Figure 6.4.6 : Estimate of solid waste output (from Buryniuk et al. 2006).

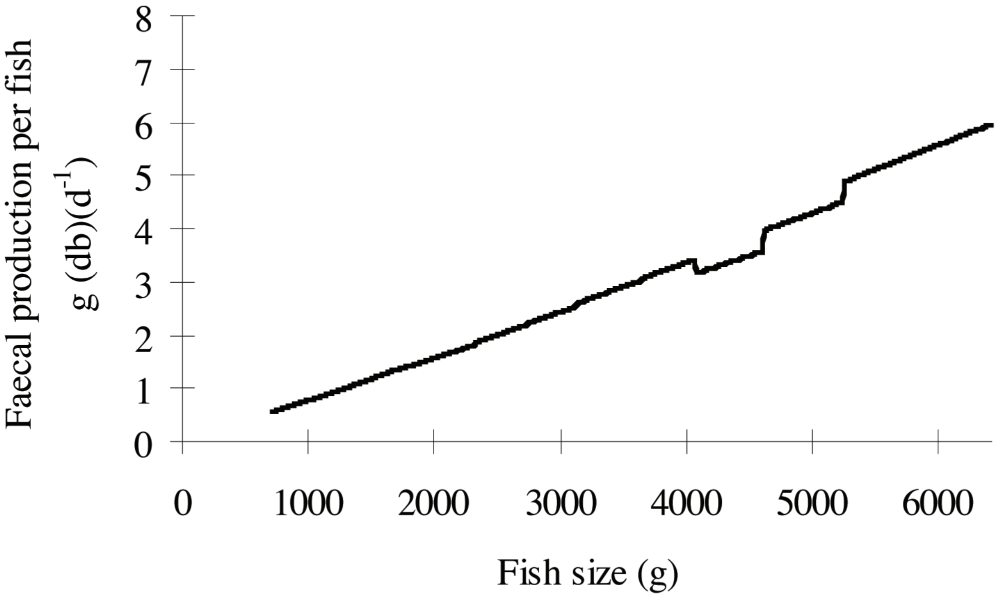
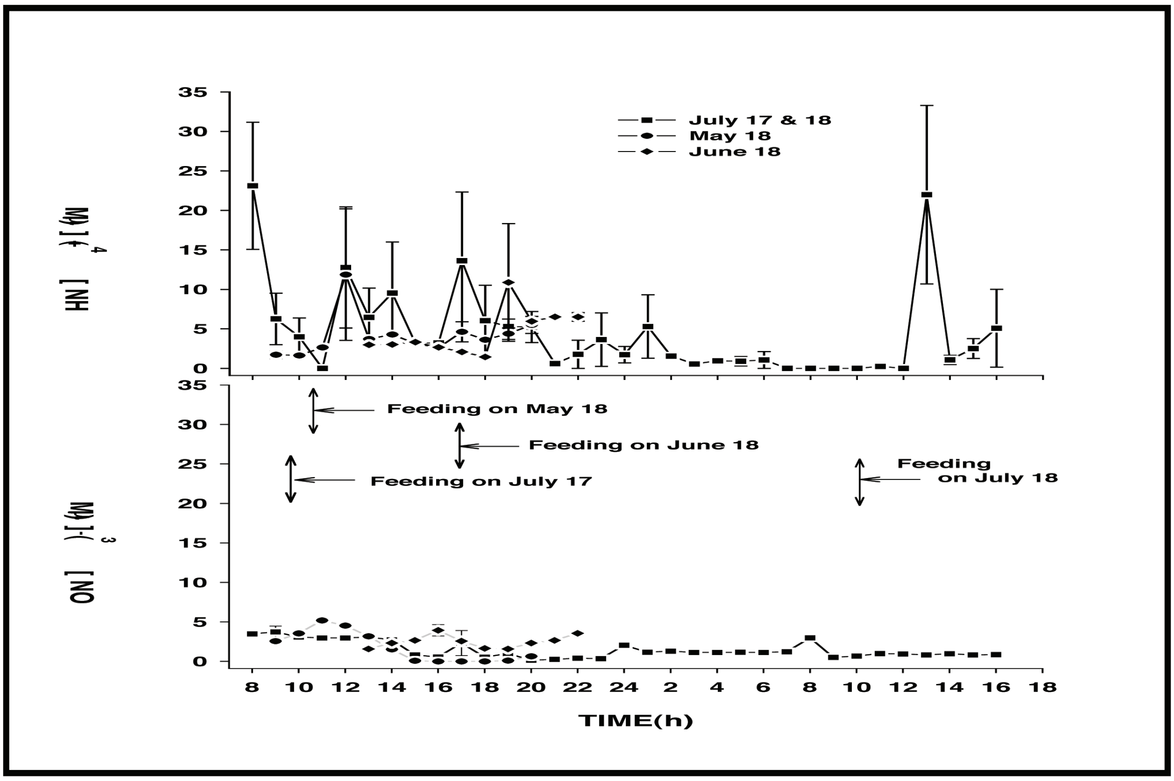


Figure 6.4.7 : Ammonium output at a fish farm (from Ahn et al. *1998).*



Using the above information and references, we estimated the dissolved nitrogen concentration for Sites A and B to be as follows. Between July and September, Site A produces a dissolved ammonium concentration within the cage site when fish are nearing harvest size and four hours following fish feeding time of between 10 and 30 µM. Between 10 and 40 m from the farm site, at the same time, the farm derived ammonium levels fluctuate to always exceed the background nitrogen concentration (2 µM) for that time of year. Fish are fed twice a day during the summer, so this pattern would occur twice daily. Site A with fewer fish produces less ammonium than Site B (Table 6.4.I), but because the current speed or dilution factor is lower at Site A, both sites would have similar ammonium levels surrounding the farm. The ammonium pattern in terms of range and concentration expected at Site B is, therefore, the same as at Site A. Due to lower dissolved nutrients in winter in general and early in the production cycle, we assumed that dissolved nutrients outside of the fish harvesting period would be undetectable anywhere other than within the fish cage.

6.4.3.1.2 Zone of solid waste accumulation

Tests on a number of salmon farming sites in Norway and Chile indicated that neither depth below the site or current correlate with the level of disturbance in the benthos below the farm. As well, below all fish farms, benthic conditions change due to depositing of organic waste material (Carroll *et al.* 2003; Soto and Norambuena 2003). Biological change is evident even at sites with rocky bottoms, although, these sites had been previously considered to be less sensitive to environmental change due to the higher flushing conditions normally associated with rocky bottoms.

Many former investigations were focused on measuring benthic enrichment, while others were focused on developing predictive models for estimating the zone of organic enrichment. Models exist that can be used to predict the amount of solid waste output, and benthic accumulation models have been developed for sheltered sites. Benthic accumulation models have not been proven effective for exposed sites such as Site B, so we used empirical data collected from a number of salmon farms (including Norwegian farms) to assess the accumulation of waste products at Sites A and B. A description of the empirical data follows.

The change in benthos due to organic enrichment from waste matter is evidenced by the presence of organic carbon-tolerant opportunistic species whose range extends to at least 50-100 m from a fish farm perimeter on a down current transect (Brooks *et al.* 2003). In a study of 80 farming sites in Norway, the sediments below 32% of the farms were classified as being poor, or very poor and 10% of the sediments were similarly characterized at 50 to 100 m from the fish site (Carroll *et al.* 2003). Poor in this study meant chemically, structurally (grain size) and biologically altered as compared to a reference site. After comparing site characteristics among the farms, no particular characteristic such as depth or current velocity could be associated with either little change or a major change (poor). Rather, little change in sediments was only associated with fish farms that were left vacate (or fallow) between production cycles.

In terms of heavy metal release from salmon farms, Cu and Zn are normally considered. Copper is incorporated as trace metals in fish feed by manufacturers (for example, 4.8-5.6 µg/g dry weight, Kempf *et al.* 2002) and in anti-foulant paint. In two studies, sediment Cu levels below fish farms were elevated as compared to control sites (actual values: 10-20 µg/g and 100-320 µg/g) (Kempf *et al.* 2002; Uotila 1991). Cu was elevated in most seaweed samples obtained on salmon farms, and this indicates that dissolved heavy metal ions are available for uptake in the water near salmon farms (Solberg 2002). Zinc is included in farmed fish feed in order to prevent cataracts in juveniles. The Interim Marine Sediment Quality Guidelines, produced by Environment Canada, estimate that the threshold level of Zn corresponding to adverse biological effects in marine sediments is 124 µg g^{-1} (Environment Canada 1995). In Finland, Uotila (1991) found zinc to be elevated near the fish farm site (100-500 µg/g). Below a fish farm site in France, it was also elevated (100-200 µg g^{-1}) (Kempf *et al.* 2002). Five years after cessation of fish farming operations at a sheltered site in British Columbia, Canada, Zn levels in the sediments were above background levels 160 m from the farm site, but biological sediment remediation appeared to be completed at 80 m. The initial value below the farm site that had been in operation for seven years, loading conditions was 351 µg Zn/g dry sediment (Brooks *et al.* 2004). Heavy metals in the underlying sediment decrease over time after cessation of fish farming, but it is not clear whether burial or chemical change was the overlying cause of the decrease. At the same site, free sediment sulphides were initially 9410 µM $S^{=}$ and five years later they were still elevated at 1270 (0.1 H_2S) and 225 to 549 µM $S^{=}$ (at 75 m and beyond, respectively). Note: to give meaning to these values recall that we previously mentioned that sulphide is toxic between 250 and 2500 µM.

Table 6.4.I : Salmon farming characteristics (from Carroll et al. 2003).

Site	Current speed, m/s	Depth m	12-mo feed tonnes	Years in operation	Below farm sediment condition
A	0.04-.06	25-50	500	4	Sediment over 0.05 m deep containing coarse and fine grain size fractions
B	0.1-.25	75	1000	10	Rocky, waste debris only in some places

Data on metals and sulphide at four more exposed salmon farming sites in British Columbia Canada are presented in Brooks *et al.* (2003). Unfortunately, no information on kelp at these sites is available, because farms according to B.C. regulations must be at least one kilometer from a kelp bed (Levings *et al.* 1995). At one of the four sites, current speed varied between 0.05 m/s and 0.25 m/s and the substratum was sandy with 30–40% silt and clay. Data from two production cycles interrupted by a four month fallow period indicated that mean sediment free sulphide concentration during the first cycle was 12,375 µM at the farm, 14,213 µM at 30 m, and 3285 µM at least 100 m from the net pens. Two months after the fish were completely harvested, sulphide levels were 40 µM at 100 m, but remained very high at the site. During the second production cycle, fewer fish were produced, and all sulphide levels (farm and 100 m) were below 960 µM. Data from all sites indicated that sulphide levels quickly increase at the site and generally peak at the time of maximum biomass. Elevated levels were observed at 100 m at most sites. Fallowing and farm fish biomass control was seen to be effective at reducing the sulphide levels to a level (960 µM) at which more than half the reference area taxa was found able to recruit and survive. Sediment Zn levels were monitored during and post production. Due to the high levels of sulphides, Zn was deemed not bioavailable at the sites (for example, Zn was most likely bound to sulphide).

Using the above information and references, we estimated the zone surrounding the farm sites reflecting change in relation to sediment grain, sediment heavy metals (Cu and Zn) and sediment sulphide levels. We assumed that the benthos within at least 100 m from the farm at both sites would change as organic particulates accumulate. Further, after the start up of the farm, we assumed that the sediments quickly became organically enriched, and sulphides quickly reached potentially toxic levels. Zinc and Cu deriving from uneaten feed and faecal matter are bound to the sulphides. Species composition changed to the point where only sulphide insensitive species now exist. Sediment quality and taxa would return to approach background levels if sites are fallowed for 4 to 12 months between production cycles. At site A (the sheltered site), without site fallowing between production cycles, sediment remediation would likely require more than five years after the site has been vacated. During remediation, heavy metals would become bioavailable as sediments as the anoxic zone reduces in depth and potentially toxic to kelp. At rocky substratum sites typical of more exposed salmon farming sites (for example, Site B), species composition also changes (although it is not clear what happens at these sites, as waste material does not accumulate).

6.4.3.2 Exposure Assessment

This process consists of a description and quantification of the relevant conditions and characteristics of kelp exposure to the various risk agents in fish farming effluents. Typically (as mentioned in the biological section) at the sheltered Site A, *L. saccharina* would be the dominant kelp species, while at the more exposed Site B both species would be present in varying proportions.

At Site A, kelp could be growing in the benthos over a section of the farm where the water depth does not exceed 30 m. At Site B, kelp would not be growing under the farm site, as the water depth (75 m) is too deep. Likely, they would be growing between 2 and 20 m from the shore in water to a depth of 30 m; this means that the outer edge of the kelp bed would be 40 m from the farm perimeter. Most of kelp at both sites would be restricted to a depth of 8 m, as light tends to limit production at deeper water depth unless the water is very clear, and this means, most of the kelp bed will not be below the farm at Site A.

Waste effluents from Site A have the potential to affect the kelp, because the zones of dissolved nutrients (40 m) and waste particle fallout (100 m) overlap with the kelp bed. Only the particulate waste matter from Site B has the potential to adversely affect the kelp because the zone of dissolved nutrients does not extend to the kelp bed.

6.4.3.2.1 Exposure assessment of kelp to dissolved nutrients

According to the fish biomass/ harvest schedule and background dissolved nitrogen seasonal trends at Site A, dissolved nutrients originating from the farm would be highest just before the fish are harvested. So, bi-yearly during the time naturally occurring nutrients levels are low, the kelp bed has the potential to be fertilized to significant levels by the fish farm. During periods of slack current and fish feeding, or periods when the ammonium concentration would be the greatest, Site A could offer the dominant kelp species, *L. saccharina*, that is below and adjacent to it, a dose of nutrients that could simulate its production to higher than normal background levels (Petrell and Alie 1996). The higher than normal growth would not cause light limitation, as the kelp in this region due to temperature and lighting conditions are already considered to be the largest in Norway (hence they are already known to shade under-story seaweeds). If, however, kelp are absent or reduced in population due to over predation by sea urchins, additional nutrients might provide a benefit for the kelp.

At Site A, the additional nutrients from the fish farm could increase the abundance of epiphytic algae as the duration of the nutrient pulse (twice a day for approximately 4 months) could promote the growth of epiphytes and a corresponding decline in kelp lamina biomass and sori production. A decrease in lamina biomass in the upper story would, however, prevent light limitation and thus promote growth of younger kelp in the lower story. If, however, kelp are reduced in population due to over predation by sea urchins, the adverse effects of additional epiphytic algae could put a restrain kelp recovery.

Sori production could be negatively affected by the increase in epiphytes, and decreased sori production would mean fewer gametophytes. Fewer gametophytes would mean that the kelp would have fewer defences against predation by sea urchins.

The bi-yearly unnatural fertilization scheme at Site A would modify the storage of nitrogen and carbon in

L. saccharina. The laminae in this species break off in winter storms at the holdfast, so unlike laminae of *L. hyperborea*, they can not contribute energy to the next generation. The holdfast can, however, store carbon and nutrients. These nutrients might be obtained from salmon farming effluent, and provide energy and nutrients for a new generation. Under these conditions, the contribution of salmon farming would be positive.

6.4.3.2.2 Exposure assessment of kelp to particulate matter

Toxicity due to hydrogen sulphide and burial of gametophytes is possible at Site A as the zone of particulate fallout from the farm (100 m) overlaps the kelp bed. At the more exposed site and rocky substratum, Site B, the exposed kelp will likely be adversely affected by the organic waste as the zone of particulate fallout from the farm overlaps the kelp bed. The mechanism behind the impact in the benthos is unclear, as previous studies have shown organic matter does not accumulate appreciably at more exposed salmon farming sites. Species diversity does, however, change, and as kelp are sensitive species known to decrease when exposed to organic waste, it is likely kelp exposed to organic particulates from Site B will likewise be adversely affected.

Kelp, are able to trap organic particles from the farm which sink at low to medium velocities; these would settle to the benthos to potentially impact gametophytes via burial and perhaps to the level of toxicity due to hydrogen sulphide.

6.4.3.3 Consequence Assessment

Consequence assessment involves the development of a logic model or a relationship between specify exposures to risk agents in fish farming waste matter and the consequence to the overall kelp population. From the previous section, it was shown that salmon farming waste matter at Site A has the possibility of changing the kelp population dynamics and structures due to dissolved nutrients, sediment burial and hydrogen sulphide toxicity. At Site B, salmon farming waste matter has the possibility of impacting a kelp bed due to sediment burial and hydrogen sulphide toxicity. At Site A, *L. saccharina* is most likely to be affected due to its dominance at sheltered sites, while both *L. saccharina* and *L. hyperborea* could be affected at the more exposed site, Site B. The following is an exercise that will demonstrate the likelihood that these factors change the kelp population. Below, severity at which each step occurs is derived by an examination of three factors, namely, the degree of anticipated change or intensity, the geographic extent of the effect and the duration of the effect after the farm or waste matter is no longer present. Probability is expressed qualitatively. Uncertainty is roughly equivalent to prediction accuracy in a statistical sense. When mechanistic knowledge was incomplete, correlative relationships relating cause and effects were used to make the assessment; when this occurred, our certainty weakened.

6.4.3.3.1 Logic models

The series of steps and processes leading from the establishment of salmon farms in coastal waters to decreases in wild *Laminaria* stocks as a result of waste effluent from salmon farms is conceptualised in the logic models of Figures 6.4.8 and 6.4.9, and formulated below :

Model 1: Dissolved nutrients

Process of concern : Changes in kelp population due to dissolved waste products

End Point of Concern : Decline in survival of kelp beds due to salmon farming

Logic model steps for Site A:

1. Suitable kelp habitat is in the area of interest.
2. A salmon farm is within or close to the kelp habitat
3. Kelp is growing in the area of interest
4. Dissolved nutrients change due to fish farm.

5.1.0 Dissolved nutrients cause an increase in epiphytic algae.
5.1.1 Light limitation occurs.
5.1.2 Lamina production changes
5.1.3 Decrease in kelp productivity
5.2.0 Dissolved nutrients cause an increase in epi phytic algae.
5.2.1 Kelp lamina erosion increases
5.2.2 Sori production decreases
5.2.3 Decrease in kelp productivity
5.3.0 Dissolved nutrients change the way the kelp stores C and N.
5.3.1 Lamina production changes
5.3.2 Decrease in kelp productivity
5.4.0 Lamina grows
5.4.1 Light limitation occurs
5.4.2 Lamina production changes
5.4.3 Decrease in kelp productivity
5.5.0 Lamina production changes
5.5.1 Light limitation occurs
5.5.2 Lamina production changes
5.5.3 Sori production changes
5.5.4 Decrease in kelp productivity
6.0 Change in kelp population

Model 2: Particulate matter

Process of concern : Changes in kelp population due to particulate matter

End Point of Concern : Decline in survival of kelp beds due to salmon farming

Logic model steps for Sites A and B:

1. Suitable kelp habitat is in the area of interest.
2. A fish farm is within or close to kelp habitat
3. Kelp is growing in the area of interest
4. Particulate matter from the salmon farm accumulates in benthos.

5.1.0 Particulate matter affects gametophytes via burial.
5.2.0 Decrease in kelp productivity
5.2.0 Kelp is affected by hydrogen sulphide toxicity.
5.2.1 Decrease in kelp productivity
5.3.0 Exposure to dissolved heavy metals

Figure 6.4.8 : Conceptual model representing the potential impact of fish farming dissolved nutrients waste on kelp. Dashed lines represent the release assessment, and the numbers, steps in the logic model.

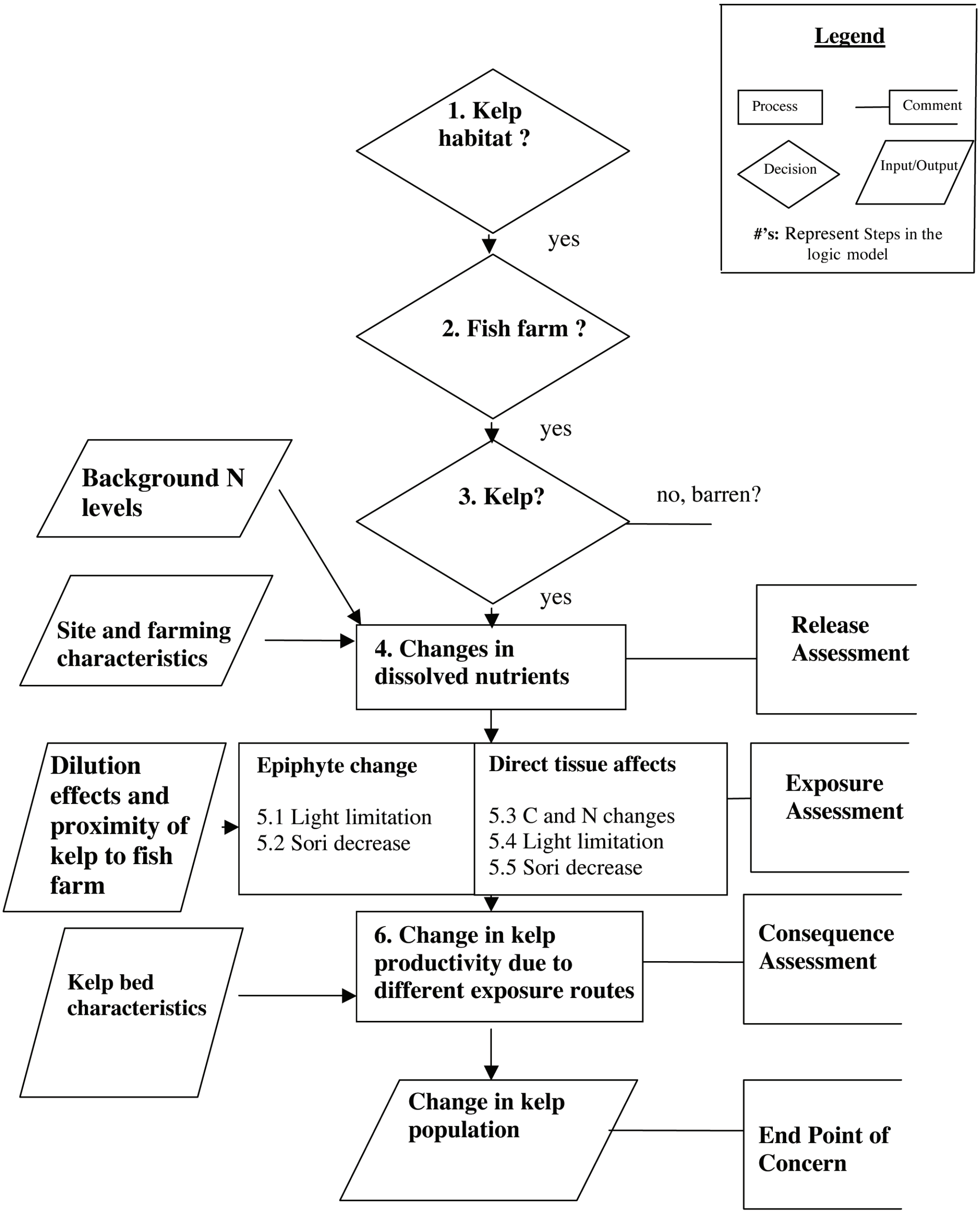
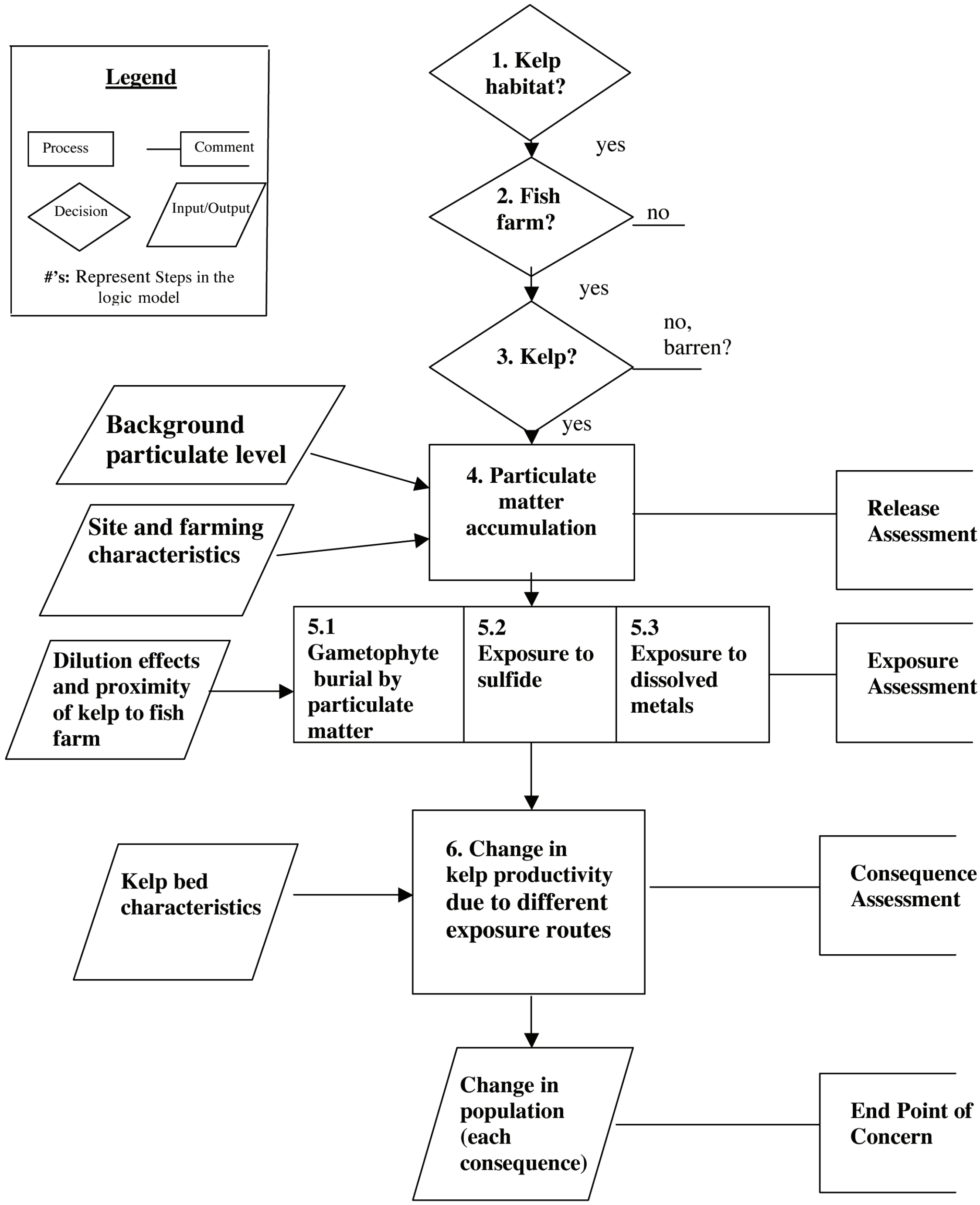


Figure 6.4.9 : Conceptual model representing the potential impact of fish farming particulate matter on kelp population. Dashed lines represent the release assessment, and the numbers, steps in the logic model.



5.3.1 Decrease in kelp productivity
6. Change in kelp population

The information presented in the preceding sections of this risk analysis allows the annotation of each step in the logic model to indicate the likelihood that each step has been, or will be, completed.

6.4.3.3.2 Likelihood of occurrence

The material below is summarised in Table 6.4.II.

Steps in logic Model 1.

1. Good kelp habitat is in the area of interest.
   High probability - Different species of macrophytes require different substratum for attachment, and the type of substratum necessary for *L. saccharina* and *hyperborea* can be found near salmon farms. As well, water temperature and lighting requirements are met there. In addition, they grow in sheltered to completely exposed sites to a depth of 30 m; although they tend to be more robust in more exposed sites, and weaker in more sheltered sites. More habitat is available for kelp due to suitable water profiles at Site A than B. The geographical extent of the suitable habitat can be large at both sites, as kelp habitat tends to follow coast lines. The habitat is not expected to change as this would imply a change in substratum and climatic conditions not associated with fish farming. The combined effects of depth and current supports the case for a intensity value of medium for both sites. Uncertainity is low, as published reports indicate that kelp habitat is in the areas of interest.

2. The fish farm is within or close to kelp habitat.
   Highly probable - *Laminaria* and salmon share same habitat requirements, namely non toxic water, and similar water temperature and salinity requirements. In Norway no regulations exist that stipulate how far a fish farm must be from a kelp bed. The salmon farming intensity at Site A is lower than at Site B, because fewer fish are produced at Site A than at Site B. Kelp habitat extends to below the farm at Site A, and to 40 m from the farm at Site B, hence, the geographic effect of the farm is greater at Site A than at Site B. The likelihood that the farms will remain in the area is very high. Atlantic salmon is considered a stable in the regional diet and is well distributed over the Europe. Growth in salmon farming is not being planned for the coming years, but growth in the production of other fish species is being planned. Aquaculture offers the population a source of employment. The uncertainty associated with this prediction is low, as is it reported that both kelp resources and fish farming are in the area of interest.

3. Kelp is growing in the area of interest.
   Medium probability - In Norway, *Laminaria* grow in sheltered and semi-exposed areas where salmon farms are often sited as long as their preferred substrate is available. They will grow to a depth of 30 m in clear water. We considered the probability to be medium because as kelps in the area of interest are highly impacted by sea urchins, there is a possibility that there are no or few kelp growing there. As well, it has been reported that in many sheltered and somewhat exposed sites there are many urchin barrens. Recovery of these kelp beds has been said to be unlikely within a 25 year time frame, so that situation is expected to endure for some time. We considered the maximum intensity of the kelp beds at both sites to be medium due to the following reasoning. At the sheltered Site A, substratum and depth would provide a large resource area, but as individuals are weak at sheltered sites, the maximal population size is expected to be lower than at completely exposed sites. At Site B, site depth limits the extent of the kelp resource area, but the individual plants are expected to be more robust than those at Site A. The combined conditions of plant density, shelter and depth make the intensity values the same for both sites. The uncertainty associated with this prediction is low because of the predicted 25 year wait period for the sea urchin predators to return and permanence of site conditions.

4. Dissolved nutrients in the area change due to the salmon farm.
   Highly probable at Site A - Kelp are right underneath the farm, and the bed extends 60 to the shore. Background water quality is considered excellent in the area in spite of measurable changes in sediment and water quality surrounding the salmon farming sites due to the high flushing conditions in the area and strong dissolved nitrogen limitation in the water column. Background nitrate levels are highest in the spring, so any contribution of dissolved N from the farm would be minimal then. During the later stages of the fish production cycle when fish biomass is maximal, the output of farmed-derived dissolved nutrients would be measurable in the water during late summer to early fall. This would occur biyearly as long as the fish farm remained in the area and if the site was not stocked with fish in between cycles. At this time, at least 40 m from the farm site the contribution of dissolved nutrients from the farm would elevate the available dissolved nitrogen levels to exceed the growth saturation level for kelp at least twice a day after the fish have been fed. The geographical effect is considered medium as only that part of the kelp bed closest to the farm would receive additional nutrients. Intensity is considered to be high as the nutrient concentration would permit adequate kelp growth conditions.

5.1.0 Dissolved nutrients from the salmon farm at Site A are sufficient to enhance the growth of epiphytic algae.

Table 6.4.II : Table summarising risk estimation for logic model.

Steps in logic model 1 (Site A only)	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	H	H	M	H	L	
2.A salmon farm is within or close to kelp habitat	M	H	H	M	H	L	
3.Kelp are growing in the area of interest	M	M	H	M	M	L	
4.Dissolved nutrients change relative to back-ground levels	M	M	M	M	H	L	Release
Release summary				M	M	L	
5.1 Dissolved nutrients increase epiphytic algae on kelp	M	M	L	M	H	L	Exposure
Change in epiphytic algae promote light limitation in kelp	L	L	L	L	H	L	Exposure
Light limitation promotes change in lamina production	L	L	L	L	M	L	Exposure
Exposure Assessment				L	M	L	
Change in lamina production decreases kelp productivity	L	L	L	L	H	H	Consequence
Consequence Assessment				L	M	H	
5.2 Dissolved nutrients increase epiphytic algae on kelp	M	M	L	M	H	L	Exposure
Epiphytic algae increase lamina erosion	L	L	L	L	H	L	Exposure
Lamina erosion promotes change in sori production	M	L	L	L	H	L	Exposure
Exposure Assessment				L	H	L	
Change in sori production changes kelp productivity	M	L	L	L	H	H	Consequence
Consequence Assessment				L	H	H	

Table 6.4.II. Table summarising risk estimation for logic model (continued).

Steps in logic model 1 (Site A only)	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity**	**Probability**	**Uncertainty**	Stage of assessment
5.3 C and N storage pattern changes	M	L	L	L	M	H	Exposure
Lamina production changes	M	L	L	L	L	H	Exposure
Exposure Assessment				L	L	H	
Change in C and N changes kelp productivity	M	L	L	L	L	H	
Consequence Assessment				L	L	H	
5.4 Dissolved nutrients affect lamina growth	L	L	L	L	H	L	Exposure
Increase in lamina growth causes light limitation	L	L	L	L	H	L	Exposure
Light limitation promotes change in lamina production	L	L	L	L	H	L	Exposure
Change in lamina production changes sori production	L	L	L	H	H	L	Exposure
Exposure Assessment				L	H	L	
Change in sori production changes kelp productivity	L	L	L	L	H	L	Consequence
Consequence Assessment				L	H	L	
5.5 Sori production changes as a result of changes in lamina production	L	L	L	L	H	L	Exposure
Exposure assessment				L	H	L	
Kelp productive changes as a result of changes in sori production	L	L	L	L	L	L	Consequence
Consequence Assessment				L	L	L	
Overall risk of a drop in local kelp population (highest severity and probability)				L	L	H	

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).