophytes.
Low probability - Heavy metals such as zinc and copper are bioavailable in sediments under oxygenated conditions; this condition is not expected when the fish farm is active. Sediments are only expected to buildup at site A. In the area of the salmon farm, *Laminaria* are heavily preyed upon by sea urchins. Therefore, their survival depends on new recruitment. New kelp recruits would attempt to colonize the sediments affected by salmon farming between production cycles or post farming. At these times, sediments can be come oxygenized, and dissolved heavy metals can become bioavailable, and potentially toxic to the recruits. Toxicity would be most pronounced at the front of the kelp bed closest to the farm. Severity is low. It is unlikely the benthos would become sufficiently oxygenized between production cycles. Uncertainity is high, as little research has been conducted on heavy metals during times of sediment recovery.

5.3.1 *Laminaria* population decreases.
Low Probability - Heavy metals can be released from sediments but it is unlikely the affected area would greatly affect a local kelp population. The affected kelp would be those attempting to colonise under the fish farm (a small area). The depth prohibits good kelp density, and the sheltered site, produces weak kelp. Uncertainity is high, as there has been little research conducted on heavy metals during times of sediment recovery.

From the risk estimation (Tables 6.4.II and 6.4.III), ammonium from the fish farms does not appear to be a significant hazard to adjacent kelp beds. The only possible concern related to dissolved nutrients is epiphytes affecting sori production on kelp that are being heavily preyed upon by sea urchins. Although the likelihood of occurrence is low, this effect combined with heavy sea urchin predation can set back attempts to maintain or restore kelp populations especially at sheltered sites. It is important to point out that the kelp stocks that would be affected would be very low, a small amount of the kelp along the entire coast line.

From the risk estimation, the particulate matter from the fish farms has the potential to bury and kill the gametophytes. In addition, waste deposition also has the potential to kill seaweeds via sulphide formation at sheltered sites. As the kelps that we studied are perenials, it is likely the affects would take years to be noticed, but once the population declines, recovery would be slow because of lingering toxic effects. Our assessment was, therefore, effective at pointing out a potential future problem. It is important to point out that the number of afflicted individuals would represent only a tiny fraction of the total number growing in the area.

Information relating to this assessment should ideally be communicated to local and national fish farming associations, local fishers, regional science and environmental officers, and the Norwegian Ministry of Fisheries and Coastal Affairs. Fishers might enquire if the kelp near the fish farm serve as important nursey grounds for fish. If so, some of the ratings given to severity and intensity could be changed to reflect their concerns. As much of the assessment in terms of procedures and results is relevant to other species and areas, it should be published if possible in science and trade journals and given to international environmental groups, such as the World Wildlife Federation.

We also found potential benefits of waste. In the sheltered sites where *L. Saccharina* predominants, the waste material has the potential to increase kelp production and at both exposed and sheltered, dissolved nutrients could help aid in kelp recovery from predation via fertilization. These benefits could, however, be overshadowed by the negative effects of the solid waste.

6.4.3.4 Risk Estimation

In the earlier discription of the farm no special technologies were identified as in use nor were specific regulatory requirements mentioned that might reduce the effect of that farm from that which might be anticipated based on past experience with this type of development. For that reason the risk level identified in the consequence assessment is the same as that for the risk estimation. Should any of the recommended risk management activities be undertaken that level of risk may be modified.

Table 6.4.IV : Summary of risk mitigation and research derived from the analysis.

	Logic Model Step	Probability	Mitigation (regulate/design/ modified practices)	Uncertainty	Research/Development
2	Salmon farms are established near Laminaria beds in coastal waters.	M	Where feasible site farm 200 m away from established or barren kelp grounds. This is the dispersion distance for gametophytes, and generally benthic changes due to salmon farming is low at this distance.	L	Verify the distance a salmon farm should be from a kelp bed.
4	Particulate matter from the salmon farm accumulates within kelp bed.	H	See step 2 above.	M	• Determine the ability of kelp to trap and settle waste particles. from salmon farm • Develop ways to trap sediment on site.
5.1	Organic waste particles promote the formation of sulfide in kelp bed.	H	See step 2 above.	M	Determine whether sulfide can form in a kelp bed due to the accumulation of organic particles from a salmon farm.

6.4.4 Risk Management

Option evaluation in risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. This can be addressed through consideration of the series of steps in the logic model discussed above. The process identifies, for each step, 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 associated with predicting that the step will happen. Usually this involves further research or development. Table 6.4.IV identifies both mitigation and research or development steps that could be considered in addressing risks associated with waste effluent, particularly solid waste effluent) from salmon farms on *Laminaria* populations.

Whether there will be an impact from waste material from fish farms on kelp will depend on how close the kelp beds are to the farm and the size of the kelp bed. For instance, it can be envisaged that the impact would be minimal if farming remained distal from kelp beds (greater than 200 m from frontal edges to take into consideration spore dispersal and waste fallout zones). Also if the salmon farm remained distal from barrens, the farm would not impact the remediation of kelp beds over preyed upon by sea urchins. Site fallowing, a farming practice that is often mentioned to be a suitable method for benthic remediation, is not useful if sulphide levels increase to toxic levels during production cycles.

Much information is still unknown. For example, kelp beds are probably capable of trapping tiny particles from the farm that normally would not otherwise settle within the vicinity. As a result, over a period of time, effects of burial and sulphide toxicity may appear on the fringe of the kelp bed, and move back into the bed over time as the frontal individuals die off. The size of the particle capable to be trapped and its relationship to fish farming waste needs to be ascertained. The abilities of kelp to trap particles and provide a surface for their degradation, as well as to remove dissolved nutrients should, also, be explored. Particle entrapment could be done with suitable cultivated stock grown on ropes, and placed adjacent to a sea farm site. The cultivated stock must be locally obtained, so as not to affect the genetics of the wild stocks. The integrated cultivation of seaweed and fish in open systems was suggested as early as 1993 (Petrell *et al.* 1993), but was not accepted by industry due to difficulties associated with marketing kelp and work related issues associated with the handling two very different species. With more help with marketing, cultivated kelp may be grown to protect the wild ones.

To reduce the effects of waste sedimentation, several methods have been developed to prevent the particles from entering the environment. An expensive and energy demanding method is close containment. As an alternative, particles might be managed on site after they have been trapped on a screen (Burynuik *et al.* 2006). As well, a seaweed curtain as describe above may be effective. Others are experimenting with mussels and other species. The correct choice must be based on issues related to long-term sustainability.

6.4.4.1 Risk Mitigation

As indicated in the risk management table (Table 6.4.IV), two broad approaches can be taken to manage risk. The first is direct mitigation which generally reduces the likelihood of a step in the logic model being fully realized. These mitigation measures usually take the form of regulatory strictures such as enforcing a set distance between a salmon farm and a kelp bed. The second approach can be placed *via* a code of practice. This approach is seen when fish stocking considers output of nutrients and solid waste.

The other approach to manage risk is to reduce sources of high or moderate uncertainty. 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, research might be used to confirm that only a small portion of a kelp bed is affected by particulate matter or dissolved nutrients, and hydrogen sulphide never builds up to toxic levels. Further research is needed to answer these questions. As well, research might find that a kelp bed is highly effective at trapping particulates, and the overall environment improves as a result. That research could be used to develop artificial kelp beds.

6.4.5 Evaluation of risk assessment model

The assessment was successful in identifying new risks associated with fish farming. This scoping exercise was difficult to carry out due to the large amount of information that had to be acquired and analyzed. In fact, we chose Norwegian sites largely because of the amount and quality of available information on fish farms, kelp resources, basic biology, oceanic currents, water quality and predators of kelp. Without this large database, the study would have been too difficult and costly, and uncertainty would have increased. Fortunately, this assessment can be applied to other sites and macrophytes. This is because the major effects relate to solid waste, and these affects appear to be independent of the species of macrophyte.

In this assessment, although several exposure paths relating to solid waste were ruled out due to dilution or temporal effects, they were still all examined. Local science officers can use this extensive review, and basic and generally available knowledge concerning the biology of local macrophytes to determine what exposure pathways are pertinent to the macrophytes in their areas of concern. For example, annual species capable of growing near a coastal fish farm could experience an immediate loss in recruitment if a thin layer of solid waste covers them or farm-derived nutrients causes them too grow to the level where they block the light needed for further growth. The latter effect, although not a major concern in our test sites due to the ideal growing conditions there, could decrease the growth of perennial species in non-ideal areas. The latter effect could also occur to *L. hyperborea* and *saccharina* in other parts of Norway where the growth conditions are not as ideal as they are in our test sites.

In general, much was learned in the process, and new knowledge and research paths were created. To protect macrophytes, we suggest that fish farms are sited at least 200 m from a macrophyte bed.

6.4.6 Literature cited

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