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ARTICLE

Mismatches in spatial scale of supply and demand and their consequences for local welfare in Scottish aquaculture[1]

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Abstract: Mismatches in spatial scales, or spatial disconnections between causes and effects of ecosystem degradation, can reduce resilience in social–ecological systems. These mismatches can be particularly disruptive in coastal and marine areas, where multiple social and ecological systems are multi-layered. Scotland's Western Isles have a history of local resource exploitation to meet extra-regional, larger-scale demands, which has resulted in a long process of socio-demographic decline. Salmon aquaculture is a major and expanding industry in the area, often linked to "Blue Growth". The expansion of this industry operates within and contributes to create several scale mismatches. Combining a systems approach across nested scales with a classification of scale mismatches, this work analyses the characteristics of the Western Isles salmon aquaculture industry, and it explores effects on social–ecological resilience. An extent scale mismatch between the global stocks of fishmeal species and the local capacity to respond to fluctuations is identified. The implications for this mismatch for the Western Isles are discussed. Some potential policy arrangements for incorporating matched spatial scales are considered.

Key words: scale, spatial mismatches, DPSWR, Scotland, aquaculture.

1. Introduction

Management of complex adaptive systems is a major challenge facing global society today (Holland 1992; Folke 2006; Rammel et al. 2007). The increasing recognition of human capacity to exceed planetary boundaries (Rockström et al. 2009), coupled with our growing understanding of nonlinear dynamics and regime shifts in social–ecological systems (Duarte et al. 2009), has led to an increased awareness of the requirement to build resilience. There are multiple definitions of resilience used in many different disciplines: at its essence, resilience is the adaptive capacity to respond to disruptions and make timely recovery of a specific process, and this may apply to economic activities, such as supply chains (Tukamuhabwa et al. 2015), or to ecological processes (Gunderson and Holling

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2001). Maintaining resilience in social–ecological systems is seen as critical to achieving long-term sustainability in societies. Yet, in a world of globalised supply chains, our understanding of the connections between particular activities and the ecological and social systems that support them across different spatial scales is easily obscured, undermining our ability to improve the resilience of a system.

Whether pertaining to an ecological, a social, or a social–ecological paradigm (Epstein et al. 2015), problems associated with resource management may arise "because of a mismatch between the scale of management and the scale(s) of the ecological processes being managed" (Cumming et al. 2006, p. 14). These scale mismatches are evident in the food sector, where regional or international ownership systems are driven by globalized demand and are capable of arbitraging decision processes across various producing regions, whilst relying on localized ecosystem services and social–ecological interactions (Poppy et al. 2014). At the same time, communities relying on single, export-oriented food commodities, whose management is external to the community and whose demand is influenced by global macroeconomic events, may be highly susceptible to negative social shocks (FAO 2004; UNCTAD 2012). Furthermore, there is the potential for mismanagement of natural resources as non-local producers aim for short-term output maximization in times of increased demand for the commodity, thus putting pressure on local ecosystems, which are relatively non-flexible in the short-to-medium period (Eakin et al. 2009; Ross 2013). Analytical approaches toward treatment of social and ecological scale mismatches are emerging (Cash et al. 2006; Cumming et al. 2006; Henle et al. 2010; Veldkamp et al. 2011), and classification of scale mismatches has been useful in examining governance arrangements for management of the marine environment (O'Higgins et al. 2014). Matching the scales of social and economic activities with the scales of the ecological processes supporting them is fundamental to the management and development of resilient social–ecological systems, because it ensures that any potential dramatic changes are manageable by that system (Elliott 2011). The first step for understanding these processes is to map them, thus linking the processes to their driving forces, whether these are anthropogenic (e.g., a sudden surge in demand for a product) or natural (e.g., a shift of migratory patterns).

The international trade in seafood provides a perfect example of a truly global sector. Supply of fish protein, traditionally met by capture fisheries, is now being surpassed by aquaculture (FAO 2014) as a response to growing human demand. Commercial fishery for wild salmon has declined significantly in many areas around the world and salmon aquaculture has proven to be a commercially viable alternative in Europe. In the U.S., hatchery programmes are the more common solution to the same problem. Salmon aquaculture is growing faster than total aquaculture production (Asche et al. 2013), and has been referred to as "super-chicken of the sea" (Torrissen et al. 2011). Unlike most fish species cultured globally, Atlantic Salmon (*Salmo salar*) are carnivorous. The farming process has heavily relied upon a continuous supply of fishmeal and fish oil, and the sustainability of the sector has been criticised on this basis (Rosamond et al. 2000; Deutsch et al. 2007). Though making up only a small part of the global aquaculture market, salmon aquaculture is a major industry in a few countries, including Scotland, where it represents one of the main export products and plays a major role in rural Scottish economies. The expansion of an extractive industry in Scotland is far from new; history offers several examples of management where local human welfare has been traded off against larger-scale, often national, interests, as in the case of the Highland Clearances in the 19th century (Richards 1982; Shields 2005), and the development of the aluminium and logging industries in the first four decades of the 20th century (Lea 1969; Robbins and Fraser 2003).

Within the Highland and Islands regions of Scotland, the Western Isles (WI) rely heavily on farmed salmon as a way in which to strengthen a rural local economy that has struggled in terms of economic and demographic performance (Alexander et al. 2014). While the Scottish landscape and demographic make-up today reflect the history of shifting exploitation and rural de-population, great efforts are being made to ensure the viability of fragile coastal communities, which rely heavily on marine activities (Ross 2013).

Ecosystem services are the benefits obtained by humans from nature that are used to produce societal goods and benefits through complementary assets. When taking an holistic social–ecological systems approach it is essential to consider ecosystems services, because many of these lie outside the accounting frame of standard economics. From the perspective of sustainable local or regional economic development, balancing the local benefits from economic drivers against the local costs in terms of lost ecosystem services can determine the value of development to the local area. If a driver has the capacity to secure benefits outweighing in the long term any social or environmental costs and to adapt to changing circumstances, it should be economically, socially, and environmentally acceptable and contribute to social–ecological resilience (i.e., the ability to recover from external shocks). However, where supply chains are global, economic, environmental, and social costs and benefits may not necessarily be geographically co-located and this can result in situations where local costs are borne to produce global benefits. This is particularly important when company ownership is located abroad; it operates across multiple local areas (Asche et al. 2013), and can locate more labour-intensive processes where labour costs are lower, or where ancillary services and logistics are better (e.g., Alexander et al. 2014). Thus, mapping (i.e., spatially understanding) and investigating the spatial mismatches in aquaculture is important for implementing a sustainable production system that can benefit both producers and local communities, while not overestimating or underestimating the effects on local ecosystems.

This paper focuses on two scales: local salmon aquaculture in the WI (which is nested in a national context) and its relationship with the globalised industry. We aim to (*i*) identify and characterise scale mismatches in the Scottish aquaculture industry (using salmon farming in the WI of Scotland as a case study) and their effects on regional resilience; (*ii*) demonstrate the utility of a systems approach in analysis of scale mismatches for nested social–ecological systems; and (*iii*) examine the implications for future economic development with matched spatial scales.

2. Case studies and DPSWR

2.1. The case study: salmon farming in the WI — a localised global industry

The WI are located on the northern periphery of Europe, approximately 45 km off the coast of Scotland (Fig. 1). The islands are sparsely populated (~9 inhabitants/km^2) and have experienced decades-long demographic decline, resulting in a population structure 28% older than the rest of Scotland. Economically, the WI have average earnings 12% lower than the rest of Scotland, with a similar share of population considered "income deprived" (Table 1). All but four local town council areas within the broader *Comhairle nan Eilean Siar* local government council area are considered "fragile economic areas" (Pacione 1995; HIE 2011). Despite suffering from a difficult economic outlook and demographic dynamics, the communities in the WI show a high level of community engagement and have strong cultural identities.

Whether in the form of fishery or aquaculture, the seafood sector in the WI is vital to the local economy through direct and indirect employment: approximately 22% of Scottish Aquaculture production is located in the WI (based on production volume) and the total gross value added (GVA) of aquaculture is estimated at £20 million in 2014 (Alexander et al. 2014) accounting for about 10% of local gross regional domestic product (GRDP) and employing about 1% of the local population. Salmon farming is the major focus of aquaculture in this area. According to the Scottish Salmon Producers

Fig. 1. The WI showing the location of salmon farms.

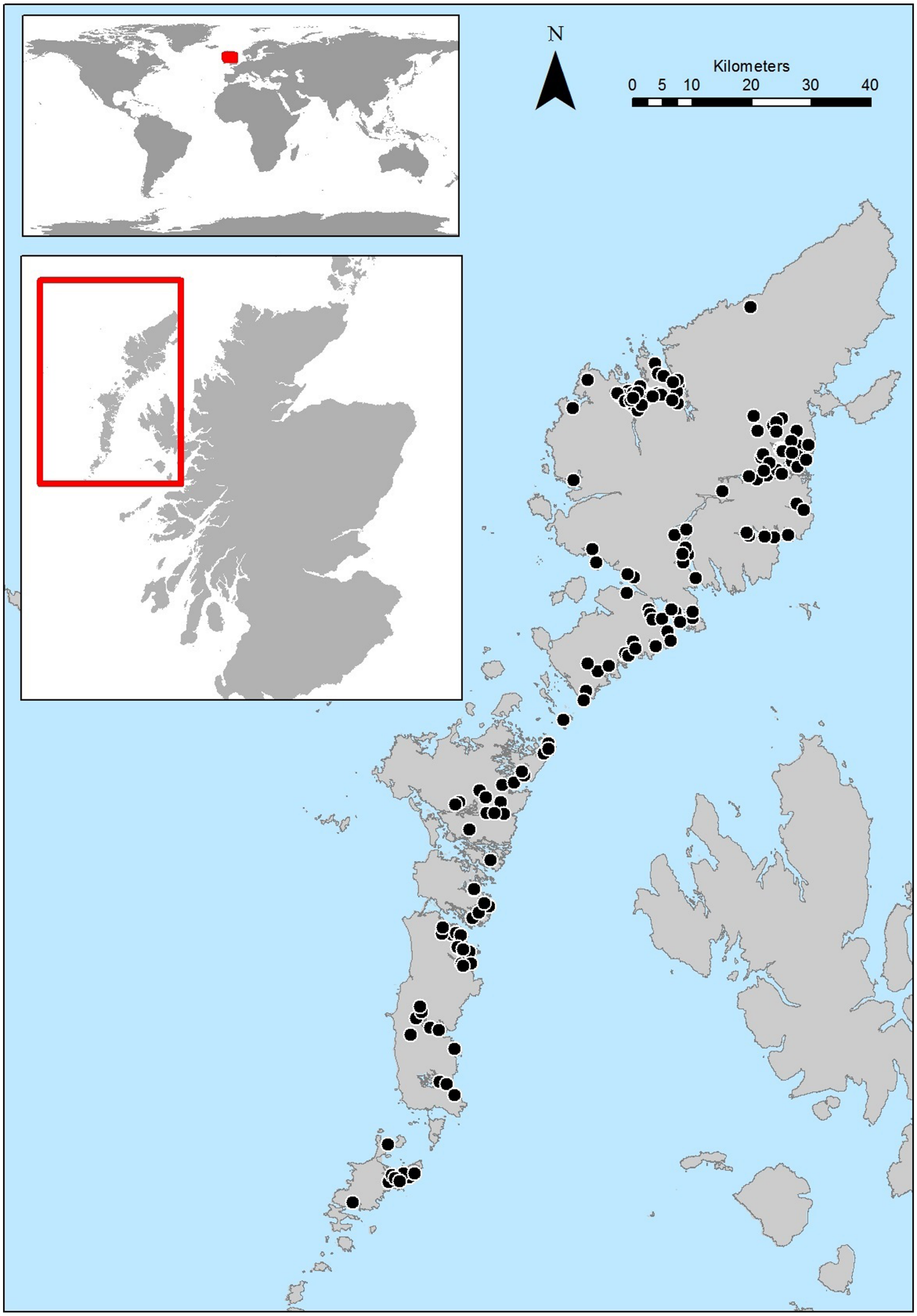


Table 1. Social and economic indicators: WI and Scotland.

Indicator	WI Council	Scotland	Difference WI – Scotland (%)
Population			
Total population, 2013	27 400	5 327 700	N/A
Total population — children, 2013 (%)	16.28	17.11	−4.85
Total population — working age, 2013 (%)	58.29	63.08	−7.59
Total population — pensionable age, 2013 (%)	25.42	19.81	28.32
Economic activity			
Percentage of working age population who are employment deprived	11	13	−15.38
Median weekly earnings (£)	438.3	498.3	−12.04
Percentage of residents employed in primary sector (excl. farm data)	3.8	1.53	148.37
Place wellbeing			
Percentage of people participating in cultural activities	80.8	69	17.10
Percentage of adults participating in volunteering organizations	41.9	30.2	38.74
Percentage of residents rating their neighbourhood "very good"	78.4	55.2	42.03

Organisation (SSPO), salaries paid out to its 264 aquaculture employees in the WI were £6 098 939 (SSPO 2012), giving average weekly earnings of £444, or about £6 per week above the mean weekly income for the region. If the national growth targets for salmon aquaculture (Scottish Government 2016) are to be met proportionally across Scotland, the WI is likely to see an annual increase in production of about 1500 tonnes per year until 2020.

Increasing market dominance by a handful of key players at the national level has been mirrored in the WI where the number of full- and part-time staff has declined by 63% while the efficiency of production (tonnes per person), though variable, has more than doubled from a minimum in 2005 (95 t/person) to a record 229 t/person in 2011, and then down to 121 t/person in 2014 (SMI 2015) as the number of individual companies involved has declined. This consolidation is in line with the global trend in the sector, which has seen larger, vertically integrated, transnational corporations increasing their market share (Österblom et al. 2015), and with few, large firms supplying as much as 93% of the Scottish farmed salmon (Marine Harvest 2015). At current efficiencies described above, the planned increase in salmon production would result in an additional 12 jobs annually in the WI aquaculture sector until 2020.

2.2. Using the DPSWR framework to identify scale mismatches

The Driver Pressure State Impact Response (DPSIR) framework, was developed in the late 1990s by the Organization for Economic Co-operation and Development (OECD 2003) as a tool for the analysis of environmental problems. DPSIR is a causal framework that can be used to describe the economic, ecological, and social flow of effects stemming from anthropogenic influence on the environment. According to the framework, there is a chain of causal links starting with driving forces (needs) leading to pressures (because of human activity), and in turn to altered states (of the environment) and therefore impacts on ecosystems and societies, which eventually lead to management responses, which may be directed at any other element of the system. The DPSIR framework was further refined by Cooper (2012) who replaced the "I" for Impact with a "W" for (changes in) welfare, re-defining the components of the framework (Table 2) to formalize the relationship between the benefits accruing from drivers and the environmental costs of welfare changes caused by changes in environmental state (Cooper 2012). See Patricio et al. (2016) for a full treatment of development and refinements to the DPSIR.

Table 2. Definitions of DPSWR information categories as set out by Cooper (2012).

Information category	Definition
Driver	An activity or process intended to enhance human welfare.
Pressure	A means by which at least one driver causes or contributes to a change in state.
State (change)	An attribute or set of attributes of the natural environment that reflect its integrity relative to a specified issue (or change therein).
Welfare	A change in human welfare attributable to a change in state.
Response	An initiative intended to reduce at least one impact (state or welfare change).

Based on the amended framework (Cooper 2012), O'Higgins et al. (2014) proposed a classification of scale mismatches, identifying two types of mismatch based on their scale relative to the spatially fixed scale of legislative response. "Extent" mismatches were classified as those where aspects of the ecological system lay outside the jurisdiction of a response, for example, where part of a fishery lies outside the exclusive economic zone of a nation. "Grain" mismatches were those where ecological aspects occurred within the jurisdiction of the response but at scales smaller than those where enforcement of legislation could be implemented, for example, where breaches in regulation are widespread within a national jurisdiction but there is insufficient resource to enforce the regulations on an individual basis.

In this study, we applied the DPSWR framework to salmon aquaculture in the WI to describe the economic, ecological, and social flow of effects, explicitly recognising local aquaculture as a nested subsystem within the wider global aquaculture industry. We specifically distinguished between local and global phenomena and, for the purposes of analysis, we used the subscripts LOCAL and GLOBAL to distinguish between the DPSWR elements at different scales. Thus, D_{LOCAL} is the proportion of the benefits from aquaculture activities that accrue to the WI, while D_{GLOBAL} is the size of the global salmon aquaculture industry. Following O'Higgins et al. (2014), we then identified mismatches relative to the scale of response — in this case, R_{GLOBAL} and R_{LOCAL} are the relevant frames of reference. Extent mismatches were identified where essential elements of the social–ecological system were exogenous, lying beyond the boundary control of R_{GLOBAL} and (or) R_{LOCAL}. Grain-scale mismatches were identified where DPSWR elements were endogenous but occurred on scales too fine to be effectively managed. Figure 2 illustrates the nested local and global DPSWR and scale mismatches conceptual model.

3. DPSWR at work

3.1. Results of DPSWR assessment

The elements of DPSWR at the global scale for our case study are summarised in Fig. 3.

3.1.1. D_{GLOBAL}

Aquaculture is the fastest growing food-producing sector in the world. It provides multiple benefits in terms of producing food, creating employment, and generating revenue. In 2012, global aquaculture production attained an all-time high of 90.4 million tonnes, worth US$144.4 billion. In the same year, world food fish aquaculture production was 66.6 million tonnes, having doubled from 2000 values (FAO 2014). The key underlying driver of growth in aquaculture is demand for fish protein to feed an increasing global population (Tidwell and Allan 2001). While internationally most aquaculture is based on lower trophic level species, salmon are a high trophic level species and, as such, production of meal-based food is the major input and input cost, oscillating between 41% and 48% of total costs (Tacon and Metian 2008; Marine Harvest 2015). As an economic sector, despite the high cost for inputs, salmon aquaculture remains viable due to the high value of the final salmon product, and a

Fig. 2. The DPSWR framework and scale mismatch classification.

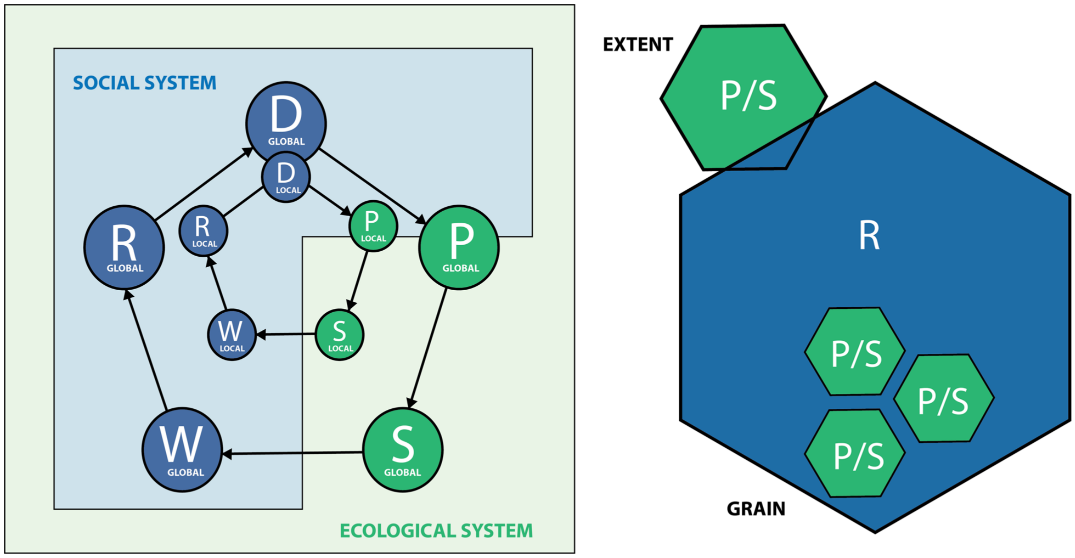
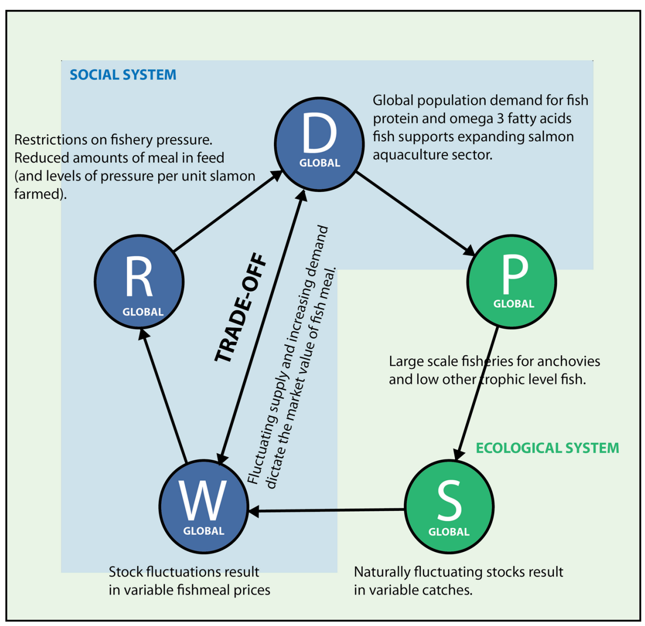


Fig. 3. DPSWR for salmon aquaculture at the global scale.

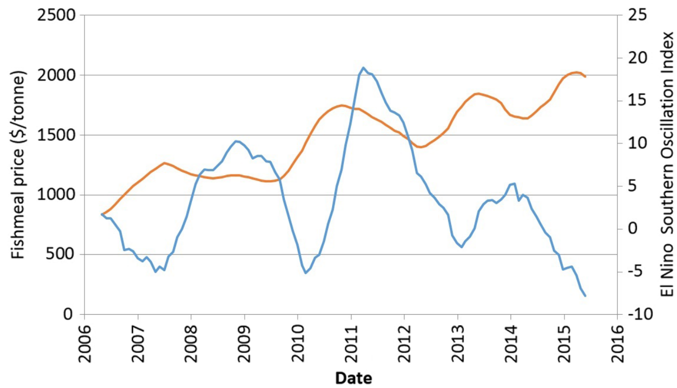


demand largely still untapped, both in the European Union and globally, although this demand is highly volatile, thus exposing firms to periods of contraction (Asche et al. 2011).

3.1.2. P_{GLOBAL}

Globally, the main pressure caused by salmon aquaculture is the removal of fish stocks. At the global scale, the requirement for fishmeal in the salmon industry (and for other

Fig. 4. Time series of fishmeal price (yellow) and El Nino Southern Oscillation Index (blue).



species that do not necessarily rely on fishmeal, such as carp) is met by commercial fisheries of species at the base of marine food webs primarily through the Peruvian anchovy fishery, the largest single-species fishery in the world (Christensen et al. 2014). Fishmeal is a global commodity; between Peru and its neighbour Chile, the anchovy fisheries off the West coast of South America provide 47% of global supply and these are the main locations of pressure caused by the global salmon industry (Tacon and Metian 2009). These South American fisheries make up about 20% of European fish feed (Huntington and Hasan 2009). It should also be noted that during times of resource scarcity, the market will adjust to ensure that those industries which require fishmeal (salmon rather than carp) continue to receive a relatively stable flow of this input, at least until ecological limits are reached. Despite this ability to divert fishmeal from other industries, the farmed salmon sector is still facing stably high and volatile prices, and planned production expansions in other countries, most notably in Norway, will put more pressure on these commercial fisheries (Graziano et al. 2018). Alternatives, such as soy beans, are likely to become widely available in the medium, rather than the shorter, run (GlobeFish 2016).

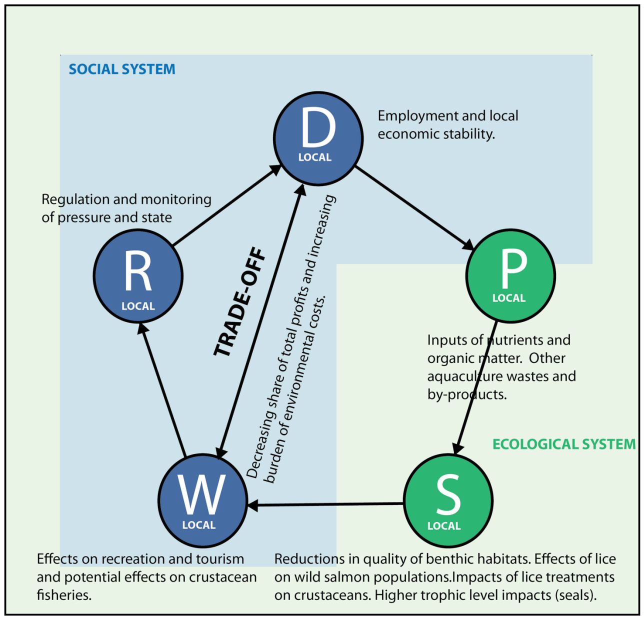
3.1.3. S_{GLOBAL}

The size of stocks (S_{GLOBAL}) of the two largest anchovy fisheries (Peru and Chile) is highly variable, depending not just on fishery pressure, but also critically on environmental fluctuations. These fisheries are particularly productive due to their location in eastern boundary currents and the associated upwelling of nutrients, which fuel primary production (Freon et al. 2008). The rate and extent of upwelling and the productivity of the fisheries are in turn controlled by unpredictable atmospheric forcing, and subject to the well-known El Niño, La Niña (ENSO) cycles (Chavez et al. 2003; Freon et al. 2008).

3.1.4. W_{GLOBAL}

Because the Chilean and Peruvian anchovy stocks make up such a high proportion of global fishmeal, these environmental fluctuations result in variable annual levels of anchovy catch, affecting the price of anchovies and fishmeal globally. In this case, the changes in human welfare attributable to changes in environmental state are felt directly through markets for anchovies and fishmeal, and the costs are borne globally by the salmon aquaculture industry, in competition with other aquaculture industries, such as trout, sea bream, and tilapia. Figure 4 shows the trend in fishmeal prices (W_{GLOBAL}) over the last decade. The growth in demand for fishmeal, caused by both human population

Fig. 5. The DPSWR at the local scale for salmon aquaculture in the WI.



and demand for protein, results in an increasing trend in price. Price maxima are associated with catch and stock levels ultimately determined by climatic, ENSO events.

3.1.5. R_{GLOBAL}

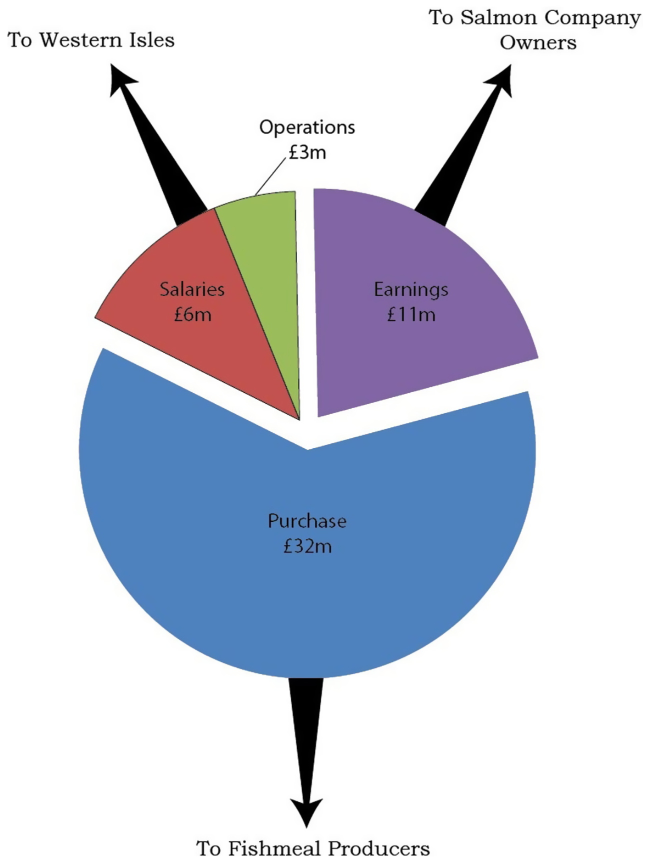
Responses to fluctuations in stocks of anchovies have included strict regulation of the Peruvian anchovy fishery introducing quotas to restrict the fishing pressure (Aranda 2009; Freon et al. 2014). The fishery operates under a catch share and quota system that treats anchovies caught commercially for fishmeal separately from those caught by artisanal fishers for human consumption and can be modified to decrease the likelihood of severe collapses (Christensen et al. 2014). The salmon aquaculture industry has responded to the fluctuations in anchovy stocks through efforts to develop alternative feeds (Rosenlund et al. 2001) replacing fishmeal with insects, algae, and transgenic plants, yet no practical solution has been developed to entirely replace the inclusion of fishmeal and fish oil in diets while maintaining fish health and welfare. However, inclusion of oils from plant sources that have been genetically modified to produce omega 3 fatty acids may change the situation, but only in the medium term (Betancor et al. 2015; GlobeFish 2016). Despite considerable success with substitution, fishmeal and fish oil remain essential components in the pelleted feeds for salmon (Tacon et al. 2011; Ytrestøyl et al. 2015), and further research to overcome nutritional limits is needed (Tocher 2015).

The elements of DPSWR at the global scale for our case study are summarised in Fig. 5.

3.1.6. D_{GLOBAL}

At a local level, the Scottish Government has recently laid out plans for major expansion of salmon farming. Furthermore, the Outer Hebrides Local Development Plan suggests that local policy is to continue to grow the industry with proposals for fish farming developments (accounting for an additional 1500 tonnes of fish per year), which have the potential to sustain and grow the industry, being viewed positively. This is largely

Fig. 6. Approximate apportionment of revenue from the WI aquaculture industry based on annual reports from major Scottish Aquaculture companies.



based around a need to improve the social, economic, and environmental well-being of those who live in the Outer Hebrides, an area currently suffering from difficult population dynamics and economic outlook.

Though the total value of the salmon industry output in the WI is increasing, the proportion of that value retained within the area is decreasing with increasing industrial efficiency. At present, for example, the annual pre-tax earnings of major companies are the same as the amounts received in salary by workers on the farms (SSC 2014). Figure 6 illustrates how the proportions of salmon farm revenue are divided between, owners, fishmeal producers (D_{GLOBAL}), and local workers (D_{LOCAL}). As the industry continues to develop and employ more people, efficiency improvements mean that the proportion of earnings from the production operations accruing within the WI will diminish as the profits of the shareholders increase. At present, the costs of salaries and operation of major salmon producers are of the same order of magnitude as the annual earnings of the company, while most of the capital flows to the purchase of increasingly expensive fishmeal.

3.1.7. P_{LOCAL}

Salmon aquaculture results in several local environmental pressures (P_{LOCAL}). These pressures include increased quantities of organic matter and increased loadings of nutrients, such as nitrogen and phosphorus (Brown et al. 1987; Wu 1995). Fish farms may also act as a source of sea lice infection for wild salmon populations, although this remains controversial (see Krkosek et al. 2014 and literature cited therein) and concerns exist around the issue of introgression threatening the genetic integrity and life-history traits of wild salmon stocks (Le Cam et al. 2015). Pesticides commonly used in control of sea lice may have local impacts on crustaceans (Burridge et al. 2010). At higher trophic levels, pinnipeds are acoustically deterred from fish farms (Götz and Janik 2013) and in some cases seals are shot.

3.1.8. S_{LOCAL}

These environmental changes can affect many aspects of food chains around aquaculture activities. Organic deposits from feces and food waste adversely affect several benthic habitats and biotopes (Wilding and Hughes 2010; Wilding 2011) and also individual components of benthic habitats, including microbenthic organisms (Lejzerowicz et al. 2015) and the megabenthos (Wilding et al. 2012). High concentrations of nutrients, such as nitrogen can promote excessive algal growth resulting in severe reductions in water quality and eutrophication. However, eutrophication events that can be attributed to aquaculture are relatively rare globally and especially so in the UK (Davidson et al. 2014), but can disrupt local ecosystem services and their associated industries, as happened in 1998 and 2009 in Scotland (Hastings et al. 1999; Murray et al. 2010). Pressures on marine species, such as wild salmon, crustacean species, and marine mammals may alter food-web structures and ecosystem functioning. The exposed coastlines and flushing actions of the Atlantic Ocean mean that measurable changes in the state of the environment are mostly confined to the areas immediately around the salmon cages. In the absence of new measures to reduce the pressures, changes in environmental state (S_{LOCAL}) are likely to scale proportionally with expansion of the industry in the area.

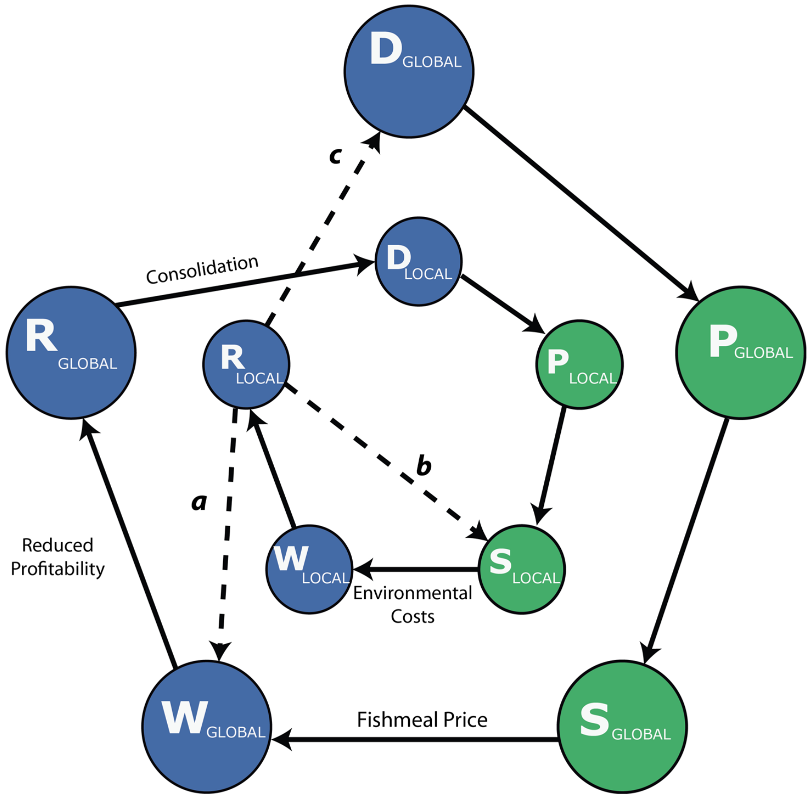
3.1.9. W_{LOCAL}

While there is much quantitative ecological information concerning the effects of salmon farming on the environment, the economic consequences (W_{LOCAL}) of these environmental changes are not as well understood and remain an unquantified externality, although previous assessments of the direct costs associated with infection salmon anaemia outbreaks have recorded remediation costs of £33 million (2016 value) in Scotland (Hastings et al. 1999). While the visual and benthic impacts of salmon aquaculture are already considered and traded off implicitly against the value of development in the consenting process, potential local effects on the supply of ecosystem services and their environmental and economic impacts may include knock-on effects on angling, wildlife tourism, and recreational fisheries (involving cultural ecosystem services) and commercial crustacean fisheries (involving provisioning services). Similarly, the social consequences of changes to the marine environment are not well known or understood, but there is the potential that cultural ecosystem services provided by the marine environment may be lost, such as health and recreational benefits provided by, for example, good-quality bathing water.

3.1.10. R_{LOCAL}

Responses to state changes and welfare impacts are mostly applied through regulation and legislation. Several bodies are responsible for aquaculture in Scotland. Consents must be obtained from Marine Scotland, the Crown Estate, the Scottish Environment Protection Agency (SEPA), and local planning authorities. Scottish Natural Heritage (SNH), as the statutory guardian of Scotland's natural heritage, must also be consulted regarding environmental and visual impacts before consents are granted. The Fish Health Inspectorate (Marine Scotland), SEPA, the Health and Safety Executive, the Food Standards

Fig. 7. Mismatches in the nested global and local DPSWR analysis. The locations of the mismatches are indicated by dashed lines *a*, *b*, and *c*.



Agency (FSA), and local authorities are involved in regulating the operational aspects of aquaculture. Finally, the Fish Health Inspectorate and the FSA are key bodies in respect of food safety.

Carrying out an Environmental Impact Assessment (EIA) is an integral part of the legal process of determining planning applications for marine aquaculture under the *Environmental Impact Assessment (Fish Farming in Marine Waters) Regulations 1999*, the Scottish Statutory Instrument that enables the *EU EIA Directive (85/337/EEC as amended in 1997, 2003, 2009 and 2014)*. These regulations require that an EIA be undertaken when any part of the proposed development is in a sensitive area, will hold a biomass of 100 t or more, or where the development will extend to 0.1 ha or more of the surface area of marine waters. This includes changes or extensions to existing developments.

3.2. Applying the mismatch typology

Figure 7 illustrates the locations of scale mismatches across the nested DPSWR. At the global scale, the links between drivers, pressures, state, and welfare are mediated within the global market for fishmeal. In tandem with the growing driver, the demand for protein and price of fishmeal, the pressure on global lower trophic level fish species (P_{GLOBAL}) is likely to continue to increase, and the existing natural fluctuations in stock size for small pelagics are likely to be compounded by increased pressures resulting in continuing stably high but volatile prices (W_{GLOBAL}). The consolidation of the local industry from many players to a few large companies may be viewed as an economic response (R_{GLOBAL}) to reduce the impact of rising fishmeal prices by achieving economies of scale locally, that is, only larger scale companies have been able to survive in the global competition for the fishmeal resource. This has resulted in an extent scale mismatch where the employees of fish farms and the inhabitants of the WI lack any capacity to respond to the global forces (population, climate, and remote fishing pressures) that control W_{GLOBAL} and determine the profitability of the roles in which they are employed (Fig. 7, arrow labelled *a*).

With further development as planned, the local growth in production of salmon will cause a proportional increase in the fluxes of nutrients and organic matter to the region P_{LOCAL}, associated with increasing changes in S_{LOCAL} (reduced environmental conditions). The environmental burden of the industry and its environmental costs W_{LOCAL} will increase while increasing efficiency, which means that the share of total benefits $D_{\mathrm{LOCAL}} : D_{\mathrm{GLOBAL}}$ may decrease (depending on the behavior of, and incentives offered to, fish farmers) making the tradeoff between aquaculture and the environment less favorable from the local perspective. There is little capacity for response to environmental degradation at the local scale other than the local planning regime, which is largely unresponsive to post-authorisation impacts and this results in a grain-scale mismatch (Fig. 7, arrow labelled *b*). Critically, if P_{LOCAL} or S_{LOCAL} begin to exceed the thresholds set out by national legislation, W_{LOCAL} will begin to incur real internalized economic costs adding an additional burden to the local industry (reducing the profitability of D_{LOCAL} and D_{GLOBAL}). Given the constraints of ever-increasing prices, and competition from less heavily regulated nations, local responses adversely affecting the global profitability are highly unlikely to be pursued effectively resulting in an extent scale mismatch between R_{LOCAL} and D_{GLOBAL} (Fig. 7, arrow labelled *c*).

4. Discussion

There is a long history of social and economic decline in the WI and historic precedents have favoured the commodification and export of Scottish natural resources at the expense of local societies. The early aquaculture industry in Scotland was heavily subsidized by the government (Wood et al. 1990) as it was seen as a major potential player in the economy of rural Scotland. The global market for fishmeal with its volatile and high-trending prices has resulted throughout the salmon aquaculture sector in the consolidation of the industry from many smaller companies to a small number of large companies. The economies of scale resulting from this consolidation, combined with a strong brand image and relatively high-quality product, have allowed Scottish aquaculture and the WI local industry to remain competitive, although translating into a reduction of the relative share of benefits to the local community, and an increasing out-flow of benefits from the WI. This consolidation has also resulted in scale mismatches in local response options (R_{LOCAL}). Aquaculturists in the WI have no control over global drivers (D_{GLOBAL}), nor do they have any influence on the price of fishmeal (W_{GLOBAL}), and this leads to limited capacity for the local industry to adapt independently to changing market conditions, leaving it vulnerable to shocks. Similarly, at the local scale, there is little capacity for adaptation to less sudden changes, such as long-term national objectives. Fish farms already endeavour to keep environmental pressures (P_{LOCAL}) to a minimum (waste feed represents an inefficiency to the farms and is therefore minimised) and the local pressure–state relations are regulated nationally under existing licensing conditions.

The ambitious national growth targets for the Scottish industry mean that there is little doubt that aquaculture in the WI will continue to grow, at least until 2020. Because of indirect and induced economic effects, there is also no doubt that the growth of the sector within the WI will introduce welcome (economic) benefits to the area in terms of new jobs.

The mismatch classification has identified parts of the system on which local responses cannot act. To maintain adaptive capacity and enhance resilience, the WI aquaculture industry should therefore consider actions targeted to parts of the system where influence can be exercised. The major challenge to the salmon aquaculture industry globally is the price of fishmeal and fish oil, and the current lack of a feasible alternative. Consequently, the industry is critically reliant on the maintenance of global small pelagic fish stocks (S_{GLOBAL}), which are likely to face increasing pressures (P_{GLOBAL}) as global demand continues to rise. Continuity of the stocks, and the industry (globally and locally), therefore depends on management of these two system components.

While the WI cannot directly influence the sustainability of global pelagic fish stock, its reputation and profitability are dependent on its high-quality image. Recent research suggests that consumers will pay a premium for sustainably farmed aquaculture products (Van Osch et al. 2019), and similar results have been demonstrated for wild-caught products through seafood certification processes, such as those under the Marine Stewardship Council Schemes. Therefore, local producers could potentially enhance its value and reduce impacts on global stocks by sustainably sourcing and certifying its feed products. In a similar way, diversification through integrated multi-trophic aquaculture (co-culture of shellfish with salmon) offers the potential to buffer against volatility in fishmeal prices (by providing an additional product) as well as improving environmental sustainability through more efficient use of nutrients in aquaculture systems and securing the premium that comes with it.

An alternative, but more ambitious, solution lies in addressing P_{GLOBAL}, that is, decoupling the driver from the pressure on small pelagic stocks. This strategy implies the development of alternative sources of feed. Critically, these include fish oils rich in omega 3 fatty acids for which there is currently no alternative. While lab-scale culture of omega 3 oils is technically feasible, commercial-scale operation for aquaculture is currently not cost effective. From a longer-term perspective, and building upon the success of community energy (Haggett et al. 2012) the WI have the potential to follow the example set by other energy-rich regions, such as Iceland, in hosting electricity-intensive productions, such as greenhouses (Graziano et al. 2017), which could provide a cost effective alternative to globally sourced fish oils eliminating the scale mismatches and bringing relative autonomy to the WI aquaculture sector.

Irrespective of scale mismatch, adaptive capacity, and resilience, there are several avenues by which the WI aquaculture industry could more evenly distribute benefits to the region. Scotland as a region, and the WI as one of its constituents, has the opportunity to capture further benefits from the expansion of the local value-chain in the salmon sector beyond the transformation of its final (or intermediate) product. For example, the WI can exploit the potential for developing a local supply-chain servicing farmed salmon, such as kit-production and analytical services, or other food and tourist sectors, which may become themselves export goods and services or attractions for tourism, similarly to the strategies implemented by the Orkney and Shetland islands (Courtney et al. 2006; McAuley and Pervan 2014). These sectors represent the second part of a "twin-engine economy" based on both natural resources and high tech sectors (Alexander et al. 2014).

Our analysis in this paper has focussed on issues of scale in the global and local salmon aquaculture industry, but such issues are also likely to be found in relation to natural resource use or extraction in other developed (and potentially developing) countries. As with many other natural resource sectors, the WI aquaculture sector is a small part of a large global economic system dictated by supply and demand, and regulated by national government. The critical mismatches and potential responses identified above to mitigate loss of adaptive capacity and to increase local equity within the salmon aquaculture industry require the existence of effective governance mechanisms at appropriate spatial scales, which, as of 2016, the WI do not posses (Graziano et al. 2017).

The results of the recent referendum on the U.K. exit from the European Union and the recent U.S. presidential election illustrate an international trend toward fragmentation and isolationism, which has been attributed to disenfranchisement from central government following the world's first truly global economic crisis (Inglehart and Norris 2016). In this era of globalisation, there is a real need to understand how social–ecological systems are tied at global, national, and local scales. Systematic analysis of scale offers the potential to identify scale relations between components of social–ecological systems, to pinpoint mismatches, and provide a rational basis for the (re)design of governance institutions as well as policies directed at appropriate system components and levels.

5. Conclusions

The WI offer an insight into the benefits and risks associated with natural resource use and (or) extraction. In this case, the environmental externalities — the costs — are likely to grow proportionally as production increases, while the proportional trend of economic benefits remaining within the island is one of decline. There is a risk that aquaculture will become a decreasingly attractive prospect for such rural locations, especially when in competition with other Blue Growth sectors for either space or institutional support.

While other authors have criticised salmon aquaculture on the grounds of environmental sustainability (Rosamond et al. 2000; Deutsch et al. 2007), the nested DPSWR approach we have used here has proven useful in elucidating the social and economic implications of scale mismatch between the nested global and local aquaculture systems. We argue that explicit consideration of scale mismatches may help to inform decisions for more resilient future development and that the novel combination of scale mismatch classification with DPSWR on nested spatial scale provides a useful basis for such analysis.

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