the assimilative capacity of an ecosystem and this information is necessary to manage the overall scale of aquaculture. At present, far-field effects have not been observed at the relatively low density of netpen operations in the Pacific Northeast. They are therefore a Category IV hazard and a quantitative environmental cost assessment is not possible at this time.

PUTTING THE ENVIRONMENTAL COSTS OF SALMON PRODUCTION IN PERSPECTIVE WITH THE COSTS ASSOCIATED WITH OTHER FORMS OF FOOD PRODUCTION

Assessing the environmental costs of other food producing activities is being undertaken by other contributors in these proceedings. However, the following comments are provided in an attempt to put the costs of salmon aquaculture into perspective with the environmental costs of producing an equivalent amount of beef.

Beef cattle production

Image 1 is a photograph of an old growth forest in the Canadian Rockies. These forests and their associated wetlands support small, but diverse, communities of plants and animals. The organic debris created by wind-thrown old-growth cedar, Douglas fir, true firs, hemlocks and birch trees creates a dense detrital food web that support marvelous communities of fungi, ferns, mosses and lichens. Many of the Douglas fir trees are five and six feet in diameter. They do not have a limb on them for perhaps the first hundred feet of their 200 foot heights and they are (by actual tree-ring counts) several hundred years old. The creation of such a forest takes centuries, if not eons.

IMAGE 1
Old growth forest on Horsefly Lake in the Canadian Rockies

Image 2 describes a beef cattle farm on the Olympic Peninsula in Washington State, which was once home to a similar forest. Its remnants are seen in a few mature Douglas fir trees and in the eight to twelve foot diameter cedar stumps left from the original logging, which occurred in the middle of the 19th century. Today, about half of the farm has been replanted to Douglas fir and half remains as pasture for Angus beef cattle (Image 3). The hanging weight of a black Angus steer is about 70 percent of its live weight and rendering the carcass into edible meat further reduces the yield to about 42 percent of the animal's live weight. Gutted and bled Atlantic salmon represent 84 percent of their live weight. Assuming that the heads are not consumed, the yield of salmon filets is approximately 50 percent of the live weight

IMAGE 2
Whispering Ridge farm on the Olympic Peninsula in Washington State, which was once covered with old growth forests

IMAGE 3
Black angus cattle grazing on pasture that was once old growth forest, but which was removed in an effort to feed Washington State's growing population in the later part of the 19th and early part of the 20th centuries

(Gary Robinson, Marine Harvest, personal communication). Therefore a salmon farm producing 2 500 tonnes of live salmon would supply 1 250 tonnes of edible filets which are equivalent to 5 411 steers weighing 550 kg each. In the Pacific Northwest, one acre of actively managed pastureland will support one cow for 7.5 months (7.5 animal month units or AMUs). It takes approximately 30 months (30 AMU) to produce a marketable steer and the 5 411 steers require 162 338 AMU or 8 658 acres (3 504 hectares) for 2.5 years. As noted earlier, the benthos under well sited salmon farms chemically remediates in six months to a year and biologically remediates in another year. In contrast, in the Pacific Northwest, it will take hundreds or a thousand years for the pastures seen in Image 2 to remediate back to the original old growth forest seen in Image 1.

Table 5 compares the near field land use costs associated with raising equivalent amounts of edible beef and Atlantic salmon. The table does not assess the possible water column eutrophication associated with tonnes of fish and cattle waste that enters aquatic environments each year. Nor does it assess the ammonium released to the atmosphere, contributing to global warming, or the differences in oxygen resulting from photosynthesis of a mature old growth forest in comparison with pastures. A meaningful life cycle analysis that considers all of the environmental costs associated with both forms of food production would have to be accomplished with the same rigor provided herein for near-field effects and it would span volumes. That is beyond the scope of this report. However, this limited assessment suggests that the landscape directly affected for cattle production is several hundred times greater than it is for production of the same amount of food in salmon aquaculture.

Harvesting of the ocean's natural bounty

An accurate assessment of the environmental costs associated with recreational and commercial fishing must take into account not only the physical destruction associated with bottom trawling and the poorly accounted for bicatch that is discarded. It must include, among other factors, an accounting of the costs associated with lost production to derelict fishing gear. In 2004, a group of Washington State sport fishermen used side-scanning sonar to identify over 2 000 derelict (lost) shrimp and crab pots in three embayments on the North Olympic Peninsula (Port Angeles Harbor, Sequim Bay and Discovery Bay). They were able to successfully retrieve 292 of these pots. Anecdotal evidence suggests that 40 percent of the pots were not equipped with sacrificial closure devices designed to deteriorate in relatively short periods to stop long-term entrapment of sea-life. Image 4 describes the contents of just one of these pots and many similar photographs are available.

TABLE 5
Comparisons of the physical footprints associated with production of 1,250 tonnes of the edible portions of Atlantic salmon or beef cattle

Type of food	Edible portion	Live weight	Yield	Spatial footprint	Remediation time
Atlantic salmon	1 250 000 kg	2 500 000 kg	0.50	1.6 hectares	2 years
Angus beef cattle	1 250 000 kg	2 976 190 kg	0.42	6 982 hectares	200 plus years

Using grant money from Washington State, the fishermen obtained the services of a larger vessel and were able to retrieve masses of lost trawl and gill nets (Image 5). Lost fishing gear is a world-wide problem that has not been quantified or effectively managed by any jurisdiction that the author is aware of. The recreational fishermen responsible for the program described here commented that the Department of Fish and Wildlife estimated that the several thousand lost pots were killing approximately 10 percent of the allowable prawn and crab harvests. The same problem occurs in other areas.

IMAGE 4
One of over 2 000 lost prawn and crab pots identified using side-scanning sonar in three embayments along the Straits of Juan de Fuca in Washington State. As of 2004, 292 of these derelict traps had been retrieved

The point in this discussion is not to decry cattle farming or commercial and recreational fishing. The point is to put a portion of the environmental costs associated with Atlantic salmon production in perspective with the environmental costs associated with these more traditional ways of producing food and to assert that the path to sustainability requires fixing the tough problems first and then moving down the scale of effects to fine-tune food production in an effort to achieve true sustainability.

IMAGE 5
Mass of derelict fishing nets retrieved from the Straits of Juan de Fuca in Washington State containing hundreds of kilograms of dead and dying fish

CONCLUSIONS AND RECOMENDATIONS

There are costs associated with every form of food production. Certainly the loss of topsoil at rates that are 17 to 80 times faster than it is being replenished in association with the production of grains needed to bake loaves of bread is not sustainable. Wild stocks of fish are being depleted in an effort to supply humankind's demand for aquatic protein. Almost none of these more traditional ways of producing food have received the scrutiny that aquaculture has. For instance, what are the long-term costs associated with soil loss around the world? What are the environmental costs (as defined in this paper) associated with derelict (lost) nets and pots? The scrutiny of these issues is so low that no literature was found quantifying lost fishing gear, let alone the environmental cost in terms of fish and shellfish that dies in these traps each year. In this respect, some of the current emphasis on eliminating environmental effects associated with aquaculture is akin to Nero playing his fiddle while Rome was burning. The path to sustainability can only be achieved through a holistic and scientifically rigorous approach to managing earth's resources. A systematic approach to these assessments requires the following:

- An acknowledgement that there are environmental costs associated with all forms of food production;
- Identification of the direct and indirect environmental costs associated with all forms of food production;
- Prioritization of the identified costs of food production;

- Focused research to minimize (not eliminate) costs associated with the least sustainable production methods.

Regional nature of costs
It should be emphasized that environmental responses depend not only on the hazards associated with food production, but also on specific environments. For instance, adding nutrients to open Northeast Pacific ocean water does result in a significant response. Adding the same amount of nutrient in another region or in closed estuaries in the Northeast Pacific might result in significant effects.

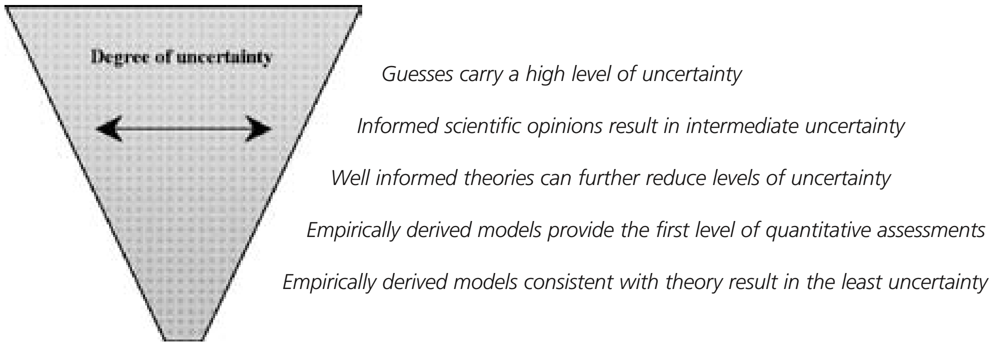
Identifying real effects versus effects "per se"
An assessment that allows quantification of actual effects rather than *effects per se* associated with food production is needed. That requires development of an understanding of the environmental response to the agricultural activity. For instance, the discharge of nutrients in water from shrimp culture ponds is an *effect per se.* The environmental cost of that effect requires an understanding of background nutrient concentrations in the receiving water and other conditions (turbidity, light availability, etc.) affecting primary productivity. Direct measurement of natural productivity is the most direct and sensitive way of measuring environmental costs. Surrogate endpoints, such as free sulfides and redox potential are far less time consuming and expensive than macrofaunal community assessments. However, these are effects *per se* until quantitative cause and negative affect relationships with valuable resources are demonstrated. For instance, the discharge of nutrients can have positive or negative effect on primary production and unless the actual response is understood, it is not possible to assess the cost with confidence.

Uncertainty associated with environmental cost assessments
As shown in this paper, several effects associated with Category II hazards are reasonably well understood and based on empirical evidence. Other Category II hazards, such as the environmental response to exceedances of an ecosystem's *carrying capacity* are less well understood. The environmental response to many, if not most, Category IV hazards are not well understood and cannot be quantified. Development of the understanding required to quantify environmental costs typically requires years of effort and significant investment of resources. In the absence of empirical data, estimates must be made on qualitative determinations, which increase uncertainty in cost assessments (Figure 19). The point is that quantifying the costs associated with various food producing sectors will take decades and future investments in research. In these instances, people and organizations interested in sustainable food production can either throw up their hands in frustration or they can make best use of the information and experience available to complete the assessments. This is conceptually illustrated in Figure 19. The advantage of this approach is that it allows at least a qualitative understanding of the costs of food production and it allows us to focus our energy on mitigating the most pressing costs.

Transparency
It is important that the identification and prioritization of environmental costs associated with food production be conducted in a transparent manner. That implies acknowledging, and where possible quantifying, the uncertainty described inFigure 19. Every report assessing the environmental costs associated with food production should include an acknowledgement of the costs included in the assessment and those that are excluded.

The body of this report has focused on the effects associated with organic enrichment from salmon aquaculture to illustrate the level of detail and years of work

FIGURE 19
Relationship between the uncertainties of cost comparisons between food producing sectors and the uncertainty of the assessments



necessary to understand just one facet of the costs associated with a single hazard. Understanding these costs is not a trivial pursuit. However, achieving sustainable use of earth's resources is an important goal that must be undertaken in a systematic way if future generations will not look back at the 21st century and condemn us for unwise use and management of these resources. A beginning can be made by bringing together multidisciplinary teams of scientists to define the scope and context of the problem. Such an effort will help guide existing and future work to focus on the most pressing problems. This need and approach is frequently cited and often discussed. Unfortunately programs to accomplish it are infrequently, if ever, implemented.

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APPENDIX 1

Environmental costs and possible hazards associated with salmon farming

1. **Energy** (damming of rivers; hydrocarbon pollution, CO_2, nitrous oxides, acidification)

2. **Metals** (copper and zinc from structures and feed)

3. **Aquatic feed stuffs such as fishmeal (FM) and fish oil (FO)** (management of reduction fisheries; bycatch; modification of wild food-webs; infrastructure costs; energy for catching, processing and distributing FM & FO; disposition of waste; concentration of persistent organic pollutants (PCBs);

4. **Terrestrial feeds** (Land use; loss of biodiversity; wind and water erosion; energy costs for production of fertilizers and crops; eutrophication; contamination of groundwater and surface waters by pesticides associated with runoff; physical disruption of the landscape; surface water depletion; groundwater depletion; CO_2, N_2, and NH_4^+ inputs to the atmosphere;

5. **Construction of infrastructure** (Human and environmental energy required to construct and maintain infrastructure including netpens; vessels; processing plants; office buildings).

6. **Social costs** (Changes in nature of work in rural areas; development of governmental bureaucracies needed to manage environmental costs; environmental compliance costs; intrusion into areas where jurisdictional authority is in dispute; change from small entrepreneurial seafood production associated with a family fishermen owning a small capture vessel to multinational corporate production.)

7. **Atlantic salmon production**

    Hatchery phase:
    Costs of constructing infrastructure
    Water use
    Introduction of pesticides and pharmaceuticals
    Eutrophication in flow-through systems
    Genetic modification of stocks – loss of vigor
    Electricity use
    Petroleum use
    Feed use

    Juvenile growout to smolting:
    Occupies space in freshwater
    Eutrophication of lakes
    Organic enrichment of sediments
    Pesticides and pharmaceutical inputs to surface and groundwater

All of the factors involved in the production of feed
Wild animal control and inadvertent loss to nets and etc.

Saltwater growout to harvest:
Benthic enrichment effects (loss of diversity and biomass of benthic organisms)
Physical modification of the environment (anchoring and the netpens themselves)
Copper contamination of the water and sediments

Saltwater growout to harvest continued:
Zinc contamination of the water and sediments
Eutrophication in the water column (stimulation of phytoplankton & macroalgae)
Pesticides and pharmaceuticals (pharmaceutical and antibiotics transfer to wild fish)
Contribution to atmospheric CO_2 associated with energy use
Depletion of dissolved oxygen
Accumulation of metabolic waste (NH_4)
Genetic pollution and introduction of exotic species
Production waste – particularly harvest blood and disposal of mortalities
Disposal of human waste in remote areas
Energy and resources required to construct infrastructure
Ecosystem modification associated with escapee interactions with the environment
Disease transfer between wild and cultured stocks (both ways).

Processing:
Land use
Blood
Offal
Electrical power use
Equipment – infrastructure
Refrigeration and refrigerants
Packaging
Shipping
Ammonia and CO_2 associated with composting
Waste disposal (landfills)

APPENDIX 2

Hazards associated with various types of aquaculture. Hazards identified by GESAMP 31 that are associated with the coastal culture of bivalves, finfish, shrimp and macroalgae

Bivalve aquaculture

a. Extractive – carrying capacity becomes a concern as production increases (Category 2)
b. Benthic effects can be significant (Category 2)
c. Nutrient cycling can be affected (Category 4)
d. Potential for genetic interaction is actually higher than for fin-fish (Category 4)
e. Potential to change hydrodynamics and sedimentation patterns (Category 4)
f. Has a relatively high potential for beneficial effects, eg habitat for eider ducks, juvenile fish, etc (Category 2)
g. Habitat modification such as addition of shell to sediments, displacement of seagrasses and/or macroalgae (Category 2)
h. Disease spread associated with intensive culture – particularly monocultures. This can pose a hazard to both the cultured and sympatric populations of uncultured bivalves (Category 4)
i. Use of pesticides, e.g. carbaryl (Category 3)
j. Predator control; skate, starfish, eider ducks, crabs (Category 1)
k. Zoonoses – disease transfer to humans PCP, DSP, *Vibrio parahaemoliticus, Vibrio vulnificus* (Category 3)
l. Harvesting (bottom disturbance during oyster dredging; turbidity during

mechanical harvesting in intertidal areas) (Category 3)

m. Navigation hazards (Category 1)
n. Debris associated with Styrofoam, and plastic protective netting and cages (Category 1)
o. Aesthetics, visual impacts and/or exclusion of other stakeholders from intertidal areas (Category 1)

Finfish aquaculture

a. Sedimentation of waste (Category 2)
b. Dissolved waste – eutrophication (Category 2)
c. Internal effects possible but fairly easily managed – oxygen; metabolites. May be different for other cultivation species (Category 3)
d. Susceptible to a number of environmental factors, which may create or complicate environmental hazards. Examples include phytoplankton, low dissolved oxygen (Category 4)
e. Disease transmission to and from wild stocks (Category 4)
f. Genetic interactions with wild stocks – escapes – depends on locality (Category 4)
g. Pharmaceutical/pesticide use (Category 3)
h. Antifoulant use and net cleaning (Category 3)
i. Biocide use such as in foot-baths (Category 3)
j. Habitat modification associated with presence of structures – fish ponds and cages, shore-side developments and jetties (Category 1)
k. Predator control – seals, sea lions, otters, etc. (Category 1)
l. Noise (generators, ADDs, etc.) (Category 1 for generators, Category 4 for ADDs)
m. Aesthetics, visual impacts (Category 1)

Shrimp culture

a. Internal risks to the cultured species associated with nutrients and metabolites (Category 2)
b. Nutrients can enter adjacent waterways – especially when the shrimp are harvested. However, waters in areas of shrimp culture are typically eutrophic already in association with rice farming and other activities and the added nutrients do not significantly further degrade water quality. Nutrients could be a problem in estuaries. However, turbidity generally reduces primary productivity mitigating the potential for eutrophication. (Category 2)
c. Habitat destruction, such as removal of mangroves, can be a primary hazard associated with shrimp production. The effects of this hazard on natural production can vary significantly in association with the location of the mangroves. (Category 1)
d. Ponds can become acidic associated with sulfides excavated during pond construction. This can result in reduced pH in downstream areas. Effects on estuaries – salt marsh, etc. due to the construction of ponds. (Category 1)
e. Disease transmission to and from wild stocks is a hazard that is acknowledged but not well studied or understood. (Category 4)
f. Antibiotic use, including uncertainty of fate in the environment. (Category 3)
g. Pesticide use in adjacent agriculture may adversely affect the culture. Emphasize the need to manage risks to the stocks as well as risks caused by the cultured stocks (Category 1 or Category 4).
h. Interactions with wild stocks. Depletion for production of juveniles. This

may be particularly important with the introduction of new species such as *Penaeus vannamei* which may interact genetically with native species and/or which may escape. (Category 4)

i. Salinisation, salt intrusion (Category 3)
j. Depletion of wild stocks for production of juveniles (harvesting of broodstock or larvae). Associated by-catch problems. (Category 3)
k. Disposal of mud from the bottom of ponds between growing cycles. (Category 1)

Sea weed cultivation

a. Competition for space with other resource users. There can be a very large demand for space to attain a commercially viable scale (Category 1)
b. Changes in hydrodynamics, for example altering sedimentation patterns (Category 4)
c. Competition for nutrients with other primary producers (Category 4)
d. Losses of product during bad weather leading to nuisance on the sea bed and beaches (Category 3).