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Sustainable Mariculture at High Latitudes

Paul Tett, Kenny Black, Ruth Brennan, Elizabeth Cook, Keith Davidson

Laurence Mee Centre for People and the Sea, Working Papers 2014-05

December 2014

Online at

www.sams.ac.uk/lmc

Abstract

The first part of this paper is a manuscript submitted as a chapter in *Coastal Zones: Developing Solutions for the 21st Century*, to be published by Elsevier. It starts from the premise that glacial retreat at high latitudes is exposing new coastlines where mariculture might help satisfy demand for protein and provide economic opportunities for a locally expanding human population. Scottish sea-farming takes place along a previously glaciated coast. Based on experience here, we propose a general framework for sustainable mariculture based on *ecological, economic and social licences*.

The second part is an appendix that extends the argument in the main text, but which (for reasons of length) was not submitted. It concludes that maricultural carrying capacity is more than a matter for ecologists. It involves complex issues and wicked problems. We have argued that a top-down approach using content rules is not best suited to deal with these. Instead, we suggest flexible and dynamic regulation based on communicative action in local fora, drawing on expert knowledge and modelling tools, and supported by process rules operated by appropriate governance.

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SUSTAINABLE MARICULTURE AT HIGH LATITUDES

Paul Tett, Kenny Black, Ruth Brennan, Elizabeth Cook, Keith Davidson
SAMS

8 December 2014

Abstract

Glacial retreat at high latitudes is exposing new coastlines where mariculture might help satisfy demand for protein and provide economic opportunities for a locally expanding human population. Scottish sea-farming takes place along a previously glaciated coast. Based on experience here, we propose a general framework for sustainable mariculture based on *ecological, economic and social licences*.

1 Introduction

In the 21st century there will be more people than ever on Earth. If economic growth continues, many of them will be more prosperous than their grandparents. One of the challenges of the new century is that of satisfying the resulting demand for protein. Some of this will be met by marine farming of fin-fish, shellfish and seaweeds (Duarte et al., 2009).

Nevertheless, mariculture can overload the sea's capacity to dispose of farm wastes or to provide food for shellfish. The challenge addressed in this chapter concerns the setting of safe limits to the biomass that can be farmed sustainably in coastal waters at high latitudes. This focus allows us to deal with the comparatively few types of farmed fish and shellfish that are capable of flourishing in cold stormy waters, and allows us to generalise from our experience with mariculture in Scotland, north of

55°. Similar coastal environments are emerging in arctic coastal zones as ice-cover decreases.

2 Mariculture

Salmon and sea-trout, collectively called salmonids, are silvery carnivorous fish that spend most of their adult lives at sea, returning to rivers to breed. They have proven adaptable to rearing in large floating cages, where they are fed on pelleted food made (at least in part) from small wild fish and hence rich in organic nitrogen and phosphorus. Uneaten food and fish faeces can accumulate on the sea-bed, smothering the animals that live here; in addition, the fish excrete ammonia and phosphate, which might stimulate excess growth of phytoplankton (microscopic single-celled algae).

Mussels are black-shelled bivalves that grow in clumps attached to rocks by byssus threads; they feed by pumping sea-water over their gills and filtering out phytoplankton and particulate organic matter. Mussels can be grown attached to ropes, or in suspended bags of netting, or on the seabed. Harvested, they provide an efficient means of converting phytoplankton into food, but excess cultivation may leave too little phytoplankton for the rest of the ecosystem, and the mussels give rise to a rain of (mainly inorganic) pseudo-faeces onto the seabed.

3 Regions of Restricted Exchange

A ‘Region of Restricted Exchange’ (RRE) is a semi-enclosed body of seawater, in which exchange with the open sea is restricted by, and governed mainly by, conditions at the RRE mouth (Tett et al., 2003). Fjords, called in Scotland ‘sea-lochs’ are examples of RREs; they are glacially over-deepened river valleys that, post-glaciation, have been flooded by the sea. Fjords characterise the coasts of Scotland and Norway, which were covered in ice until about 10 thousand years ago, and are opening on Arctic coasts as the ice begins to retreat here. They are sheltered and they provide good environments for salmonid and mussel cultivation. Despite their restricted entrances, circulations driven by river discharges provide continuous refreshment of their upper layers, which are cool and well-oxygenated - ideal conditions for salmonids - and which are, seasonally, rich in phytoplankton - good conditions for mussels.

In 2012 about 140 thousand tonnes of farmed fish (mainly salmon) were harvested from Scottish sea-lochs, and the UK’s devolved administration in Scotland, the Scottish Government, plans to increase this to about 210 thousand tonnes in 2020. There are also plans to double mussel-farming. An obvious question is, do the lochs have the capacity to house this increase?

4 Carrying Capacities

Estimating the carrying capacity of a site, water body or region for mariculture would seem at first sight to require only ecological study. However, successful sea-farming requires collective action to fund, build and maintain the activity, and to provide a demand for its products. Such actions are the result of social decisions, whether or not these involve ex-

pert evidence and whether or not they are made democratically or transparently. These issues have been addressed by McKindsey et al. (2006), who set out ‘a hierarchical approach to determining the carrying capacity of an area for bivalve culture’, a framework that can be adapted for mariculture in general. The (adapted) levels are:

1. **The physical carrying capacity** is the area that is ‘geographically available and physically adequate’ for a given type of mariculture.
2. **The production carrying capacity** is the ‘optimized level of production of the target species’, which might be set by the availability of food for filter-feeding shellfish or the site’s ability to disperse wastes from fin-fish.
3. **Ecological carrying capacity** is the level of production that does not impact undesirably on the surrounding ecosystem(s);
4. **Social carrying capacity** takes account of 1 - 3, plus other stakeholder interests.

Figure 1 illustrates production and ecological capacities as well as introducing **economic capacity**, which might be seen as a part of the social capacity. *Production capacity* is shown as increasing with stocking, up to a maximum. This maximum might be set, in the case of cultivated filter-feeding bivalves, by the local availability of planktonic food. Above this level, shellfish grow less well because they compete with each other for food. In the case of fin-fish, the level might be set by the extent to which local water movements can remove fish waste and supply oxygen, or by the need to prevent the build-up of infectious diseases. *Economic capacity* might be lower than this, because the greatest profit occurs when

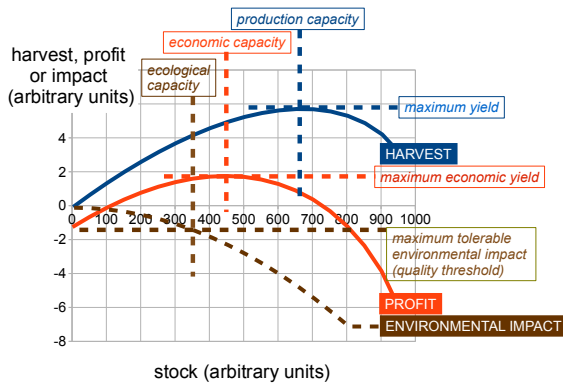


Figure 1: Several types of carrying capacity. *Ecological capacity* is set by a (possibly socially-determined) threshold for maximum tolerable environmental impact. *Production capacity* is the maximum harvest obtainable at a given site. The diagram also introduces the idea of *economic capacity*, set by the maximum profit that can be extracted from a farm.

the market value of the harvest maximally exceeds the costs of buying and feeding the stock, plus overheads. These components of income and expenditure - and, thus, the stock level for maximum profit - are sensitive to many external factors.

Finally, *ecological capacity* is determined by (i) the impacting activities of the farm, (ii) the properties of the local ecosystem, and (iii) the thresholds that are set. Item (i) is manageable by the farm. Item (iii) is a complicated matter. In a permissive planning environment, the thresholds might be set by farm management, simply to ensure that environmental impact does not have knock-back effects on farm structure (e.g. through fouling), farmed organisms (e.g. through deoxygenation or enhanced blooms of harmful micro-algae) or farm workers (e.g. through generation of toxic gases). In such a planning environment, wise managers - those with a view to sustainability or their

insurance premiums - might wish to acquire much local scientific evidence.

Alternatively, farmers and society might rely on public regulators to set the thresholds. This could be done ‘objectively’: for example, an approach based on ecosystem health (Tett et al., 2013) might tolerate any disturbance that did not impact on ecosystem resilience. However, many current limits are set by social processes: for example, nutrient thresholds result from political decisions in international fora such as OSPAR (Painting et al., 2005).

5 Scales

An *ecosystem* is ‘composed of the physical-chemical-biological processes active within a space-time unit of any magnitude’ (Lindeman, 1942). However, processes tend to have dominant space-time scales, and by specifying these it is possible to identify 3 nested scales for mariculture (Figure 2).

In the case of fin-fish in floating net cages, the zone A scale is that of the seabed directly impacted by falling farm waste, and of the water immediately around the farm, where oxygen might be depleted and ammonia increased. Conceptually, zone B provides the boundary conditions for zone A - e.g. the background levels of ammonia and oxygen - and is also the scale on which nutrients may get converted into phytoplankters, because it is defined as having water residence time of order days. Thus effects of sites can be cumulative.

In many cases, the zone B scale can be equated with a water body, as exemplified in the diagram, where the water bodies are, schematically, Scottish sea-lochs, residence times for upper waters are of the order of days, and boundary conditions are those at the fjord’s mouth (those of the zone C scale).

Zone C is the scale of a regional sea, where water residence times are weeks or months. It

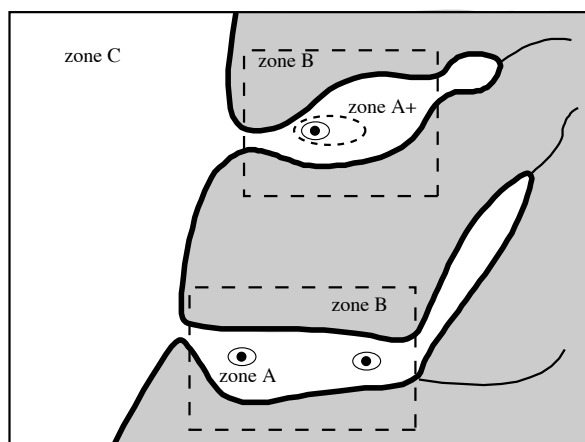


Figure 2: Scales for aquaculture (Tett, 2008). Zone A is the farm-site scale; it includes the part of the seabed that receives organic waste sinking from a farm and the part of the water column in which pollutants remain for a few hours. In tidally active waters, this water column zone is shown as A+. Zone B is the water body scale, relevant to most pelagic processes including eutrophication, where water remains for several days. Zone C is the regional scale, with residence times of weeks or months.

is processes on this scale that set the ecological carrying capacity for a regional maricultural industry comprising many farms and sites.

6 Socially-determined Carrying Capacity

There are many examples of models that can be used to estimate ecological carrying capacity on particular scales (see review by McKindsey et al., 2006 for shellfish farming and e.g. Cromey et al., 2002, and Tett et al., 2011, concerning salmonids). However, *socially-determined carrying capacity* is less well understood and modelled. Its complexity might best be understood in terms of *ecological, eco-*

nomic and social licences (Figure 3).

The diagram shows a local social-ecological system, centering on an maricultural activity, embedded with a larger system. In order to operate successfully and sustainably, the farm requires three sorts of licence or permission:

1. **An ecological licence** to ensure that the farm is not causing, and will not cause, ecological damage that degrades the system's resilience and natural functions;
2. **An economic licence** to ensure that the farm can continue to operate profitably;
3. **A social licence** to ensure that local people find the farm's operation to be acceptable, taking account of ecological impact, provision of employment, interests of other stakeholders, etc.

In Figure 3, the larger scale system interacts with the local-scale system through ecological, economic and social processes. Outside ecosystems provide the boundary conditions for the local ecosystem, and perhaps also the source of fish feed. The larger scale economy - shown here in terms of markets, owners, providers of capital, and taxes and subsidies - influences financial sustainability, and, more generally, efficiency of utilisation of the finite resources available to a society. Larger scale society is shown impacting through both social norms and through formal governance. The latter may be multi-tiered, as in the case of EU Directives transposed into member states' laws and implemented by regulating agencies.

7 Regulation of mariculture in Scotland

The United Kingdom, with its parliament in London, fully devolves environmental and planning matters to the Scottish Government

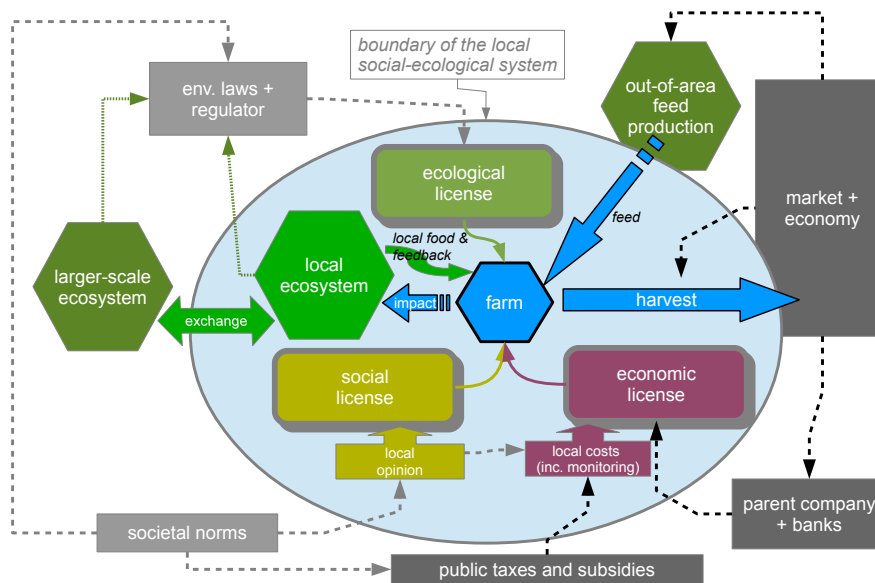


Figure 3: Issues related to *social carrying capacity* considered in terms of *ecological, economic and social licences*, for a local system embedded in a larger scale social-ecological system.

(SG), responsible to a parliament in Edinburgh since 1999. Any new development, such as a salmon farm, needs planning permission, granted by elected local authorities (which we'll call 'county councils'), who require an Environmental Impact Assessment (EIA). The Scottish Environment Protection Agency (SEPA) must issue a CAR (Controlled Activities Regulations) licence to confirm that discharges from the farm will have no adverse environmental impact. The SG must grant a 'marine licence' to confirm that the farm's structure will not interfere with shipping. It will consult with the conservation agency Scottish Natural Heritage about impact on nature protection areas, and in future (Cook et al. 2014) to prevent import of alien species. A final complication is that the UK sea-bed is owned by the Crown Estate, an institution founded in the 18th century to nationalise royal land-holdings. A new farm must rent a site

from this body.

Mussel farmers must also rent their sites from the Crown Estate, and get planning permission, but are otherwise less regulated. They do not require SEPA CAR licences, nor SG marine licences (so long as they avoid seaways). Small developments may not need EIA. Whereas fin-fish regulation is characteristically restrictive, seeing farms as potentially polluting, governance is more supportive of shellfisheries. SEPA is charged with maintaining high water quality in 'Shellfish Growing Areas' recognised under an EU Directive. Shellfish can act as vectors of micro-algal toxins, harmless to invertebrates, but poisonous to people. The UK Food Standards Agency (FSA) provides regular, publicly-funded, monitoring of these waters for the harmful algae and their toxins, and forbids harvesting when there is a risk to human health.

8 Discussion

Scottish regulation can be mapped to social and ecological licences and has proven successful in ameliorating the sea-bed impact of salmon-farms. Nevertheless, it suffers from several deficiencies. With one exception, it focuses on sites (the A-scale) rather than water-bodies (the B scale). It is top-down and rule-bound. By this we mean that both SEPA and local authorities appear increasingly to work to a set of pre-defined criteria so as to minimize regulatory costs and the risk of legal challenges. Such procedures often frustrate citizens, and the criteria can become outdated. Finally, the EIA process, and the getting of permissions, are slow, leading to calls for less regulation, with consequent risks of exceeding the carrying capacity of sea-lochs.

The exception to the focus on sites is provided by the 'Locational Guidelines', SG advice to county councils and SEPA that categorises sea-lochs according to their suitability for salmonid-farming. It does this on the basis of ecological carrying capacities estimated from seabed impact and nutrient enrichment (Gillibrand et al., 2002). However, the guidelines do not consider whole-ecosystem interactions, or synergies such as the use of cultivated mussels to remove phytoplankton generated by fish-farm waste nutrients.

Figure 3 suggests that the factors setting carrying capacities for mariculture are both complex and dynamic. Even if ecosystems themselves remain unchanged, social and economic change might influence both ecological quality thresholds and profitability. Whereas farm managers will have their eyes on profitability, and public regulators on environmental quality, local society (and the idea of social licence) embodies a wider range of interests and thus, collectively, a more holistic view.

Ostrom (2009) argues that 'common-pool' resources, such as environmental capacity for

waste assimilation and food provision, are best governed locally within a larger-scale framework. What we propose is based on Ostrom's argument and the 'Systems Approach Framework' developed during the EU research project 'SPICOSA' (Hopkins et al., 2012; Tett et al., 2011). First, decisions about capacity ought, we think, to be reached locally, in local government-supported stakeholder fora dealing with whole water bodies (e.g., entire lochs). The fora should adopt the 'Ecosystem Approach' (Atkins et al., 2011) and should seek synergies: for example, those between mussel and salmon cultivation. Second, decisions should be flexible, to reflect changing circumstances, but should not impact on long-term sustainability; thus, fora should periodically review conclusions about capacity in the light of experience. Third, scientists, regulators and managers should use best-available ecological and economic models to provide the evidential basis on which stakeholders can reach decisions about capacity.

Scottish institutions of local government and environment protection are capable of supporting such an approach, which would however require changes in both policy (see Shipman & Stojanovic, 2007) and law. The UK is moving to devolve the Crown Estate in Scotland, at least to the SG and perhaps to county councils in the main maricultural regions. Ownership of the coastal zone at this level could provide a sound basis for local management.

Norway has devolved control of fish-farming to county councils. Sandersen & Kvalvik (2014) conclude that this has been good for integrated coastal zone management, but may have reduced capacity for larger-scale ecosystem-based management. This, it seems to us, is an argument for matching multi-level governance to spatial scale. For example, the SG could (in our model) retain control of regional-scale (zone C) nutrient loadings, allocating or selling quotas to water-body fora.

Finally, the requirement for the three licences, acquired in ways appropriate to local coastal zone geography, cultures, and governance, could provide a framework for the sustainable development of mariculture in the high-latitude RREs that will be exposed as glaciers retreat.

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Appendix

Last updated December 18, 2014.

Mapping social processes to licences

Licences can be related to social (mainly governance) processes. Table 1 shows direct relationships; the need for ecological and social licences will influence an enterprise's costs and hence impact on the economic licence. Further institutional analysis would be useful.

Table 1: Mapping social processes to licences. 'CC' = 'County' Councils; 'Gov' = multi-tier governance, including EU aid, UK and SG taxes and subsidies.

agency	process	licence	scale
CC	Planning permission	social	A
FSA	Monitoring for toxic algae	social	B
Gov	Tax and subsidy regimes	economic	A
SEPA	CAR licence	ecological	A
SEPA	Shellfish	ecological	B
	Growing Waters quality		
SG	Locational Guidelines	ecological	B
SG	Marine licence	social	A

Devolution

In section 8 we referred to the current Scottish system of regulation as being increasingly rule-bound. The main point at which citizens can influence a maricultural development is by commenting on, or objecting to, the granting of planning permission. However, County Councils appear increasingly to grant permission

whenever the appropriate licences have been issued, leaving citizens feeling left out.

What's proposed in this chapter is more than devolution to a lower tier of governance. In the understanding of society developed by Habermas (1987), 'the system' comprises the institutions of governance, steered by (the use of) power, and of the market, steered by money. According to Luhmann (1989), these institutions are best seen as impersonal programs: sets of rules that behave algorithmically as they process information. The living social part of human existence takes place in what Habermas calls the 'lifeworld', in which people can engage in, amongst other things, 'communicative action'. The SPICOSA SAF understood 'fora' as lifeworld places, occasions for communicative action, where interests could be registered and claims subjected to discursive testing, leading ideally to positive-sum outcomes.

The proposed changes in consenting mariculture are in part based on a distinction between *process rules* and *content rules*. We argue for an approach in which content remains dynamic and open to discussion and modification in fora, while the process rules focus on agency and evidence: who may speak, and what criteria should be used to evaluate their claims?

Process rules and content rules

Process rules and *content rules* can be exemplified from the UK response to a European Directive (91/271/EEC concerning urban wastewater treatment). Article 6 of this Directive allowed Member States to identify areas that were less sensitive to eutrophication, so long as 'comprehensive studies indicate that such discharges will not adversely affect the environment.' The UK, wishing to use this article, followed the *process rule* and set up a 'Comprehensive Studies Task Team'. The team drafted

a procedure for identifying areas at risk of eutrophication, based on a simple (highly idealised) model for the worst-case effects of enrichment by nutrients in waste-water (CSTT, 1994). They also suggested that a water body would be at risk of eutrophication if the procedure estimated summer chlorophyll concentrations exceeding 10 mg m^{-3} . This specific threshold exemplifies a *content rule*, although one that was made universal through the UK.

The main reason for this was the need for a common standard in order to avoid local argument. Against this are three arguments. First, the threshold value might have been wrongly set. Second, the green plant pigment chlorophyll itself is not harmful. Although high chlorophyll does decrease water transparency, the crucial point is that pigment concentration is being used as a proxy for the potential disturbance to community structure and water quality that characterises eutrophication. The link from proxy to disturbance might differ depending on type of water body, or might change with time. Third, the proxy might not be adequate: a water body might be certified as ‘less sensitive’, based on chlorophyll calculations, and yet experience undesirable changes in its ecology as a result of nutrient enrichment.

These are points that might be discussed, and kept under review in, local fora, where citizens trade off extra costs (in sewage treatment) against the benefits of good water quality.

Is the ‘CSTT model’ to be seen as a process rule or a content rule? It has qualities of both. Mathematically simple, it was introduced to provide a common basis for estimating waste-water nutrient impact. However, much has changed since 1994. Knowledge has increased, and improved personal computers make it easier to apply more complex models. In a rule-based approach, the model-specifying rule would need to be changed to take account of newer, hopefully better, models. In a forum-based approach, such models become

tools available to the technical experts advising the forum, and hence might be deployed more flexibly and appropriately.

Licences, programs and codes

Licences are binary: if granted, they allow something to be done; if not granted, then that thing should not be done. Luhmann (1989) saw institutions in terms of programs and codes; the program was used to process information so as to arrive at a binary code, either (in our case) grant, or don’t grant, the licence. Any of the organisations currently involved in the regulation of mariculture might be analysed in this way. As entities, each is a complex program, capable of self-change, but for the purposes of regulation the program is the set of rules that are applied to reach a yes/no decision. Attempting a more detailed analysis of the governance system in these terms, as part of the further institutional analysis proposed above, would be useful.

Models of increasing complexity

Occam’s razor advises the cutting out of unnecessary complexity in explanations, but what is necessary? In the present context, it is what is needed for a reliable assessment of RRE carrying capacity.

During the 1990s this was done using ‘equilibrium concentration enhancement’ (ECE) models (Gowen et al., 1989; Gillibrand & Turrell (1997). These were based on simple physical and mathematical principles, explicable by analogy to a bath with open drain and both taps running. The bath’s *flushing rate* E is the rate at which water flows down the drain, divided by the volume V of water in the bath. The temperature of the bath water is a result of the mix of hot and cold water, the flushing rate, and the bathroom temperature. Ignoring the latter, the bathwater temperature will be

that of the cold inflow plus the rate Q at which heat is added by the hot inflow. The warming due to the hot tap - which can be likened to the nutrient concentration increase caused by a waste discharge - is proportional to $Q/(EV)$.

Scaling up from a bath to a sea-loch requires simplifying assumptions. The original ECE approach assumed constant E . Better physical models (e.g. Gillibrand et al., 2013) can predict flushing as a function of tide, wind and river discharge into the RRE. Biological models can convert nutrient increase into predicted increase in phytoplankton and can begin to examine the impact on the 'balance of organisms' (Tett et al., 2011). However, the Scottish 'Locational Guidelines' still use the original ECE model. Is this because the newer models are, or are deemed, still too complex for routine use? Or because of institutional inertia, so that a procedure becomes hard to change once it is embedded in a rule-set? In the forum approach models will be seen as tools not rules: tools that might be deployed during communicative action in order to test stakeholder claims about carrying capacities.

Scottish issues

The two main issues that have dominated recent Scottish debates about mariculture were not mentioned in the main text. They are the effects on wild salmon populations of farmed salmon (i) escapes and (ii) sea-lice infestations. Catches of wild salmon have been decreasing in Scotland, and although this may be part of a long-term global decline (Curd, 2010), explanations have been sought in the local effects.

It is claimed that escaped salmon interbreed with wild salmon, lowering the adaptive fitness of the offspring for life in Highland rivers. This is, mainly, an economic issue for aquaculture: more robust cages and more frequent maintenance can reduce escapes, but add to farm costs. Farmed salmon, closely packed,

can act as breeding-grounds for sea-lice, which propagate by planktonic larvae. It is claimed that wild salmon become infected as they pass farms and that this weakens the natural fish. Farmers are under pressure to treat their fish for lice, both for this reason and because of concerns about fish well-being. Most treatments however involve toxic chemicals - arthropocides - that may harm plankton if released into the water. Thus they are mostly supplied systemically (i.e. in fish feed), shifting concern to effects on benthos when the chemicals reach the sea-bed in faeces or uneaten food. Currently, the benthic effects of fish medicines (as they are called) are strictly regulated by SEPA CAR licences, while modelling research is being carried out to understand the spread of sea-lice between fish and between farms. However, to see this as a purely ecological matter is to miss sight of the tensions between the different social groups engaged in the apparently competing activities of fishing and farming. For some people, salmon are totemic and should not be caged (Brennan & Rodwell, 2008).

The problem of feed

In addition to the matter of social conflict, there is a more fundamental social-ecological question. Would it be better for Scottish society to invest resources in optimally harvesting wild salmon rather than developing salmonid aquaculture? Being carnivores by nature, salmonids need a diet high in animal matter - which they get in the wild by feeding on smaller fish and invertebrates. Caged salmon must have their food brought to them, which might seem to be a disadvantage. But it is more than counterbalanced, in the modern world, by the advantages of ownership of caged fish, which do not have to risk the natural and anthropogenic hazards to which wild salmon are exposed. Furthermore, fish bred for growth (rather than survival) can be reared

more efficiently - i.e. on less food - than wild fish. Finally, farming on an industrial scale guarantees a supply of salmon for the market.

However, there is the out-of-area problem of getting a supply of feed for caged salmon. During recent decades, they have been fed on diets made from 'forage fish' such as young herring, sardines and anchovies that contain the 'omega-3' fatty acids needed by salmon and which is advertised as one of the health benefits of eating salmon. The problem is that the global supply of forage fish, and of fish oil, is finite, and much of it is already used to make feed. Any in any case, it might be better if these little fish were directly part of human diet (Naylor & Burke, 2005). A possible solution is to include more plant material in salmon feed, and to use genetic modifications to increase amounts of the omega-3 fats in the plants. Of course, growing such plants might displace crops raised for direct human consumption, and some people might prefer to eat the plants rather than the fish. Furthermore, there are strongly held and contrasting views about both the social and ecological desirability of 'genetic engineering'.¹

Basin-scale multitrophic mariculture

Farmed fish excrete nutrients and solid wastes. Why not attempt to capture some of these, by growing nutrient-absorbing seaweed and filter-feeding mussels close to fish cages? Could this reduce pollution whilst providing an additional cash-crop? This is a matter that is relevant not only to ecological licensing, but also to farm economics (Whitmarsh et al., 2006).

¹ Humans have been altering plant genomes through selective breeding for millennia. The modern concern relates especially to *transgenic* modification, involving the introduction of a gene for a specific trait, usually taken from an unrelated organism. In addition to any biological problems, there is concern that such methods might lead to commercial ownership of genomes. See Huxham et al., 2014, for a discussion.

This would not work on the site (zone A) scale. Seaweeds or mussels, grown at sufficient density to remove significant amounts of nutrients and particles, would impede water movements to an extent that farmed fish would be at risk of de-oxygenation. This difficulty does not apply to *basin-scale multitrophic mariculture*, in which seaweeds, mussels and fish are grown at separate sites to take advantage of water-body increases in nutrients and phytoplankton. Models suggest that up to 10% of fish-excreted nutrients could be recovered through mussel harvesting of micro-algae, and seaweed cultivation might increase this percentage. However, there is little in the current regulatory framework to support such synergies.

Fish well-being

And how do farmed salmon feel, as they swim round and round in their cages? Do they sense that their ancestors lived free in rivers and oceans, journeying for thousands of miles between their freshwater hatcheries and their oceanic feeding grounds? Or are they no more than automata for turning unwanted fish into tasty dinners? Do we care, as we buy our salmon steaks over supermarket counters? Some of us do, so this touches on social licence. It also touches on economic licence: does providing humane conditions for fish cost money, or does expenditure pay back in the long-run as fewer fish are lost to disease? Anti-lice treatments may be justified on the grounds of animal welfare, but they can lead to ecological impact, which needs regulation.

Branding and social licence

Finally, *social licence* has so far been presented as relating to local opinion and hence as a set of permissions best explored through fora. However, out-of-area considerations might also need to be taken into account. Society as

a whole might demand higher animal welfare standards, and might impose these through law. And social considerations enter into food purchase. When salmon-farming commenced in Scotland, it was thought that crofters might keep a small fish cage as they might keep chickens, and so one might buy a salmon from Hamish, knowing something about the conditions in which he had grown it. A generation later, most farms are owned by large companies, who grow mainly for supermarkets. *Brand* provides, for consumers, the possibility of institutionalised trust - of knowing, or at least, believing, that company X's fish have been grown in humane conditions with minimum environmental impact, are safe to eat because they receive the minimum of chemical treatments, and, perhaps, have minimised global impact by reducing the proportion of wild fish used in feeds.

These out-of-area considerations have power insofar as consumers, making individual choices, do so in ways that have collective impact. At the local level, citizens might, also, reason that social-ecological sustainability could best be ensured by socially licensing fish-farmers with better brand images, if these led to a positive synergy between maintaining good local conditions and high-margin sales of the resulting fish.

Change

Medieval monasteries kept fish ponds, and hatcheries have been used to restock rivers for at least a century. In contrast, Scottish mariculture is young: it is only about 4 decades since turbot and salmon were domesticated. Nevertheless, during this time the industry has greatly changed both in its production methods and its economic organisation. It is likely that even greater changes will take place during the next four decades. Warmer coastal waters might favour cultivation of fish such as sea-

bream. Global competition for protein might require new diets for farmed fish, or might shift tastes towards shellfish.

As in the past, so in the future: top-down regulation might have to run fast to catch up. Social changes are very difficult to predict, and it is usual to apply a range of scenarios for the evolution of governance and society when attempting to forecast the future of marine ecosystem services (Tett & Mee, 2015). Scotland might develop differently from the remainder of the UK, perhaps in the direction of a more Nordic type of social democracy. Indeed, the regulatory model we suggest, based on local fora, would work best in a Norwegian-type society of confident individuals with strong social bonds. Be that as it may, it seems desirable that regulation of mariculture in Scotland becomes more flexible and dynamic, in order to cope with changing times.

Social licensing

Ecosystems and economies are resilient: they can recover from disturbance, unless excessively perturbed. What they are not is self-policing, as was shown by the economic events of 2008. Thus the need for society to intervene, to detect and correct ecological and economic problems as they begin to occur, and ideally to anticipate and prevent them. The three licences shown in figure 3 are distinguished by their epistemological bases, but it is only society that can evaluate the data and give permissions. Society could so configure the economy (through properly costing externalities) that the market forces the right decision by enabling only sustainable enterprises to be profitable. Or - as in Scotland at present - it could use institutions of governance to issue ecological part-licences and to combine these with a weak social license through local government's control of planning. Finally, as we've argued, society could arrange for governance to police

process rules and provide expertise, while the local community decides on the social licence.

Conclusions

Maricultural carrying capacity is, clearly, more than a matter for ecologists. It involves complex issues and ‘wicked problems’ (Jentoft & Chuenpagdee, 2009). We have argued that a top-down approach using content rules is not best suited to deal with these. Instead, based on the work of Ostrom (2009) and her colleagues, we suggest flexible and dynamic regulation based on ‘communicative action’ in local fora, drawing on expert knowledge and modelling tools, and supported by process rules operated by appropriate governance.

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