Aquaculture 458 (2016) 82–99

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Review

Trends during development of Scottish salmon farming: An example of sustainable intensification?

Tim Ellis [a,*], James F. Turnbull [b], Toby G. Knowles [c], Jeff A. Lines [d], Neil A. Auchterlonie [a,1]

[a] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Barrack Road, The Nothe, Weymouth, Dorset DT4 8UB, UK
[b] Institute of Aquaculture, University of Stirling, Stirling, Stirlingshire FK9 4LA, UK
[c] University of Bristol, Cabot Institute and School of Veterinary Science, Langford, Bristol BS40 5DU, UK
[d] Silsoe Livestock Systems Ltd, Wrest Park, Silsoe, Bedford, Bedfordshire MK45 4HS, UK

ARTICLE INFO

Article history:
Received 6 November 2015
Accepted 7 February 2016
Available online 9 February 2016

Keywords:
Animal welfare
Aquaculture development
Environmental impacts
Performance indicators
Salmon farming
Sustainable intensification

ABSTRACT

Commercial farming of Atlantic salmon in Scotland started in 1969 and has since expanded to produce >179,000 t year^{-1}. A government department has published annual statistics and information on the seawater and freshwater sub-sectors of the Scottish salmon farming industry since 1979, and this review collates and discusses metrics covering aspects of production, farm sites and systems, fish performance, socio-economics and environmental pressures. Trends illustrated in this case study of aquaculture development include: initial increases in numbers of farms and companies, followed by decreases due to industry consolidation; increases in average farm size, and productivity of systems and employees; increases in survival, size at age and productivity of fish (yield per smolt, ova per broodstock); reduced dependence on wild stocks for ova. This case study also illustrates the importance of disease management, control of biological processes to overcome natural seasonality (i.e. production of out-of-season smolt), and the international nature of aquaculture. Improvements in fish survival, growth and productivity are attributed to progress in vaccination and health management (including fallowing), husbandry, system design, feed formulation and provision, and introduction of technology and mechanisation. Salmon farming is discussed in relation to the challenging strategy of "sustainable intensification". Improved growth and survival over a period of increasing rearing unit size, farm size and output and decreasing relative staff input counters the common assumption that intensification compromises animal welfare. The value of capturing time series data on industry wide metrics is illustrated as it enables identification of trends, underperformance and bench-marking, as well as assessment of resource use efficiency, environmental pressures, and ultimately sustainability.

Statement of relevance: This review is an original collation of a comprehensive set of time series of official statistics on an entire, discrete and regionally important sector of commercial aquaculture.

Contents

* Corresponding author at: Cefas Weymouth Laboratory, Barrack Road, The Nothe, Weymouth, Dorset DT4 8UB, UK.
E-mail address: tim.ellis@cefas.co.uk (T. Ellis).
[1] Present address: IFFO The Marine Ingredients Organisation, Unit C, 22 Amelia Street, London, SE17 3BZ, UK.

http://dx.doi.org/10.1016/j.aquaculture.2016.02.012
0044-8486/

1. Introduction

Humans have traditionally relied upon capture fisheries for supplies of fish and shellfish. However, while production from fisheries has remained static over the last three decades, production from aquaculture has increased 12-fold (8.6% year^{-1}), providing 42% of seafood in 2012 (FAO, 2014). Continued expansion of aquaculture is viewed as a key strategy to ensure global food and nutrition security (Godfray et al., 2010; Beveridge et al., 2013) and close the "fish-gap", i.e. the disparity between seafood supply and demand (FAO, 2007). It is noteworthy that the production growth of fed farmed species (i.e. reliant on external sources of feed) has outstripped that of non-fed species (i.e. feeding on in situ food sources) (Shepherd, 2012).

The global production of farmed Atlantic salmon (*Salmo salar*), a fed aquaculture species, has followed a similar trajectory to that of global aquaculture and is the fastest growing food production system in the world (Shepherd and Little, 2014). Reported production has increased from just 1 t in 1964 in a single country (Norway) to >2 million t in 2012, across 11 different countries (Fig. 1). The apparent success of Atlantic salmon aquaculture (hereafter termed salmon farming) has been attributed to i) its ease of culture, ii) development in areas encouraged by governments, iii) development at a time coinciding with the rise of supermarkets and consumer interest in healthy eating, and iv) product attributes, i.e. a high fillet yield and a product that can be sold in diverse forms, e.g. fresh, sushi, cured, ready-meals, frozen (Forster, 2010; Asche and Bjørndal, 2011; Seafish, 2012). Farming has changed salmon from a luxury product to a global commodity that is an affordable staple seafood product for consumers in the industrialised world (Pelletier and Tyedmers, 2007; Forster, 2010).

Salmon farming has spread from Norway across the natural species range of the northern Atlantic, and outside into both the northern and southern Pacific (west Canada, Chile, Australia). In 2012, the main producing nations were Norway, Chile and the United Kingdom (60%, 19%, and 8% respectively) (Fig. 1). Salmon farming is continuing to expand, with increases in global tonnage of 20% in both 2011 and 2012. In 2013, the production of farmed Atlantic salmon was 1500 times greater than the reported fishery catch (NASCO, 2014). With the recognised need to expand global aquaculture, salmon farming provides an ideal case study, to identify and discuss trends and issues pertinent to aquaculture development.

1.1. The issues

In a prominent paper discussing strategies to meet the challenge of increasing demand for food caused by human population growth and higher consumption rates, Godfray et al. (2010) highlighted five key strategies. In addition to *expanding aquaculture*, the other strategies refer to increasing yields from food production chains by *adopting productive farming methods*, *selecting genotypes* best suited to farm conditions, *reducing waste*, and *changing human diets* to consumption of products from trophic levels and farming systems that maximise conversion efficiency. Godfray et al. (2010) also emphasised that implementing strategies of increasing agricultural (and aquacultural) food production should not be de-coupled from environmental considerations. The term "Sustainable Intensification" (SI) has been introduced to portray increasing the efficiency of agricultural food production through increases in yield relative to resource inputs (e.g. space, water, feed, energy) and outputs (e.g. greenhouse gas and eutrophication emissions, effects on biodiversity). SI therefore recognises that no food production

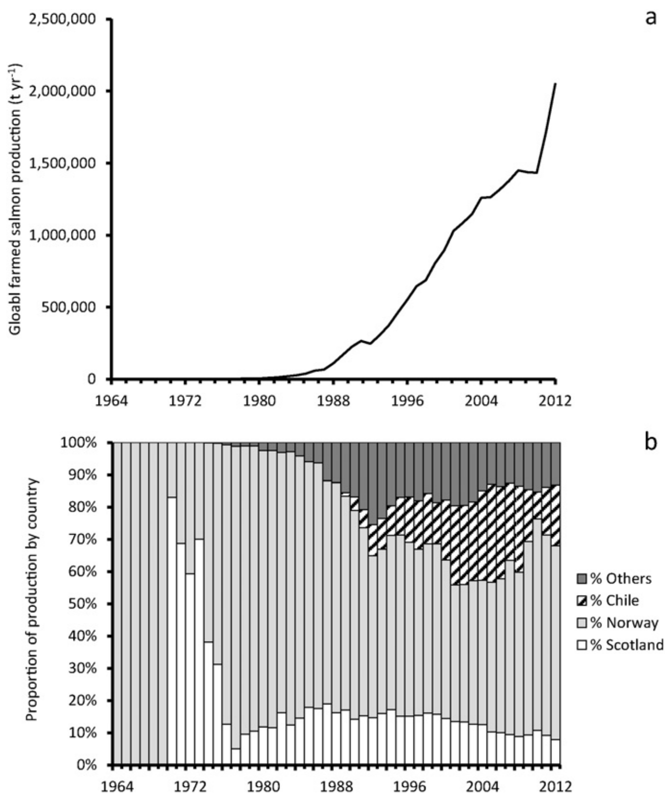

Fig. 1. Time series of global farmed Atlantic salmon production (data for 1950–2012 from http://data.fao.org (accessed 19/01/15) with nil production reported 1950–1963). a: harvest (t year^{-1}). b: Proportion contribution from Scotland, Norway, Chile and other countries (i.e. Canada, Faroe Islands, Australia, United States of America, Ireland, Russian Federation, France, Spain, Iceland, Sweden, Turkey and Denmark).

chain is environmentally benign, and the focus should be on increasing production in conjunction with reducing pressures on the environment. Garnett et al. (2013) argue that SI also needs to safeguard animal welfare, the nutritional value of products, and rural economies.

1.2. Scottish salmon farming as a case study

Assessing the past history of aquaculture and trends will help to understand the present and plan for the future (sensu Hawkins et al., 2013). The Scottish salmon farming industry provides a suitable case-study of aquaculture development for a number of reasons:

- Extensive time series of annual statistics (up to 45 years) are available for the entire industry covering production, farm sites and systems, fish performance, and some socio-economic and environmental indicators. The statistics have been published within annual reports on the commercial Scottish finfish farming industry since 1979 by the competent authority (i.e. the body responsible for official control) for fish health in Scotland (www.scotland.gov.uk/Topics/marine/Publications/stats/FishFarmProductionSurveys; accessed 5 March 2015). [The Norwegian Directorate of Fisheries also publishes time series of statistics (from 8 to 20 years) for the Norwegian aquaculture industry (http://www.fiskeridir.no/english/statistics/norwegian-aquaculture/aquaculture-statistics/atlantic-salmon-and-rainbow-trout accessed 5 March 2015) with some earlier data available in the literature (Tilseth et al., 1991)].
- Scotland is a major producer of salmon. FAO reported production tonnages (Fig. 1) show that the UK (with production almost entirely in Scotland) was the leading salmon producing country in the early 1970s, then was second behind Norway until 1999, since when Chilean production has exceeded that in Scotland (apart from in 2010).
- The Scottish Government has aspirations for salmon harvest to continue to increase (by 28% between 2012 and 2020) and expansion of the industry is valued due to the income generated and employment in rural areas (Marine Scotland, 2014).
- Farmed salmon is the most popular fresh fish with UK consumers (Seafish, 2011), reflecting price accessibility (Naylor and Burke, 2005) and consumer preferences. Farms provide a reliable and consistent source of supply suited to processing and retailing (Naylor and Burke, 2005; Asche and Bjørndal, 2011; Shepherd and Little, 2014).
- Intensive aquaculture, and salmon farming in particular, have attracted criticisms and a preponderance of bad press (Naylor and Burke, 2005; Amberg and Hall, 2008; Shepherd and Little, 2014). The various pressures that salmon farming methods place on the environment (through discharge of nutrients, organic particulates and chemicals; pathogen and escapee interactions with wild stocks; culling of predators; use of industrial fish in feed) and on fish welfare have been highlighted for Scotland (e.g. FAWC, 1996; Scottish Executive, 2002).

Freshwater salmon culture started in the UK (and elsewhere) in the 19th century producing juvenile salmon for stocking rivers (www.fao.org/fishery/culturedspecies/Salmo_salar/en accessed 5 March 2015; Forster, 2010). Commercial salmon farming, i.e. on-growing in seawater in captivity until harvest, started in Norway and Scotland in the late 1960s with the introduction of floating net-pens (sea-cages) (Munro et al., 1980; Tilseth et al., 1991; Forster, 2010). In 2014, there were 356 Scottish farms which employed 1,634 staff and produced 179,022 t wet weight at harvest (Munro et al., 2014) with a first sale value around £0.7 billion (http://news.scotland.gov.uk/News/Record-year-for-salmon-production-1cb9.aspx#downloads accessed 3 Nov. 2015). The value of the farmed salmon harvest therefore now exceeds that of the capture fishery landings in Scotland (Marine Scotland, 2014).

2. The Scottish fish farm production annual survey reports 1979–2014 as a data source

The annual reports on the Scottish finfish farming industry provide a consistent, authoritative, time series of official data that document the development of the Scottish salmon farming industry and represent the source of information for the body of this review. The importance of annual reporting was recognised at the inception to a) give confidence in the statistics and b) provide insight into trends, which less frequent snapshot views would not (Munro et al., 1980; Munro and Wadell, 1981). The reports provide one of the longest and most comprehensive time series of data available for any aquaculture sector globally, and the competent authority and Scottish industry must be commended for maintaining this output over 35 years.

The reports provide data on the Scottish salmon industry gathered largely by annual questionnaire surveys of aquaculture companies known by, or more recently compulsorily registered with, the competent authority for fish health. All companies actively engaged in freshwater and seawater salmon farming supply the requested information (e.g. Munro and Wallace, 2013); companies not returning the information are subject to additional requests (Munro and Wadell, 1981). The reports are therefore based on self-reporting by the industry, supplemented with additional information held by the competent authority (e.g. from health certificates of imports and exports; reports of escape events), and explanatory comments based upon the authors' knowledge of the industry. The data coverage is therefore of the entire industry operating in Scotland, rather than a sample (or extrapolation from a sample).

The questionnaire distributed to the industry has changed over time (e.g. DAFS, 1986), as has the extent, format and presentation of the data within the annual reports. The series of reports provide time series of variable length (up to 46 years) for various metrics of the industry. The reports frequently state that data published in previous years have been reassessed and updated where necessary (e.g. Munro and Gauld, 1996; Hastings and Smith, 2005; Munro et al., 2014). As data are necessarily collected retrospectively, changes in company ownership may introduce uncertainty for particular years (Munro et al., 2014).

We selected metrics for various aspects of the industry from the most recent report, and time series were extended by successive extraction from earlier reports. Where occasional discrepancies were noted between reports, values from the most recent reports were assumed to represent corrected values. The annual reports tabulate data, with the number of years varying for each metric (e.g. range 1 to 22 (median 11) years in Munro and Wallace, 2015). In this review, we illustrate entire time series graphically to facilitate visualisation of long-term trends, in addition to inter-annual fluctuations.

The annual reports separate salmon farming into freshwater (ova to smolt) and seawater (smolt to harvest) production. Here we report metrics together to illustrate the parallel development of the two subsectors, and group indicators relating to 1) production, 2) sites and systems, 3) biological performance, 4) socio-economics, and 5) environmental pressures. Supplementary comments from the reports are cited to aid interpretation and discussion. Since 1985 (DAFS, 1986), some metrics have been sub-divided for different geographical regions within Scotland; regional information is not discussed within this review.

3. The production cycle of farmed salmon in Scotland

Wild Atlantic salmon are anadromous: the early life stages inhabit freshwater, the main growth phase occurs in seawater and the adults return to freshwater to reproduce. Salmon farming therefore occurs in both freshwater (hatchery and nursery) and seawater (on-growing to harvest). The production cycle of farmed salmon in Scotland can divided into successive stages:

3.1. Broodstock

Potential broodstock are selected in spring–summer (mostly 2nd sea winter fish, with some 3rd sea-winter or older fish) and held until autumn–winter for stripping (Munro and Gauld, 1996). Although some broodstock may be stripped at sea sites, it is common practice to move broodstock to freshwater sites for acclimation some weeks prior to stripping (Munro and Gauld, 1996). Ova production is related to age/size: 2nd sea-winter females of 8 kg produce around 12,000 ova; 3rd sea-winter females of 12 kg produce around 16,000 ova. Ova size is variable, with around 5000 ova L^{-1} (Munro and Gauld, 1995, 1996). Although the stripping season (winter) extends over two calendar years (October through to January), ova production is reported for the year in which it starts (Munro and Gauld, 1996).

3.2. Freshwater hatchery stage (ova, alevin and parr)

The stripped ova are fertilised and "laid down", hatch as alevin 12 weeks later and grow into parr (Munro and Gauld, 1996).

3.3. Freshwater nursery stage (parr to smolt)

The parr grow and undergo smoltification (physiological, morphological and behavioural changes that enable survival in seawater) in the Spring, cued by seasonal patterns of temperature and light. Through photoperiod control, smoltification can be advanced outside the natural spring timing, and growth can be manipulated by controlling water temperature and varying feeding regimes (Munro and Gauld, 1996). Historically, natural smolt were put to sea in Spring (April–June) after 1 or 2 years in freshwater, but photoperiod manipulation now enables smolt to be put to sea throughout the year (Munro and Gauld, 1995). Natural smolt are termed S1 and S2, and "out-of-season" smolt are described as S½ or S1½, depending upon age at smoltification (Munro and Gauld, 1997; Munro and Wallace, 2013):

S½: <12 months old, i.e. transferred to sea in calendar year of hatch. NB: The synonymous term "S0" is now used by the industry, but the term S½ is retained here for consistency with the annual reports;

S1: 12–18 months old, i.e. transferred to sea in January–June in year post hatch;

S1½: 19–24 months old, i.e. transferred to sea in July–December in year post hatch;

S2: >24 months old when transferred to sea.

S½ are produced from the largest size grades and/or early spawned ova and are available for transfer to seawater as early as 6 months after first feeding (Munro and Gauld, 1996). S1½ and S2 tend to be "leftovers" or slow growers from previous batches (Munro and Gauld, 1997).

3.4. Seawater stage (smolt to harvest)

Smolt are "put to sea" to be on-grown in seawater. The normal seawater production period is 18 months to 2 years (Stagg and Allan, 1999), with fish being harvested at various ages and times of year, depending upon growth. Stagg and Gauld (1998) noted a market demand for fish in the 3–4 kg range, and that larger fish tended to go for smoking (rather than as fresh fish). The annual reports provide details of harvest of fish at different ages/timings under terminology that has been dropped by industry (Munro and Gauld, 1995; Munro et al., 2014), i.e.:

- input year fish: harvested within 1st calendar year of seawater transfer;
- Year 1 grilse: harvested January–August in the 2nd calendar year in seawater. NB: The term grilse as used in the reports (and here) reflects time of harvest, and therefore differs to use with wild salmon where it refers to maturation and return to freshwater after one winter at sea;
- Year 1 pre-salmon: harvested September–December in the 2nd calendar year in seawater;
- Year 2 "salmon": after 2 calendar years in seawater.

The annual reports do not suggest that harvest fish are held for > 2 years in seawater.

There is therefore a variety of age-classes in production in freshwater and seawater at any one time. In 2014, the Scottish salmon industry harvested 34.3 million fish (from 4 age groups), with inputs of 48 million smolt, 70.8 million ova and 0.003 million female broodstock salmon (Table 1). Having several year-classes in production at one time together with variable stage durations does compromise collation of certain metrics.

4. Production metrics

4.1. Ova

Data are available on numbers (and sources) of ova produced, exported, imported, and laid down to hatch in Scotland.

Data on ova production in Scotland (i.e. stripped from Scottish farmed broodstock) have been published since 1990. Ova production was at its peak of 224.4 M in 1990 and has since decreased by 85% to 33.5 M in 2014 ($r_s = -0.655$, $n = 25$, $p < 0.001$; Fig. 2a). Ova produced in Scotland can be marketed for human consumption (as salmon caviar; Munro and Gauld, 1996), exported to support salmon farming in other countries, or be laid down to hatch. There are no records of Scottish ova being sold for human consumption (Munro and Gauld, 1997; Stagg and Gauld, 1998). The Scottish industry has traditionally exported

Table 1
Data on inputs and outputs of salmon for the Scottish salmon farming industry in 2014 — numbers of individuals, harvest volumes (t) and mean weights (kg) (data from Munro and Wallace, 2015).

Production stage	Life history stage/origin	Number of individuals		Harvest (tonnes)		Mean weight at harvest (kg)
			Total		Total	
Broodstock in Scotland	Female fish stripped		2,711			
Ova production	Ova production — Scotland	33,450,000	92,312,000			
	Ova imported (outside GB)	58,862,000				
Ova laid down to hatch in Scotland	From Scottish production	14,418,000	70,827,000			
	Other GB production	2,725,000				
	Foreign ova	53,684,000				
Smolts produced in Scotland	S0.5	22,367,000	45,004,000			
	S1	22,473,000				
	S1.5	164,000				
Smolts put to sea in Scotland	Scottish	45,080,000	48,045,000			
	Smolts — English	893,000				
	Smolts — other	2,072,000				
Seawater harvest	Harvest in year 0: input year fish	286,000	34,314,000	720	179,022	2.5
	Harvest in year 1: grilse	9,048,000		46,686		5.2
	Harvest in year 1: pre-salmon	11,268,000		55,311		4.9
	Harvest in year 2: salmon	13,712,000		76,305		5.6

ova, although numbers have decreased over time ($r_s = -0.627$, $n = 21$, $p < 0.005$; Fig. 2a): the salmon farming industry in Chile appears to have been the main recipient of exported ova in the mid to late 1990s (Munro and Gauld, 1997; Stagg and Gauld, 1998). There was then an apparent hiatus, with export to Chile resuming in 2004 (Smith et al., 2005), but the trade ceased in 2010 (Walker and McAlister, 2011). Smaller

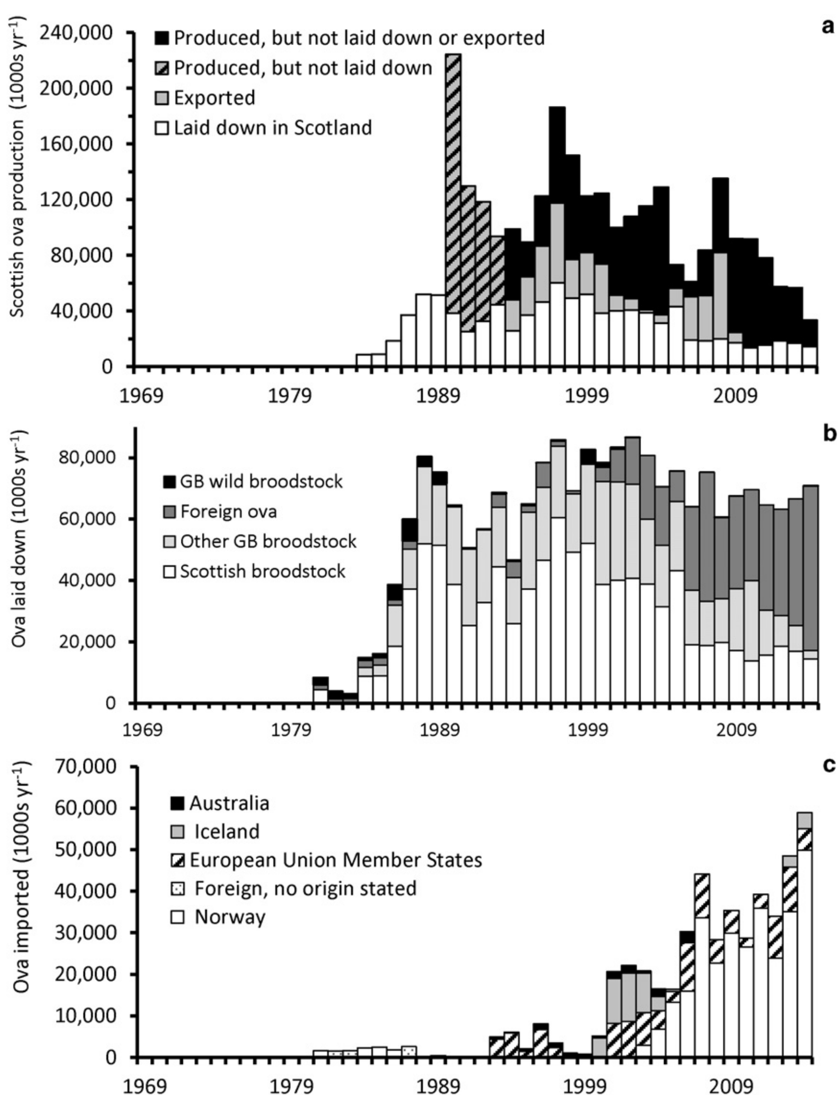

Fig. 2. Data on salmon ova in Scotland. a: Numbers of ova produced in Scotland, subdivided into laid down in Scotland, exported and not laid or exported. Data available 1984/1994/1995–2014. b: Origins of ova laid down to hatch within Scottish salmon industry. Data available 1981–2014. c: Origins of foreign (imported) ova. Data available 1981–2014.

numbers of ova from wild salmon have been exported to support restocking of European river systems (Munro and Gauld, 1997).

Typically only 31% of ova produced in Scotland are laid down to hatch in Scotland (Fig. 2a). Substantial proportions of stripped ova (mean 49%; 50% in 2014) are unaccounted for (i.e. not reported as laid down or exported) and this proportion has increased over time ($r_s = 0.506$, $n = 21$, $p < 0.05$). Unaccounted ova are likely to represent disposals due to inferior quality, disease status or as surplus (SOAFD, 1991, 1992; Munro and Gauld, 1996; Stagg and Gauld, 1998).

The total number of ova laid down to hatch in Scotland (i.e. originating from Scottish farmed broodstock and other sources) increased to a peak of 86.7 million in 2002, and has since declined (Fig. 2b). DAFS (1990) noted that the industry took a collective management decision in 1988 to limit production growth by limiting the number of ova laid down. The sources of ova laid down are: in-house broodstock (i.e. Scottish farmed broodstock); out-sourced GB broodstock (farmed broodstock held in England or Wales); GB wild broodstock; foreign ova (including from Northern Ireland, Munro et al., 2014). Key temporal trends for ova laid down are:

- the contribution from wild broodstock has decreased, being replaced by ova from farmed broodstocks;
- the contribution of imported ova, i.e. from foreign farmed broodstocks, has changed over time.

The industry was still dependent upon wild Scottish broodstock for ova in the early 1980s. Munro and Wadell (1981) noted a shortage of ova due to erratic supplies of wild eggs which was exacerbated by loss of a major source where infectious pancreatic necrosis (IPN) virus had been found. They stated that the industry needed to switch from wild eggs to farmed broodstocks, which did occur (DAFS, 1988). Although the salmon farming industry has continued to report wild ova laid down since the 1990s, these statistics are misleading as this has been on behalf of wild fisheries for stock enhancement schemes (Stagg and Allan, 2000, 2001; Walker, 2009; Munro et al., 2014; Munro and Wallace, 2015).

Imported (mainly Norwegian) eggs were used in the early and mid-1980s (DAFS, 1985, 1987), but their use decreased over time up to the late 1990s (Munro and Gauld, 1996; Stagg and Allan, 2000); domestic ova from Scottish and GB farmed broodstocks then supplied the bulk of ova, and were considered satisfactory and sufficient to supply the Scottish industry (Munro and Gauld, 1994, 1996). Munro and Gauld (1997) refer to import of ova from the southern hemisphere (Australia) to support production of out of season smolt, although this was typically minor and ceased in 2006 (Fig. 2c). However, since 2000 there has been a marked increase in the use of foreign ova (Stagg and Allan, 2002; Stagg and Smith, 2003; Hastings and Smith, 2005). In 2014, the majority (76%) of ova laid down were imported (Fig. 2b), from Norway, Northern Ireland and Iceland (85%, 9% and 6% of imports respectively; Fig. 2c). The current dominance of ova imports (over domestic production) is thought to reflect salmon farming companies centralising broodstock and selective breeding operations elsewhere. Temporal changes in ova imports also reflect the introduction of legislation for disease control over this period: Fish Health Regulations, introduced in 1993 to EU Member States, established conditions for trade in live ova and changes in 2003 enabled import of salmon ova from Norway (Walker et al., 2012; Munro et al., 2014).

4.2. Smolt

Data are available on numbers (and origin and age) of smolt produced in Scotland, imported and exported (but including fry), and put to sea in Scotland. The number of smolt produced in Scottish freshwater farms increased from 1979 to peak at 47.5 million in 2001 (Fig. 3a). The data on Scottish origin smolt put to sea (supplied by seawater farms) are in close agreement with those on smolt production (supplied by Scottish freshwater farms) although the latter are typically 3% higher (Fig. 3a; Munro and Gauld, 1995). Smolt are exported, but the available data (combined with export of fry) indicate that this does not account for the difference. The difference has been noted twice in the annual reports:

- Munro and Gauld (1997) attributed it to variation in the accuracy of the counters and counting methods. However, a consistent difference and valence seems unlikely to be due to counting methods (Aunsmo et al., 2013), although it may be associated with accounting practices (e.g. consistent rounding up v rounding down).
- Hastings and Smith (2005) briefly explained it as smolt not being put to sea in Scotland.

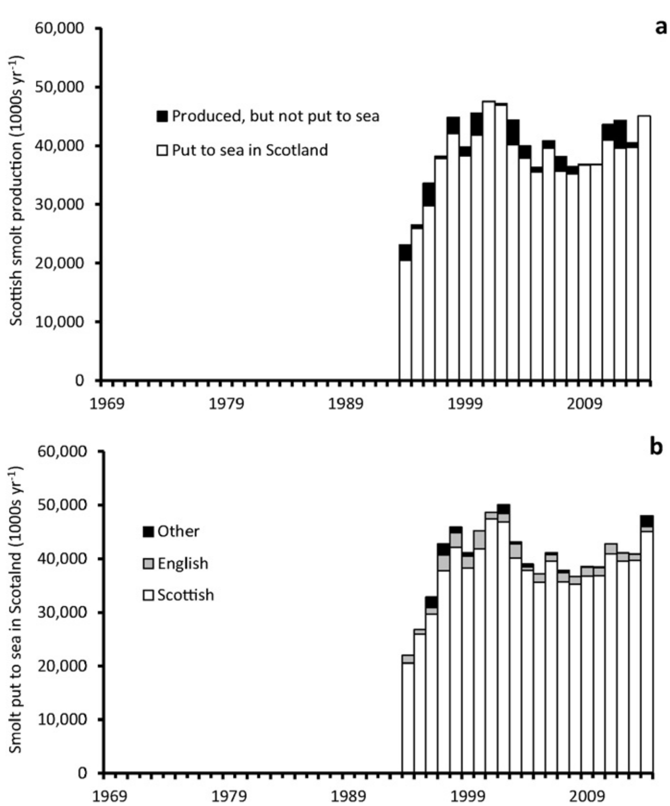

Fig. 3. a: Numbers of smolt produced in Scottish freshwater farms and reported as put to sea in Scotland. b: Origin and numbers of smolt put to sea in Scotland. Data available 1994–2014.

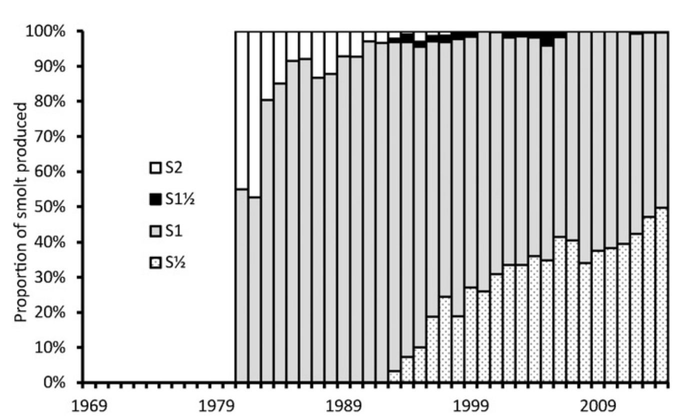

Fig. 4. Proportions of different aged smolt (S½, S1, S1½, S2) produced in Scotland. Data available 1981 to 2014.

The difference is therefore likely to be explained by either smolt that die (during transport from freshwater to seawater sites, or soon after transfer) not being counted, or surplus/poor quality smolt being culled.

The total number of smolt put to sea increased up to 2002, peaking at 50 million and has since decreased, plateaued and risen again to 48 million in 2014 (Fig. 3b). The bulk of smolt put to sea are produced in Scotland (median 95%), with the balance derived from England and EU member states (Fig. 3b). EU imports of smolt from Ireland first occurred in 1996 (Munro and Gauld, 1997). Nevertheless, Scotland can be considered to be largely self-sufficient with respect to smolt production.

Although smolt size is not reported (Munro and Gauld, 1994), Munro and Gauld (1996) noted that historically S1 smolt were 30–40 g, but size had increased and S1 smolt >80 g were now commonly produced. [Bergheim et al. (2009) report a similar increase in the size of Norwegian farmed smolt, from 30–50 g in 1985 to 70–120 g in 2000]. This increase in size reflected use of early spawned ova, increased growth associated with temperature control and improved feeding, and early placement of parr into ambient freshwater systems maximising the period of greatest natural growth during spring–autumn (Munro and Gauld, 1996). Larger smolt are favoured by seawater farmers as it enables earlier harvest, or harvest of larger fish (Munro and Gauld, 1994). However, keeping fish for longer in freshwater incurs additional costs which may outweigh the advantages of size and robustness (Munro and Gauld, 1997). Freshwater farmers therefore now cull potential S2 smolt (Munro and Gauld, 1996).

Time series data for age of smolt is available (Fig. 4), and two long-term trends are apparent:

- The introduction of out-of-season smolt, i.e. S½ and S1½;
- A reduction in age of smolt, i.e. a move from S2 to S1, and S1 to S½.

In 1981, only S1 and S2 were produced, with the proportion of S2 varying (10%–83%) between farms (DAFS, 1982). The production of out of season S½ and S1½ reflects the introduction of photoperiod control. Out of season smolt were first produced in 1993 (Munro and Gauld, 1994), and there has been a trend towards increased production of S½ (Stagg and Gauld, 1998). Early out of season smolt are produced by extracting the top sizes of normal growing populations (Munro and Gauld, 1995). Production of S½, in conjunction with S1, enables smolt to be put to sea throughout the year and hence more flexible production scheduling (Munro and Gauld, 1995; Stagg and Gauld, 1998). However, there have been some concerns about out of season smolt. Munro and Gauld (1995, 1996) noted that S1 and S2 smolt were larger and more robust than S½ and S1½ smolt, with the latter experiencing more variable and poorer survival in seawater. Although production period and feed costs may be reduced in photoperiod adapted smolt, there are additional costs for lighting and heating (Munro and Gauld, 1995). Munro and Gauld (1997) noted that farmers tended to favour out of season smolt derived from north hemisphere ova, to those from southern hemisphere ova.

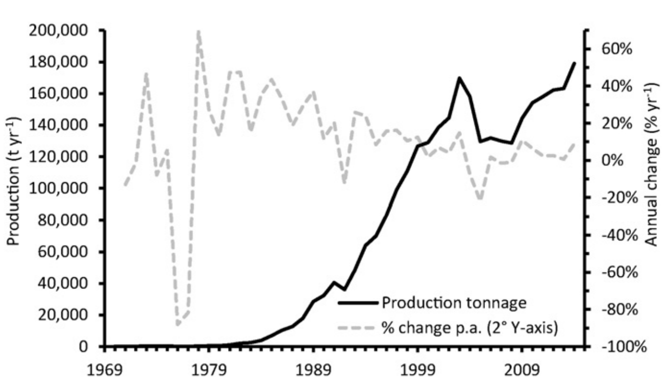

Fig. 5. Harvest (t year^{-1} wet weight whole fish) of Scottish farmed salmon and % change from previous year. Data available 1979–2014 from annual reports and earlier data (1970–1978) from http://data.fao.org (accessed 19/01/15).

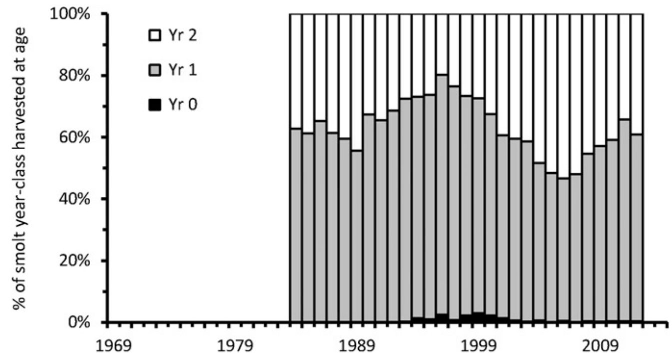

Fig. 6. Proportions of fish harvested from seawater either as year 0 (input year), year 1, or year 2 fish, relative to their year of transfer to seawater. Data available 1984–2012.

4.3. Seawater harvest

The seawater production tonnages reported are the wet weight of fish at harvest (Munro et al., 2014). Over the period for which data are available (1970–2014; NB: 1970–1978 data from http://data.fao.org accessed 5 March 2015) the annual harvest of Scottish farmed salmon has shown a 734 fold increase (from 244 to 179,022 t) (Fig. 5). Harvest initially peaked in 2003 at 169,736 t, then fell, but has recently recovered to a new peak of 179,022 t in 2014. This long term trend has been subject to short term fluctuations, varying between +70 and −88% year^{-1}, being greatest during the early development of the industry. Some explanations for the fluctuations in annual growth are provided in the annual reports:

- During the early development of the industry, growth in seawater harvest was limited by a shortage of smolt (Munro et al., 1980; Munro and Wadell, 1981);
- The reduced annual growth in the early 1990s has been attributed to management decisions within the industry due to loss of confidence in the market for farmed salmon and concern about inability to control disease (DAFS, 1990; SOAFD, 1991, 1992, 1993);
- The drop in harvest in 1992 was attributed to mortalities from the bacterial disease furunculosis caused by *Aeromonas salmonicida* (Munro and Gauld, 1996). Improved disease control and the introduction of effective vaccines, enabled subsequent growth in harvest (Munro and Gauld, 1994, 1995, 1996);
- An outbreak of infectious salmon anaemia (ISA) occurred for first time in 1997, which reduced harvest in the late 1990s (Stagg and Gauld, 1998).

The numbers of fish of different ages at harvest are also reported (Fig. 6). Although proportions have changed over time, there is no clear long-term trend. Age will be related to size at harvest, and therefore (partially) reflects market demand for different sized fish — either for whole fresh fish, fresh fillets, or for smoking (Munro and Gauld, 1996). In the early 1990s, marketable fish were harvested early due to a need for cash flow and to reduce losses due to disease (SOAFD, 1991). Input year fish were first harvested in 1993 (Munro and Gauld, 1994); their harvest allows farmers to meet specific market demand whilst simultaneously facilitating control of stocking density (Munro and Gauld, 1997). An increase in harvest of input year fish in 1998 was attributed to fish being put to sea earlier and faster growth (Stagg and Allan, 1999). Increased harvest of year 1 fish has also resulted

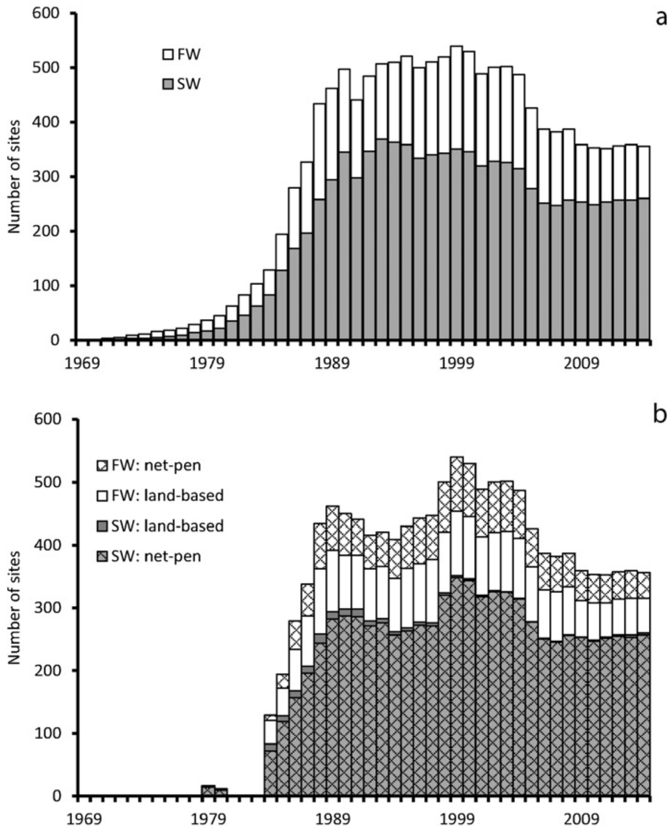

Fig. 7. a: Numbers of freshwater (FW) and seawater (SW) salmon farm sites in Scotland. Data available 1969–2014. b: Numbers of freshwater and seawater sites, subdivided into land-based and net-pen systems. Data available 1979/1984–2014.

from compulsory slaughter programmes for the control of infectious salmon anaemia (ISA) (Stagg and Allan, 1999).

5. Production site and system metrics

5.1. Numbers and types of active sites

There was a rapid expansion in numbers of active sites (farms) in both freshwater and seawater until the late 1980s–early 1990s; however, numbers have decreased since 1999 (Fig. 7a). Munro and Gauld (1997) noted a trend for companies to concentrate production at individual sites. A contraction in numbers of sites has been suggested to indicate potential for expansion (Munro and Gauld, 1995), although it is likely that vacated (inactive) sites proved unsuitable for successful rearing of salmon for various reasons (Munro and Gauld, 1997).

Freshwater sites initially (in the 1970s) outnumbered seawater sites, but this balance has reversed. Currently the number of freshwater sites is around 37% of the number of seawater sites.

Sites are categorised as either land-based (tank/trough/raceway systems sited on land) or floating net-pens sited in freshwater lochs or the sea (Fig. 7b). Net-pen systems are considered less expensive to install and run, and are simpler to operate (Munro and Gauld, 1995; Stagg and Gauld, 1998). Land-based systems are more capital intensive, may depend upon pumps and external energy sources, are more labour intensive, and have higher running costs. However, land-based systems have the advantages that direct observation of stocks is possible (facilitating prompt remedial action), environmental conditions can be controlled or modified (e.g. for production of out of season smolt), and husbandry operations (e.g. handling, grading) are easier (Munro and Gauld, 1995, 1996, 1997). Stocking density in land-based systems is typically higher than in net-pens to offset higher production costs (Munro and Gauld, 1996).

Seawater farming is dominated by net-pens, with the proportion of land-based seawater sites declining over time (Fig. 7b). New pump-ashore seawater tank sites were developed in Scotland in 1980 (Munro and Wadell, 1981). However, such systems incur high energy costs, are less economically viable than net-pen systems and have largely been redeployed as broodstock sites, or for alternative species, e.g. halibut (*Hippoglossus hippoglossus*) (Munro and Gauld, 1995; Stagg and Gauld, 1998; Stagg and Allan, 1999, 2002).

In freshwater, hatchery sites require land-based ova incubators and troughs for alevins and fry, whereas nursery sites can use either land-based systems (tanks, raceways) or net-pens (Munro and Gauld, 1994, 1995, 1996). Freshwater net-pen systems are commonly used in Scotland (Fig. 7b) which contrasts to Norway where their use is rare (Bergheim and Brinker, 2003). Bergheim et al. (2009) provide details on Scottish freshwater net-pen sizes and construction. Munro et al. (1980) noted that land-based freshwater sites were limited by abstraction volumes, and that expansion would require new sites or the introduction of technology. In the 1990s, there were three significant developments in the freshwater sector (Munro and Gauld, 1995, 1996, 1997):

- Polytunnels were introduced so traditional outdoor (open air) tank systems were under cover, allowing more control of the rearing environment and improving staff working conditions;
- High-tech recirculation aquaculture systems (RAS) were introduced. The introduction of such water reuse systems was considered especially important in areas (such as Shetland) where freshwater supplies are scarce. RAS make efficient use of the available water supply, provide control of the rearing environment, and concentrate particulate wastes within the unit for bulk disposal, reducing discharge

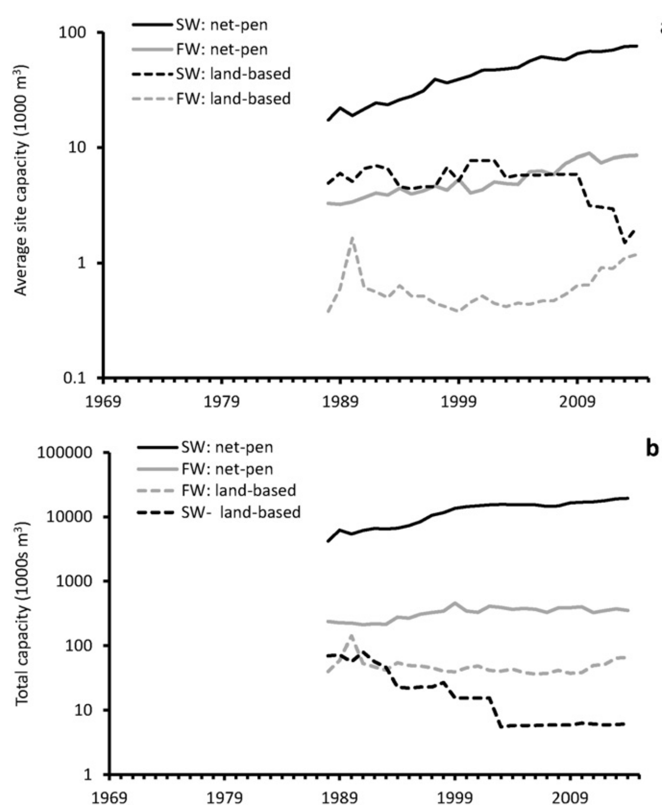

Fig. 8. Average size (a) and total capacity (b) of net-pen and land-based salmon farms in seawater (SW) and freshwater (FW) in Scotland. Please note log scales. Data available 1988–2014.

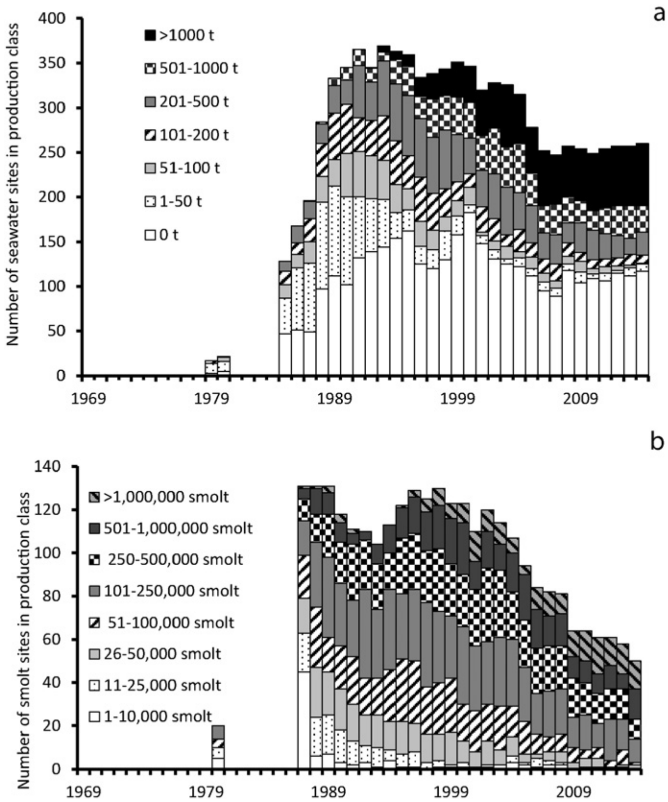

Fig. 9. Numbers of sites, grouped according to production volumes. a: Seawater sites where production is grouped by harvest tonnage. [NB: 0 t category production relates to active farms growing stock, but with no harvest in year.] b: Freshwater sites producing smolt (i.e. excluding hatchery sites) grouped according to smolt production. Data available for 1979/1980, 1985/1987–2014.

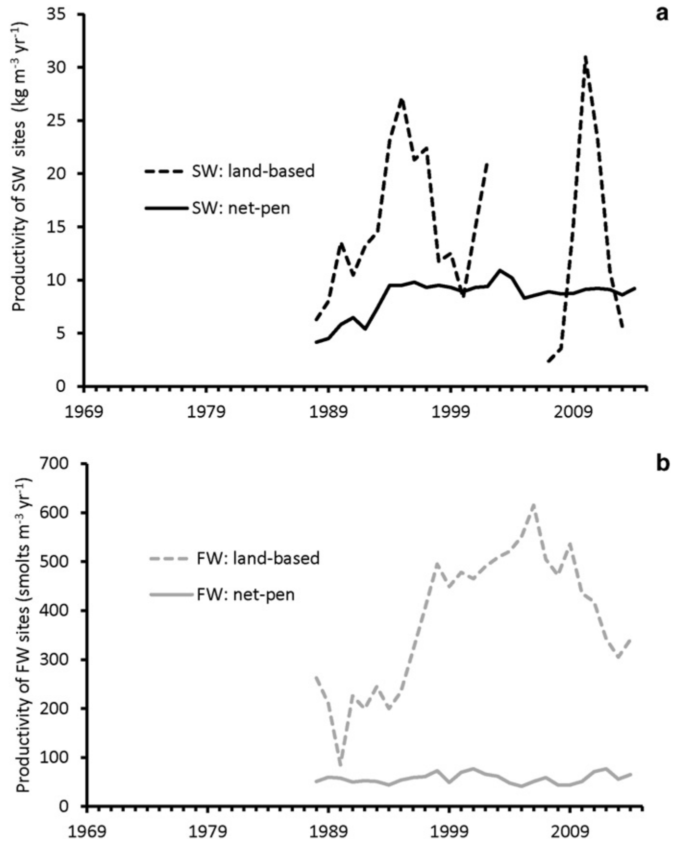

Fig. 10. System productivity in Scottish salmon farming. a: Seawater (SW) net-pens and land-based sites as kg m^{-3} $year^{-1}$. b: Freshwater (FW) net-pens and land-based sites as smolt m^{-3} $year^{-1}$. Data available 1988–2014.

to the environment. RAS enabled sites to produce more smolt through increased stocking density and increased growth (enabling the transfer of earlier and/or larger parr to other on-growing net-pen or tank systems) and have been attributed with the increased tank production of smolt in the 1990s (Stagg and Gauld, 1998). Munro and Gauld (1997) noted that: care was needed to ensure efficient operation of biofilters and prevent introduction of pathogens (as treatments can affect biofilters); that increased production was needed to offset higher installation and running costs.
- There was increasing use of remote sensors and computerised control of operations.

5.2. Farm size and capacity

The average size of net-pen farm sites in both seawater and freshwater has increased over time ($r_s = 0.994$ and 0.947, $n = 27$, $p < 0.001$), while no such trends are apparent for land-based sites (Fig. 8a). Several net-pens are typically operated at a single farm site. In seawater, larger circular net-pens of plastic construction (e.g. 100 m circumference × 22 m depth) were introduced in the mid-1990s (Munro and Gauld, 1997; Stagg and Gauld, 1998). The increases in average net-pen farm sizes over time have contributed to a continual increase in total net-pen capacity in both seawater and freshwater ($r_s = 0.963$ and $r_s = 0.699$ respectively, $n = 27$, $p < 0.001$; Fig. 8b), despite reductions in farm numbers since 1999.

Against a backdrop of decreasing numbers of seawater and freshwater farms, the proportion of farms with higher production, in both seawater (tonnage) and freshwater (smolt output), has increased (Fig. 9). This illustrates consolidation within the industry, with production being concentrated at fewer, but larger, freshwater and seawater sites (Munro and Gauld, 1996; Stagg and Gauld, 1998; Stagg and Allan, 2001, 2002; Walker, 2010; Munro and Wallace, 2013). Although concentrating production onto fewer sites provides economic advantages, it does incur the risk that an infectious disease outbreak could result in major financial loss (Munro and Gauld, 1997; Stagg and Gauld, 1998).

Scottish net-pen farms, in both freshwater and seawater, are regulated by the Scottish Environment Protection Agency on the basis of the total biomass of fish (Munro and Gauld, 1997; Stagg and Gauld, 1998). Freshwater net-pen farms tend to be stocked at or near the maximum permitted biomass (Munro and Gauld, 1997), and an increase in the numbers of smolt produced was accompanied by a reduction in

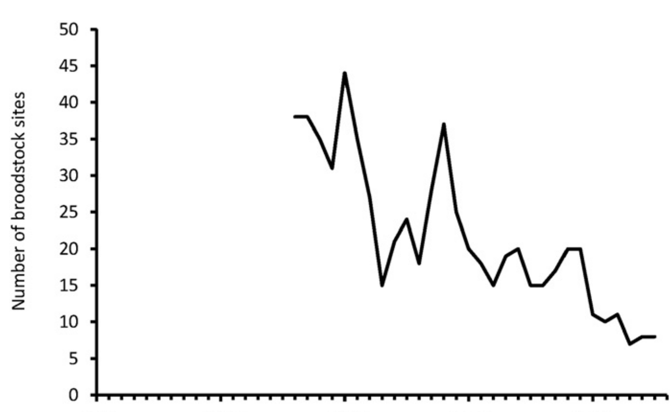

Fig. 11. Number of freshwater and seawater farm sites in Scotland holding broodstock. Data available 1985–2014.

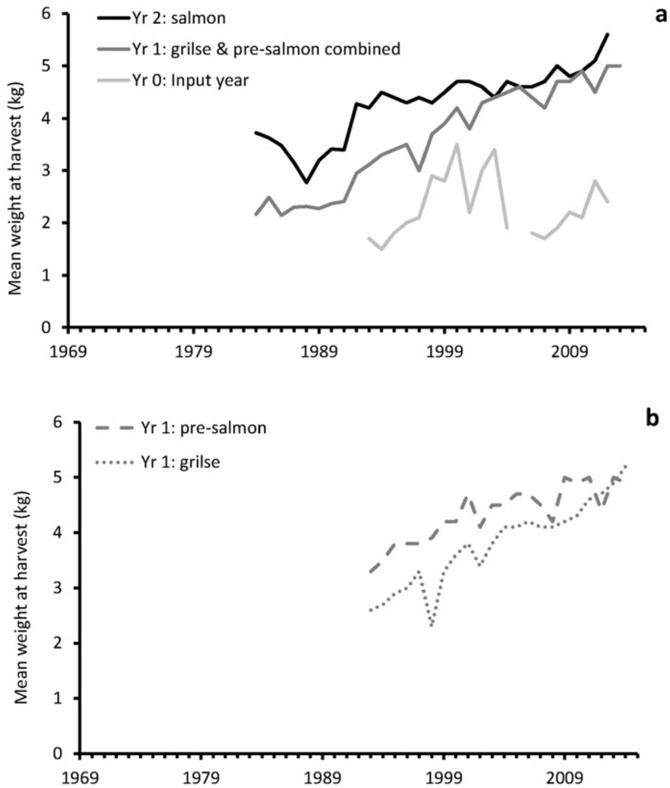

Fig. 12. Mean weight at harvest of different aged seawater salmon. a: Data refer to smolt year-classes and available 1984–2012/2013. b: data refer to year of harvest and available 1993–2014.

smolt size (Stagg and Gauld, 1998). In the 1990s, the seawater sector introduced a practice so farms operated close to permitted biomass level for as a large a proportion of the production cycle as possible: input smolt were on-grown for 6–9 months before splitting for transfer to other farms (Stagg and Gauld, 1998).

5.3. System productivity

Productivity (reported as output m^{-3} $year^{-1}$) is greater in land-based systems than net-pen systems, in both seawater and freshwater (Fig. 10; Friedman's tests blocked by year: $\chi^2_r = 27.0$, df = 1, $p < 0.001$ for freshwater; $\chi^2_r = 8.9$, df = 1, $p < 0.005$ for seawater). Although seawater net-pen productivity has not changed significantly over the entire time series available ($r_s = 0.245$, n = 27, $p > 0.2$), this obscures a significant 2-fold increase between 1988 and 1996 ($r_s = 0.946$, n = 9, $p > 0.001$) and slight subsequent decrease ($r_s = -0.492$, n = 18, $p < 0.05$). Productivity has increased over time in freshwater land-based systems ($r_s = 0.570$; n = 27, $p < 0.005$), although the plot indicates a 2-fold increase between 1988 and 2006, followed by a decrease (Fig. 10). There is no evidence of changes in system productivity over time for freshwater net-pens ($r_s = 0.111$, n = 27, $p > 0.5$) or seawater land-based systems ($r_s = 0.027$, n = 22, $p > 0.5$).

5.4. Broodstock sites

Farm sites holding salmon broodstock (both freshwater and seawater, Stagg and Allan, 2000) are reported separately to production sites. The number of sites holding broodstock has decreased by 80% over time ($r_s = -0.850$, n = 30, $p < 0.001$; Fig. 11). This is likely to be due to consolidation of the industry, but may also be related to only maintaining broodstock at sites free from diseases such as IPN virus (SOAFD, 1993).

6. Biological metrics

6.1. Size at harvest

Size at harvest has increased over time for grilse ($r_s = 0.968$, n = 22, $p < 0.001$), pre-salmon ($r_s = 0.858$, n = 22, $p < 0.001$) and salmon ($r_s = 0.925$, n = 29, $p < 0.001$), but not for input year fish ($r_s = 0.265$, n = 20, $p > 0.2$) (Fig. 12). Munro and Gauld (1994, 1996) suggested that various factors contributed to increased harvest weight in the 1990s:

- Increased smolt size and earlier transfer to seawater;
- Enhanced growth rates due to: improved feed and feeding systems (e.g. automatic feeders); reduced inappetance due to improved control of furunculosis; reduced stress due to the better health management through introduction of effective vaccines and management schemes to avoid introduction of infections (e.g. fallowing, group area agreements on single age group stocking over extended areas, stocking of smolt of common health status); reduced stress due to introduction of new husbandry technologies (e.g. air lift removal of mortalities, swim through at net changes).

Further improvements in these factors, and selective breeding, are likely to account for continuation of the trend of increasing harvest size since the 1990s.

Explanations have been provided for short-term fluctuations in harvest weight, outside the long-term trend. The low harvest weights of salmon in the late 1980s were due to a combination of marketing decisions (based on the need for cash flow) and the early removal of marketable fish to limit losses to disease (DAFS, 1990; SOAFD, 1991). The subsequent increase in harvest weight was attributed to greater confidence in achieving seawater survival and the market price of larger fish (SOAFD, 1992).

The increase in size (and numbers) of input year fish harvested in 1998 and 1999 was attributed to use of photoperiod "early smolt", rapid growth rates achieved with high energy feeds, and modern husbandry methods (Stagg and Allan, 1999, 2000).

6.2. Survival

Survival data are published for the seawater stage (i.e. % of smolt put to sea in a calendar year that are harvested over years 0, 1 and 2) and the freshwater stage (i.e. ratio of ova laid down: smolt produced within a calendar year). The values provided therefore reflect recovery of fish after mortality, culls and escapes. Although the freshwater stage metric

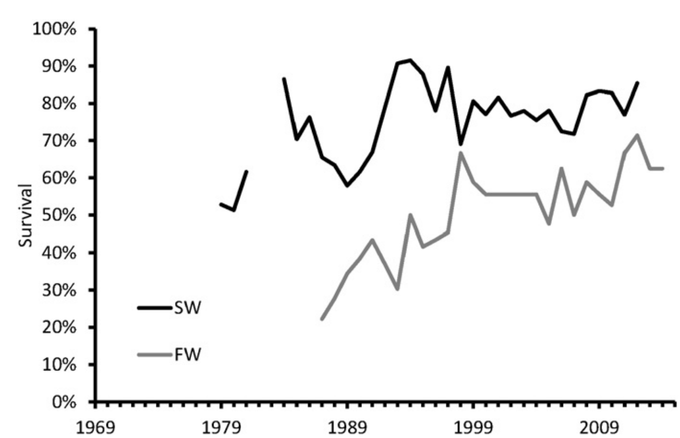

Fig. 13. Survival of Scottish farmed salmon in seawater (SW, i.e. number of year-class harvested: number of smolt put to sea; data available 1979–1981, 1984–2012) and freshwater (FW, i.e. number of smolt produced: number of eggs laid down in calendar year; data available 1987–2014).

is derived from different year-classes of ova and smolt for reasons of practicality, it does enable assessment of long-term trends.

There is a marked temporal trend for increased survival in freshwater ($r_s = 0.812$, $n = 28$, $p < 0.001$) which has improved threefold from 22% in 1987 to 63% in 2013 (Fig. 13). Increased freshwater survival has been attributed, in part, to reduced mortality between the ova and smolt stages (Munro and Gauld, 1995, 1996). Mortality at hatching and first feeding stages was estimated at 5–10% in 1996 (Munro and Gauld, 1997). Vaccination of parr against enteric redmouth disease (ERM, caused by the bacterium *Yesinia ruckeri*) was introduced in the 1990s which had previously caused mortalities in young fish in freshwater (Munro and Gauld, 1996). However, the bulk of losses in the 1990s was attributed to inadequate growth in the first summer, resulting in potential S2s (rather than S1s) which were culled (Munro and Gauld, 1995, 1996). Munro and Gauld (1997) noted that culling and production efficiency could be improved by increasing average growth rate. The continued trend from the 1990s to the present day indicates that culling has indeed been reduced.

Seawater survival was not regularly reported before 1984, although data were provided for the 1979, 1980 and 1981 smolt inputs (DAFS, 1983, 1984). Seawater survival has increased between 1979 and 2014 ($r_s = 0.462$, $n = 32$, $p < 0.01$) to around 80% (Fig. 13). Causes of loss of seawater fish are infectious diseases (furunculosis, pancreas disease, vibriosis), sea-lice, escape in storm damage incidents, a poor ability to tolerate seawater salinity, predation (by seals and birds), jellyfish and plankton blooms, poor husbandry and accidents such as losses during sea lice treatments (Munro and Wadell, 1981; DAFS, 1982; Munro and Gauld, 1996; Stagg and Gauld, 1998; Stagg and Allan, 1999, 2001). It has been noted that most of the losses occur in first summer, or first 6 months, after seawater transfer (Munro and Wadell, 1981; DAFS, 1982; Munro and Gauld, 1996).

The initial increase in seawater survival in the early 1980s was attributed to improvements in farm management (DAFS, 1984). The notable decrease in survival that followed in the mid to late 1980s was associated with disease (DAFS, 1990). SOAFD (1991, 1992, 1993) noted that furunculosis and sea-lice infestation were the major causes of loss in seawater in the early 1990s. The subsequent increase in survival was attributed to improved disease control through:

- the introduction of effective commercial vaccines for furunculosis (Munro and Gauld, 1995, 1996);
- the introduction of strategic health management agreements involving collective fallowing, group agreements on single year-classes of smolt, and stocking with vaccinated smolt of tested health status (SOAFD, 1992; Munro and Gauld, 1994).

These measures were suggested to reduce outbreaks of both furunculosis and sea-lice and reduce resistance to chemotherapeutants (lice to dichlorvos; furunculosis bacterium to antimicrobial medicines).

Munro and Gauld (1996, 1997) indicate that large numbers of smolt were lost due to "fading smolt syndrome" (i.e. mortality due to inability to adapt to the marine environment or loss of ability to withstand high salinities) and that the severity of grading may affect smolt survival (although this latter impact was not explained). Disease was also the primary cause of low survival of 1998 smolt: outbreaks of ISA and IPN losses resulted in mortalities and culling (Stagg and Allan, 2001).

6.3. Yield per smolt

Yield (in kg) per smolt is reported, and represents the total weight of seawater harvest (as input year, grilse, pre-salmon and salmon) relative to the number of smolt put to sea in a calendar year. It therefore encapsulates seawater survival of smolt and size at harvest. Yield per smolt shows a marked increase over time ($r_s = 0.902$, $n = 29$, $p < 0.001$; Fig. 14), which is attributed to increased survival and weight at harvest (Munro and Gauld, 1994). Munro and Gauld (1996) suggested that yield per smolt was unlikely to increase after 1995, but the data indicate that this performance measure has continued to improve.

6.4. Vaccination

Vaccination was introduced in the mid-1980s — against the bacterial disease furunculosis by intra-peritoneal (ip) injection of freshwater parr (Munro and Gauld, 1996). The industry experienced serious losses of seawater fish due to this disease in the late 1980s and early 1990s (Munro and Wallace, 2013). By 1992 furunculosis vaccines were used at most freshwater sites which reflected how seriously companies viewed the disease and their greater faith in the efficacy of vaccination (SOAFD, 1993). By 1996, 95% of smolt put to sea were vaccinated against furunculosis (Munro and Gauld, 1997). The introduction of vaccines was considered important to boosting industry confidence in controlling disease (SOAFD, 1991). The reports also indicate the introduction of other vaccines:

- in 1995 parr started to be vaccinated against ERM by bath immersion (Stagg and Gauld, 1998);
- In 1996/7, while monovalent vaccine (specifically against furunculosis) use continued, polyvalent ip vaccines were introduced which protected against furunculosis and cold water *Vibrio*/hitra (Munro and Gauld, 1997; Stagg and Gauld, 1998);

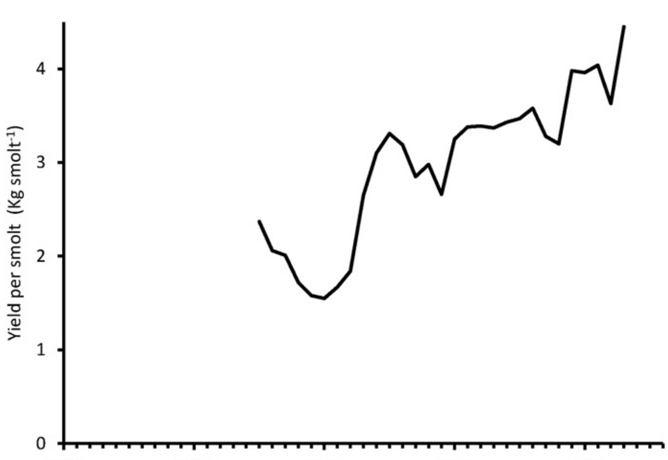

Fig. 14. Yield per smolt, i.e. total harvest of year-class relative to smolt input. Data available 1984–2012.

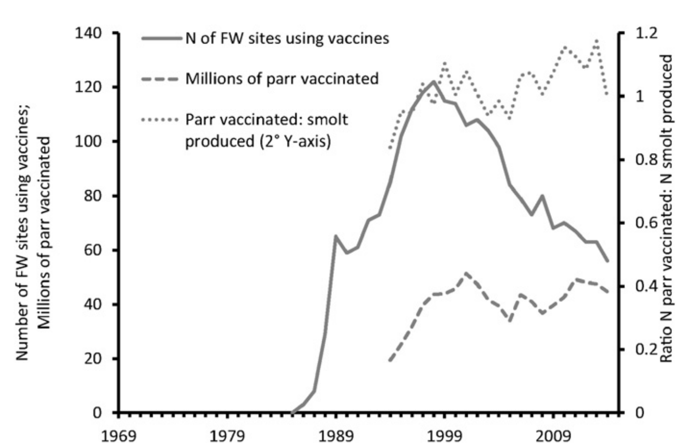

Fig. 15. Vaccination of freshwater salmon parr. Number of freshwater salmon farms using vaccines and number of parr vaccinated year^{-1} (in millions) on 1° Y-axis; ratio of numbers of parr vaccinated: smolt produced on 2° Y-axis. Data available 1985/1994–2014.

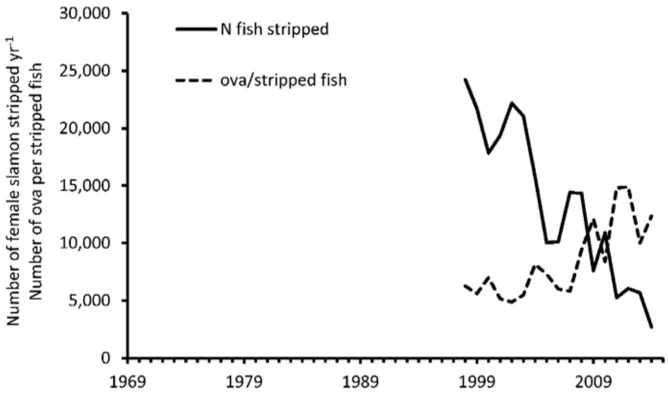

Fig. 16. Annual numbers of female salmon stripped for ova, and numbers of ova obtained per female in Scottish salmon farming industry. Data available 1998–2014.

- In 2000, vaccination against infectious pancreatic necrosis (IPN) was undertaken under animal test certificates authorised by the Veterinary Medicines Directorate (Stagg and Allan, 2001).

Currently freshwater sites vaccinate against a range of bacterial (furunculosis, ERM, vibriosis) and viral diseases (IPN, salmonid alphavirus (SAV) the causative agent of pancreas disease, PD) (Munro and Wallace, 2013). The majority of fish are vaccinated against furunculosis and IPN, but smaller numbers receive ERM, *Vibrio* and PD vaccines (Munro et al., 2014).

Data are reported on the number of freshwater sites using vaccines, and number of fish vaccinated (Fig. 15). As these statistics do not indicate the proportion of the industry, the latter has been re-expressed in relation to the number of smolt produced in Scotland (Fig. 15). The number of sites illustrates the introduction and uptake of vaccines from the mid-1980s. Although the number of sites using vaccines has decreased since 1998, this is likely to reflect the decreased number of freshwater farms. Vaccination appears to continue to be universal, with the ratio of numbers of fish vaccinated to smolt produced typically >1. It is noteworthy that in 1997, several independent, mobile, specialist vaccination teams were established (Stagg and Gauld, 1998).

6.5. Broodstock

Data are reported on the number of female broodstock stripped for ova and the average ova yield fish^{-1} (Fig. 16). Over the 17 years for which data are available, the number of fish stripped year^{-1} has decreased 9-fold ($r_s = -0.917$; $n = 17$, $p < 0.001$), while the ova yield per female has doubled ($r_s = 0.794$, $n = 17$, $p < 0.001$). No explanation is provided for the latter trend, although it can be assumed that it is related to larger sized females. Munro and Gauld (1996) noted that low spawning success in 1995 may be related to high water temperatures affecting broodstock.

7. Socio-economic metrics

7.1. Number of companies

Data on the number of companies involved in the seawater and freshwater sub-sectors are available from the mid-1980s (Fig. 17). The data therefore capture only the tail of the initial increase in the 1970s and 1980s, but do illustrate clear subsequent decreases: 15 fold for seawater ($r_s = -0.993$, $n = 26$, $p < 0.001$) and 3.5-fold for freshwater ($r_s = -0.928$, $n = 28$, $p < 0.001$). Some additional considerations when interpreting company data are:

- Companies may be double-counted if operating in both freshwater and seawater;
- Large (umbrella) companies may operate under a number of different names for business reasons, retaining the original names of smaller company after buy-outs (Munro and Gauld, 1996, 1997);
- In 1998, although there were 95 seawater companies, production was dominated by just 7 companies, which accounted for 60% of harvest (Stagg and Allan, 1999). In 2014, the number of seawater companies had reduced to 18, but production was still dominated by just 6 companies, which accounted for 99% of harvest (Munro and Wallace, 2015).

There has therefore been a clear trend since 1989 for the numbers of producing companies in both freshwater and seawater to decrease, with production being concentrated within fewer, but larger specialist companies (Munro and Gauld, 1995, 1996, 1997; Stagg and Allan, 2001). The data also indicate that industry consolidation has been more pronounced in the seawater phase. Currently (2014 data) fewer companies operate in seawater than in freshwater (18 vs 26 respectively) which contrasts with the numbers of active sites (260 vs 96 respectively) (Munro and Wallace, 2015).

The reductions in numbers of companies appear to have occurred through company buy-outs and companies leaving the industry at times of perceived poor trading prospects, market uncertainty, and concern over disease (e.g. ISA) (Munro and Gauld, 1994, 1995; Stagg and Allan, 1999). Munro and Gauld (1997) reported "*a notable increase in the number of Scottish companies coming under foreign ownership*".

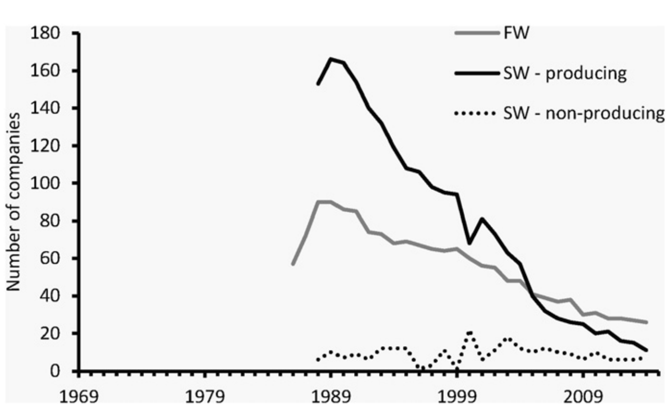

Fig. 17. Number of companies involved in freshwater (FW) or seawater (SW) salmon farming in Scotland. Data available 1986/1988–2014.

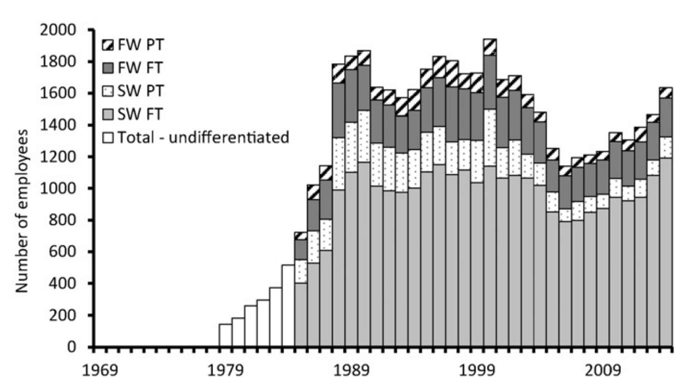

Fig. 18. Numbers of employees (FT = full time; PT = part-time) in the seawater (SW) and freshwater (FW) sectors of the Scottish salmon farming industry. Undifferentiated data available 1979–1984, differentiated data available 1985–2014.

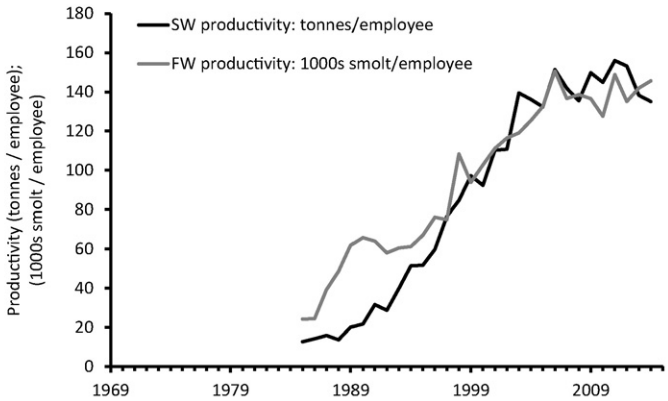

Fig. 19. Productivity of employees of the Scottish salmon industry for seawater (SW) and freshwater (FW) sectors. Data available 1985–2014.

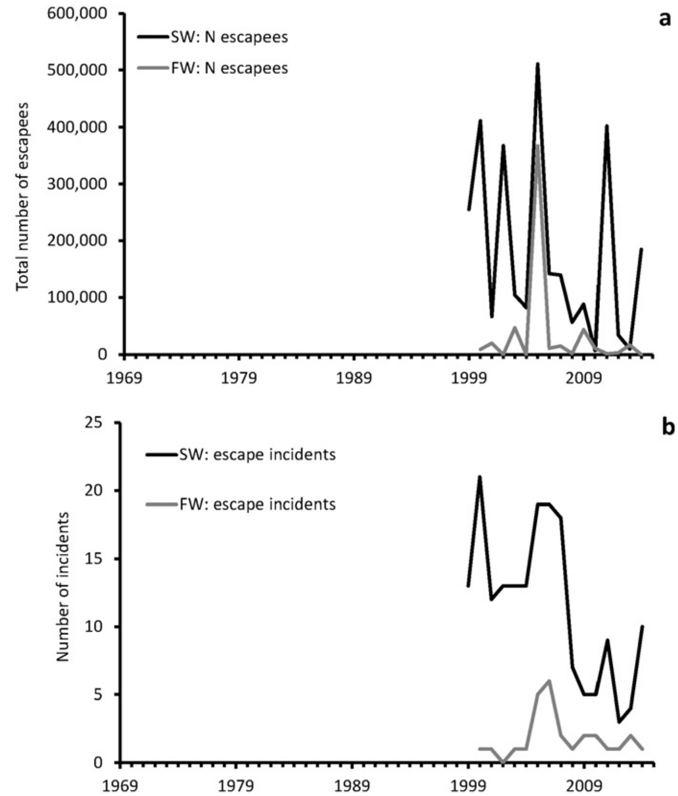

Fig. 20. Reported escapes from Scottish salmon farms in seawater (SW) and freshwater (FW). a: total number of escapees year^{-1} from freshwater (FW) and seawater (SW) farms. Data available 1999/2000–2014. b: Number of escape events (when fish escaped) year^{-1}. Data available 1999/2000–2014.

7.2. Numbers of employees

The salmon farming industry is an important source of employment to the communities of the Scottish west coast and Western Isles, and the Orkney and Shetland Islands (Stagg and Gauld, 1998; Stagg and Allan, 2000). Data on numbers of direct employees have been collated since the first report in 1979, although there was no differentiation between sectors and full- and part-time employees until 1985 (Fig. 18). Employee numbers include site, veterinary, harvesting, maintenance and administrative employees of the farming companies, but not processing or marketing staff (Munro and Gauld, 1995; Munro et al., 2014). Companies are asked to use their own discretion to categorise full- and part-time staff (Munro and Wallace, 2013). Part-time employees may therefore refer to seasonal and reduced daily hours staff.

Employment increased from 1979 to around 1700 employees in the period 1990–2000, decreased to 2006, and has since increased (Fig. 18). Employment is greater within the seawater sector than the freshwater sector, and full-time posts outnumber part-time posts. Changes in staffing levels remain largely unexplained by the annual reports, apart from:

- A sharp decrease in part-time freshwater employees in 1998 associated with the industry switching to contract vaccination service instead of direct employment of temporary staff (Stagg and Allan, 1999);
- A sudden increase in employment in 2000 when fallowed seawater sites were re-opened after the 1998 ISA outbreak (Stagg and Allan, 2001).

It has also been suggested that smaller producers employ proportionally more part-time staff and that the introduction of technology may give rise to specialist jobs (Munro and Gauld, 1997).

7.3. Employee productivity

Employee productivity is reported for both sub-sectors, i.e. production (total numbers of smolt from freshwater; total tonnage from seawater) in relation to the total number of employees (sum of full time and part time, without adjustment for hours worked) (Fig. 19). Since 1985, employee productivity has increased 6 fold for freshwater ($r_s = 0.956$, $n = 30$, $p < 0.001$) and 11-fold for seawater ($r_s = 0.946$, $n = 30$, $p < 0.001$).

The sudden increase in freshwater productivity in 1998 was associated with a reduction in temporary staff due to the switch to contract vaccination services (Stagg and Allan, 1999). However, the dramatic increases in staff productivity over the longer time period are attributed to:

- Economies of scale associated with larger sites (Munro and Gauld, 1996);
- Economies of scale associated with larger companies (Munro and Gauld, 1994, 1997; Stagg and Gauld, 1998; Walker, 2010);
- Introduction of technology, automation and mechanisation (Munro and Gauld, 1994; Stagg and Gauld, 1998);
- Increases in other efficiencies in husbandry (Stagg and Gauld, 1998), assumed to refer to improved survival, growth, and faster throughput of batches of fish.

8. Environmental pressures metrics

8.1. Escapes

Munro and Gauld (1996, 1997) suggested that escapes from seawater net-pens due to storm damage decreased in the mid-1990s as the industry and insurers gained experience. Statistics on escapes from seawater and freshwater farms have only been published since 1999 (Fig. 20). These data are based upon self-reporting by the industry, and reflect incidents when escapes occurred and, more recently, also incidents when no loss of fish was confirmed. Incidents occur when rearing units fail or are damaged (e.g. due to weather, predators, accidents) or errors are made during fish transfer. These statistics may therefore exclude any additional "trickle" losses of which farm staff are unaware. The number of fish escaping from seawater farms is greater than from freshwater farms (Fig. 20a; Friedman's test blocked by year: $\chi^2{}_r = 8.07$, $df = 1$, $p < 0.005$). For the seawater sector, the number of reported escape events has decreased ($r_s = -0.691$, $n = 16$, $p = 0.005$) although the total numbers of fish escaping has not reduced ($r_s = -0.409$, $n = 16$, $p > 0.1$). For the freshwater sector there is no evidence of change in either the number of escape events ($r_s = 0.243$, $n = 15$, $p > 0.2$) or numbers of escapees ($r_s = -0.157$, $n = 15$, $p > 0.5$).

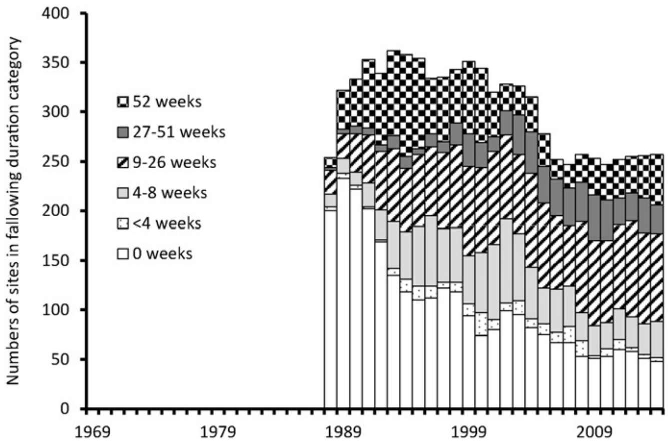

Fig. 21. Fallowing of seawater net-pen sites in Scottish salmon farming industry. Sites are categorised depending upon length of fallow period, and data is presented as number of sites in category. Data available 1988–2014.

8.2. Fallowing

Fallowing involves the removal of all fish and nets from net-pen sites and was introduced as an industry practice in the late 1980s for disease control purposes (DAFS, 1989; Munro and Gauld, 1996). A minimum routine fallow period of 6 weeks at the end of the seawater production phase is recommended by the fish health authority, to break any disease and parasite life cycles between successive salmon cohorts (Stagg and Allan, 2001). In 1998, the fish health authority imposed longer mandatory fallow periods to control outbreaks of a notifiable disease: the duration (6 weeks, 3 months or 6 months) depended upon classification of risk and confirmed or suspect disease presence, and simultaneous fallowing was coordinated within high risk zones (Stagg and Allan, 1999).

Data on fallowing of seawater net-pen sites have been reported since 1988 (Fig. 21). In 1989, the number of seawater cage sites using a fallow period was considered to be especially low at 7.4% (DAFS, 1990). However, the proportion of sites with no fallow period has decreased, and the frequency of longer fallow periods has increased. There is possible confusion in the early data due to differences in recording between years, i.e. whether sites are classed as "fallow for 52 weeks" or "not in production" (see Munro and Gauld, 1994).

Fallowing data were also reported for freshwater net-pen sites for 5 years (1988–1992), but the short time series is not presented here.

8.3. Accreditation schemes

Various accreditation schemes are available to the salmon farming industry that address control of environmental pressures, product quality, fish health, animal welfare, etc. The questionnaire asks salmon farming companies about membership of accreditation schemes, but data are only reported for organic production and since 2010. Organic production in Scotland is minor, representing 2% of seawater harvest and 3% of active seawater net-pen sites in 2014 (Munro and Wallace, 2015).

9. Discussion

9.1. Trends during the development of Scottish salmon farming

This review brings together time series data and explanatory notes from annual reports to illustrate and explain temporal trends in a wide variety of metrics for Scottish salmon farming. Key trends demonstrated during the evolution of this national aquaculture industry are likely to be relevant to other developing aquaculture sectors, i.e.:

- Improved control of production and scheduling illustrated by the switch from wild to farmed ova and the introduction of out-of-season smolt.
- Improved biological performance illustrated by increased survival, size at age (of smolt and harvested seawater fish) and yield per smolt. The reports highlight the role of improvements in husbandry, feed and disease control that have occurred through time. In the second annual report for 1980, Munro and Wadell (1981) recognised that "*salmon farming is growing rapidly and as might be expected with a species one stage removed from the wild, and with an evolving technology, the industry is experiencing some technical problems. However, it appears to be developing solutions and gaining confidence in the process*".
- Reduced duration of production cycle illustrated by the reduction in use of S2 smolt and harvest of input year fish.
- Introduction and uptake of vaccines. The reports indicate vaccines have been a key contributor to the development of salmon farming in Scotland. There are few other case studies that document vaccine usage within aquaculture (Bravo and Midtlyng, 2007).
- Introduction of technology and mechanisation. Although several reports do mention increased automation and use of technology, examples provided are restricted to remote sensors and computerised control of operations, water recirculation systems, automatic feeding systems, air lifts for mortality removal, swim through net changes, and cameras for monitoring stocks (Munro and Gauld, 1994, 1996, 1997).
- Improved supply chains illustrated by the industry overcoming the smolt supply shortage that restricted seawater production in the late 1970s, and international trade in ova.
- Consolidation. The initial increases in numbers of companies and production sites were followed by reductions. Consolidation of ownership into a few large firms has also occurred in Norway (Bergheim, 2012), and in Scotland is viewed as beneficial having professionalised the industry by improving standards, disease control and financial stability, thereby enabling growth (Marine Scotland, 2014). Naylor and Burke (2005) note vertical integration of salmon companies along a supply chain involving feed manufacture, hatchery and smolt production, seawater grow-out and processing.
- Increased production per farm — due to increased farm size and system productivity.
- Increasing productivity of manpower — attributed to increases in farm size and company size (providing economies of scale), mechanisation and system productivity.

Similar trends have been noted (albeit piecemeal) in the Norwegian salmon farming industry where expansion of production has been attributed to control of the biological production process, improved fish performance and culture systems, and economies of scale that have increased efficiency and reduced production costs (Bergheim and Brinker, 2003; Bergheim et al., 2009; Forster, 2010; Bergheim, 2012; Kristensen et al., 2012; Asche and Roll, 2013; Asche et al., 2013a,b; Shepherd and Little, 2014).

This review of the annual reports on Scottish salmon farming highlights other issues that are likely to be relevant to most aquaculture sectors:

- the importance of disease. Diseases have affected the Scottish salmon farming industry by reducing harvest through mortality of fish, lost growth (due to stress and inappetance), and early harvest. Lack of confidence in controlling disease has also affected investment, and the costs of controlling disease (manpower for application of chemical sea-lice treatments) can prove significant (Munro and Gauld, 1997). Disease has also been noted to affect ova supplies and employment. The importance of diseases to the salmon farming industries in

Norway and Chile has been highlighted (Tilseth et al., 1991; Asche et al., 2009; Forster, 2010; Asche and Bjørndal, 2011; Asche and Roll, 2013) and FAO (2012) note the common importance of disease to aquaculture. Effective disease management – via reduced stress in stocks, vaccination, fallowing, area management agreements, biosecurity etc. – is recognised to have been vital to the success of Scottish salmon farming.
- the international nature of aquaculture, as illustrated by imports and exports of ova and ownership by foreign companies. The Scottish salmon farming industry is now concentrated within four large companies, predominantly Norwegian-owned, which operate UK-registered subsidiaries within a group structure (Marine Scotland, 2014).
- the role of legislation/regulation, as illustrated by restrictions on net-pen site biomass, and increased use of foreign ova following regulatory changes.
- the occurrence of episodic events: in 1993, for example, contamination of farmed salmon from a major oil spill occurred with 3,549 t of salmon slaughtered and lost to the human food chain, being used as food for mink (Munro and Gauld, 1994).

9.2. Development of Scottish salmon farming in relation to sustainable intensification

The future challenge for both terrestrial and aquatic farming is to achieve sustainable intensification, i.e. increase production whilst increasing the efficiency of resource use and safeguarding the environment, the nutritional value of products, the welfare of farmed stocks and rural economies (Godfray et al., 2010; Garnett et al., 2013). The Scottish salmon farming industry has increased harvest production over time (Fig. 5) and shown trends in factors commonly associated with intensification, i.e. increases in system size (i.e. net-pens, Bergheim, 2012), farm size, individual farm output, and employee productivity (Figs. 8, 9, 19).

9.2.1. Increasing productivity

System productivity (i.e. production m^{-3} $year^{-1}$) has increased for freshwater land-based systems and seawater net-pens (Fig. 10). System productivity is a function of fish stocking density, throughput, and the rate of biomass increase. Freshwater land-based system productivity has increased through increased stocking density and extension of the growing season enabling production of more than one batch of fish each year (Stagg and Allan, 1999). Increases in throughput and stocking density do not appear to account for the increase in seawater net-pen productivity between 1988 and 1996: fallow (i.e. non-productive) periods increased (Fig. 21) and stocking density was decreased in the early 1990s to aid disease management (SOAFD, 1992; FAWC, 1996). Stocking density in seawater net-pens appears to have remained unchanged since with the introduction of a widely adopted fish welfare accreditation scheme (FAWC, 2014). Increased seawater net-pen productivity can therefore be assumed to be due to improved biological performance (illustrated by size at age, survival and yield relative to input; Figs. 12–14). Salmon farming is still a young industry (in comparison to agricultural activities) and such improvements can be expected with operational experience (DAFS, 1982; Marine Scotland, 2014).

9.2.2. Selecting appropriate genotypes

A key means of improving biological performance is selecting genotypes best suited to farm conditions (Godfray et al., 2010). Farmed salmon have now been selectively bred over more than eight generations for a number of traits (growth rate, resistance to disease, age at sexual maturity, feed conversion efficiency, fillet yield, flesh quality and colour) and represent one of the most genetically improved stocks within aquaculture (Asche and Bjørndal, 2011; Telechea and Fontaine, 2014). However, little information has been published on selective breeding and strains used within the Scottish industry. Munro and Gauld (1997) mention selection of broodstock for low grilsing rates (i.e. reaching sexual maturity after >1 winter at sea), and spawning early or late within the reproductive season. The wild Scottish salmon strains initially used matured early (i.e. showed a "high grilsing rate") in culture, which was undesirable as it reduced growth and market value. The industry has therefore switched to later maturing Norwegian and hybrid strains (www.fao.org/fishery/culturedspecies/Salmo_salar/en accessed 5 March 2015).

9.2.3. Reducing waste

The Scottish salmon farming industry has reduced waste associated with mortalities (Fig. 13); continued improvement in disease control and containment would further reduce such waste. Additional reductions in unused ova and smolt produced but not put to sea (Figs. 2a, 3a) may be possible. Data from Norway indicate reductions in feed waste: feed conversion ratio (FCR = mass of feed provided: net increase in fish biomass, within a specific period) has improved for freshwater (around 2 in 1985 to 1 in 2000) and seawater salmon farming (from 3 in 1980 to around 1.1) attributed to improved nutritional formulation, pellet quality, feeding systems and fish survival (Asche et al., 1999; Bergheim and Brinker, 2003; Forster, 2010; Shepherd and Little, 2014). Such temporal data are lacking for Scotland, but similar reductions are likely to have occurred. However, the seawater FCR in Scotland (1.3) has been suggested to be higher than in Norway (Pelletier et al., 2009).

9.2.4. Reducing resource inputs and environmental pressures

Environmental pressures from salmon farming are recognised as key sustainability issues for its future in Scotland and elsewhere (Jones et al., 2015). Although the different environmental pressures have each attracted considerable research attention and discussion, consensus is often lacking as to whether they do result in environmental impacts (Forster, 2010). The issues are listed below, and supporting time series data are cited where available (notably from Norway):

- Resource use and emissions: Bergheim and Brinker (2003) indicated a 5 fold improvement in the efficiency of freshwater use in Norwegian salmon smolt farms between 1985 and 2000, due to introduction of water treatment technology. Recent (snapshot) Life Cycle Assessments indicate that the global environmental pressures of farmed salmon products – via resource use (energy) and emissions (greenhouse gases, nitrogen phosphorous) – are similar to those from fishery production, and lower than terrestrial meat farming (Ellingsen and Aanondsen, 2006; Pelletier and Tyedmers, 2007; Hall et al., 2011; Ytrestøyl et al., 2011). Nevertheless, salmon production in Scotland is judged to have higher impacts than in other countries due to differences in feed ingredients (Pelletier et al., 2009).
- Eutrophication and organic enrichment: Bergheim and Brinker (2003) provided data illustrating substantial reductions in the discharge of suspended solids, nitrogen and phosphorous from Norwegian salmon smolt farms between 1985 and 2000. Comparable data for seawater farms are lacking. Temporal changes in feed formulation, feeding methodology and food conversion, improved site selection, management and regulation, and an increase in fallowing (largely for pathogen management) can be expected to have reduced discharge pressures (Shepherd and Little, 2014).
- Discharge of chemicals. Since the 1980s, there have been substantial reductions in the use and discharge of i) chemicals used to control sea-lice and algal fouling and ii) antibiotics in Norwegian seawater farms (Asche et al., 1999; Tveteras, 2002; Forster, 2010; Asche and Bjørndal, 2011); the latter reduction is attributed to the introduction of vaccines and improved disease control

(Shepherd and Little, 2014).

- Transfer of disease to wild stocks: Despite improved disease control within farmed stocks, disease pressures on wild stocks, notably from sea-lice, remain a topic of concern (Torrissen et al., 2013; Shepherd and Little, 2014). Pathogen pressures on wild stocks will depend upon pathogen prevalence in farmed stocks, the size of farmed stocks, and the overlap between farmed and wild fish in space and time (McVicar, 1997). Farmed stock sizes have increased over time within Scotland (Fig. 3b). The Scottish salmon industry is required to maintain sea-lice below threshold infection levels, and its trade body has recently started publication of sea-lice counts (e.g. SSPO, 2015), so data may become available to assess trends in pathogen pressure.
- Escapee impacts on wild populations: There is evidence that the numbers of seawater escape events in Scotland has decreased since 1999, although there are no significant trends for the numbers of freshwater escape events and freshwater and seawater escapees (Fig. 20). Reducing the number of escapees should reduce pressures (competition, introgression) on wild stocks. Concern has been focussed on genetic introgression leading to loss of local adaptations and reduced fitness (McGinnity et al., 2003). Although data are lacking for Scotland, evidence for genetic introgression in wild salmon populations has been reported from Norway, Ireland and North America (Glover et al., 2013). Production of female triploid salmon ova in Scotland was reported between 1989 and 1992 (DAFS, 1990; SOAFD, 1991, 1992, 1993) and, due to sterility, is being reconsidered to eliminate genetic introgression pressures, although concerns related to performance within aquaculture remain (Maxime, 2008). In contrast, the Scottish rainbow trout (*Oncorhynchus mykiss*) farming industry has embraced the use of triploid (and all female) ova (Munro and Wallace, 2015).
- Use of reduction fishery products in salmon feed. Although reduction fishery products (fish meal and oil) are major salmon feed components, there is evidence for trends of decreasing use (Shepherd, 2012; Shepherd and Jackson, 2013). Such components of salmon diets are increasingly sourced from certified sustainable fisheries, processing trimmings and by-products, or substituted by other vegetable and land animal sources (Shepherd, 2012; Shepherd and Jackson, 2013; Shepherd et al., 2015). An index of efficiency of conversion of the fish dietary ingredients to harvested salmonid (i.e. fish in: fish out ratio) has shown a trend for improvement over the period 2000–2010 (Shepherd and Jackson, 2013; Shepherd and Little, 2014).

9.2.5. Safeguarding nutritional value

Salmon, as an oily fish, is a source of high quality animal protein, essential fatty acids and micronutrients to human consumers (Beveridge et al., 2013). Health risks associated with consumption of farmed salmon have been raised (due to concentration of environmental contaminants within the food chain) but it is now accepted that the health benefits of eating farmed salmon far outweigh the risks (Shepherd, 2012). There is an apparent lack of data to assess whether the nutritional value (both health benefits and risks) of Scottish farmed salmon has changed over time with changes in feed composition and production. The need for the Scottish industry to maintain the nutritional value of its products has recently been highlighted (Shepherd et al., 2015).

9.2.6. Safeguarding animal welfare

Animal welfare relates to suffering. If the potential for suffering to occur during farming is considered in terms of animal-weeks (animal numbers × production cycle duration), then salmon farming does merit scrutiny of animal welfare:

- the numbers of animals involved in salmon farming is high: the 2014 year-class started with 70.8 million individual ova laid down, and 34.3 million seawater fish were slaughtered for harvest in 2014 (Table 1). Lymbery (2002) recognised the high number of individual salmon farmed, suggesting it was only exceeded by broiler (meat chicken) farming in the UK.
- The production cycle is of a long duration: 0.5–2 years in freshwater, followed by 0.5–2 years in seawater. This compares to 6 weeks from hatch to slaughter for broiler chickens (FAWC, 1992).

The data indicate that performance-based measures of fish welfare, i.e. growth and survival (Figs. 12, 13) have improved over time within freshwater and seawater Scottish salmon farms. These improvements (associated with increased productivity; Figs. 10, 14) occurred against a backdrop of increasing rearing unit size, farm size and output (Figs. 8a, 9) and reducing staff input relative to production (Fig. 19). This finding counters the common assumption that intensification compromises measures of animal welfare and supports the increasing preference for performance outcome measures over resource inputs for assessing farmed animal welfare (Main et al., 2012). Although it cannot be assumed that such performance measures do address all welfare concerns (Kristensen et al., 2012) increases in survival and growth strongly indicate improvements in health and meeting of dietary and environmental needs (Ellis et al., 2012). Kristensen et al. (2012) also concluded that intensification does not necessarily adversely affect performance measures of salmon welfare on commercial farms in Norway.

Although there is evidence that the welfare of farmed salmon in Scotland has improved over time, there may be potential for further improvement. Recent values for freshwater survival in Scotland (60–70%; Fig. 13) are apparently lower than in Norway where a value of 80% is quoted (Asche and Bjørndal, 2011). Recent values for seawater survival in Scotland (77–85%; Fig. 13) are also below the 90% figure cited by Asche and Bjørndal (2011), although similar to the 80% value suggested by Shepherd and Little (2014).

9.2.7. Safeguarding rural economies

No data are available to examine trends in the contribution of salmon farming to rural communities in Scotland. Nevertheless, a recent assessment (Marine Scotland, 2014) indicates that salmon farming in Scotland has become an “anchor industry” sustaining fragile rural communities that are at risk of population decline due to a lack of alternative economic options by providing:

- direct employment for farm-based workers at a range of skill levels. Work is suitable for school leavers and people of child bearing age, and the skills learnt are transferable;
- an income stream to local suppliers and service providers, e.g. divers, hauliers, welders, electricians, engineers and local mechanics servicing vehicles and boats, trainers in boat handling;
- support for infrastructure with shops, schools, housing, transport (roads, ferries, harbours, piers, slipways) and services (haulage, power, broadband) being sustained by the circulation of income and a strengthened local population.

Salmon farming in Scotland is viewed as a natural resource-based means of wealth creation, with socio-economic benefits extending beyond local communities (Marine Scotland, 2014). The industry also has ancillary workers (e.g. logistics and management; marketing; vaccination, veterinary and consultant services; well boat operators) and the supply chain extends both upstream (e.g. feed suppliers, equipment manufacturing, boat and feed barge suppliers, hauliers) and downstream (e.g. harvest stations, processors, retailers). The salmon farming industry in Scotland is therefore considered important for its socio-economic benefits, concurring with a similar recent assessment in Norway (Robertsen et al., 2012).

9.2.8. Maximising conversion efficiency

In addition to the strategies associated with sustainable intensification of existing farms, human diets need to change towards products from trophic levels and farming systems that maximise conversion efficiency (Godfray et al., 2010). Although concern has been expressed about the dominance of fed species such as salmon in global aquaculture:

- Food conversion efficiency in farmed salmon has improved over time (see 9.2.4);
- Farmed fish are well recognised as more efficient converters of food to edible product than terrestrial livestock as they have a low energy protein metabolism pathway, do not expend energy on maintaining body temperature (being poikilothermic) or a large bony skeleton (being supported by the water), and the latter attribute also provides a higher yield of edible flesh (Hall et al., 2011; Shepherd and Little, 2014).
- Farmed salmonids are more efficient converters of food than wild carnivorous fish as they use less energy (Shepherd and Jackson, 2013; Shepherd and Little, 2014).

9.3. The value of collecting data on aquaculture

The development of aquaculture, be it new or existing sectors, requires examination and planning by governments, regulators, and the industry itself. This review has demonstrated the merit in collecting and publishing consistent time series data on industry wide metrics enabling assessment of trends, identifying areas of underperformance, and assessing resource use, environmental pressures and sustainability. Monitoring of aquaculture sectors is therefore an important contributor to enabling sustainable development. Further examples of the use of performance indicators include:

- Strategic planning: The Scottish salmon industry is becoming increasing reliant on imports of foreign ova (Fig. 2). The annual reports of the Scottish finfish farming industry (e.g. Smith, 2006, 2007, 2008) also include production data for species proposed to diversify the seawater net-pen sector, i.e. halibut and Atlantic cod (*Gadus morhua*); such species have not yet shown substantial expansion.
- Benchmarking: Munro and Gauld (1994) suggested that i) survival higher than 90% was often recorded in individual net-pen populations of seawater salmon, and this should be a standard achievable by all sites, and ii) some companies fell below industry norms for employee productivity and could improve.
- Intra-national comparisons: SOAFD (1991, 1993) noted that the Shetland region produced the largest grilse, pre-salmon and salmon, and suggested that the more northern waters favoured salmon growth.
- International comparisons: In early reports, DAFS (1982, 1983) judged that Scottish salmon farming lagged behind the Norwegian industry, both in terms of production numbers and performance. For example, survival of 1979 and 1980 smolt to harvest in Scotland (53% and 51%) compared poorly to that in Norway of 70% (DAFS, 1983).

Salmon production in Scotland increased until 2003, but then fell and only in 2014 did production exceed that previous peak by 5% (Fig. 5). In contrast, annual production in Norway and Chile has grown by 142% and 38% respectively over a similar period (Fig. 1). Asche and Bjørndal (2011) suggest access to new farm sites is limiting expansion of salmon farming in Scotland, and increases in harvest need to come from further increases in system productivity.

Gaps in the published statistics for Scotland relate to some biological metrics (e.g. smolt size, use of cleaner fish for biological control of sea-lice), system types (e.g. RAS or flow through land-based systems; inshore or offshore net-pens) and environmental and socio-economic performance indicators. Extending publication to include environmental pressures would allow open scrutiny of evidence and trends to be assessed. Data and trends provide evidence to both highlight problems within, and respond to criticisms of, aquaculture (e.g. Naylor and Burke, 2005; Shepherd and Jackson, 2013; Shepherd and Little, 2014). Economic data on salmon farming in Norway has been collected and published for a number of years enabling analysis (Forster, 2010; Asche and Bjørndal, 2011; Asche et al., 2013a; Oglend, 2013; Shepherd and Little, 2014) but similar information is not readily available for Scotland. Within the annual reports, information is limited to a single statement for 1996, referring to a decrease in market price of salmon and profitability (Munro and Gauld, 1997). Gathering valid data on environmental and financial indicators may, however, prove difficult due to practical and confidentiality issues.

Acknowledgements

This review represents an output from two projects: SARF082 Scottish aquaculture's utilisation of environmental resources, funded by the Scottish Aquaculture Research Forum; AW1209 Study to identify ways of reducing farmed fish fin damage in hatcheries, funded by the Department of Environment, Food and Rural Affairs. Thanks to: Jackie Brown (MSS library) for providing pdfs of the historical DAFS/SOAFD/FRS annual production reports, and Sandy Murray (MSS) for commenting on a draft of the manuscript. The authors have no conflicts of interest to declare.

References

Amberg, S.M., Hall, T.E., 2008. Communicating risks and benefits of aquaculture: a content analysis of US newsprint representations of farmed salmon. J. World Aquacult. Soc. 39, 143–157.
Asche, F., Roll, K.H., 2013. Determinants of inefficiency in Norwegian salmon aquaculture. Aquac. Econ. Manag. 17, 300–321.
Asche, F., Guttormsen, A.G., Tveterås, R., 1999. Environmental problems, productivity and innovations in Norwegian salmon aquaculture. Aquac. Econ. Manag. 3, 19–29.
Asche, F., Hansen, H., Tveteras, R., Tveteras, S., 2009. The salmon disease crisis in Chile. Mar. Resour. Econ. 24, 405–411.
Asche, F., Guttormsen, A.G., Nielsen, R., 2013a. Future challenges for the maturing Norwegian salmon aquaculture industry: an analysis of total factor productivity changes from 1996 to 2008. Aquaculture 396–399.
Asche, F., Roll, K.H., Sandvold, H.N., Sorvig, A., Zhang, D., 2013b. Salmon aquaculture: larger companies and increased production. Aquac. Econ. Manag. 17, 322–339.
Asche, F., Bjørndal, T., 2011. The Economics of Salmon Aquaculture. second ed. Wiley-Blackwell, Chichester, UK.
Aunsmo, A., Skjerve, E., Midtlyng, P., 2013. Accuracy and precision of harvest stock estimation in Atlantic salmon farming. Aquaculture 396–399, 113–118.
Bergheim, A., 2012. Recent growth trends and challenges in the Norwegian aquaculture industry. Lat. Am. J. Aquat. Resour. 40, 800–807.
Bergheim, A., Brinker, A., 2003. Effluent treatment for flow through systems and European environmental regulations. Aquac. Eng. 27, 61–77.
Bergheim, A., Drengstig, A., Ulgenes, Y., Fivelstad, S., 2009. Production of Atlantic salmon smolt in Europe — current characteristics and future trends. Aquac. Eng. 41, 46–52.
Beveridge, M.C.M., Thilsted, S.H., Phillips, M.J., Metian, M., Troell, M., Hall, S.J., 2013. Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculture. J. Fish Biol. 83, 1067–1084.
Bravo, S., Midtlyng, P.J., 2007. The use of fish vaccines in the Chilean salmon industry 1999–2003. Aquaculture 270, 36–42.
DAFS, 1982. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1981. DAFS (2 pp.).
DAFS, 1983. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1982. DAFS (7 pp.).
DAFS, 1984. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1983. DAFS (11 pp.).
DAFS, 1985. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1984. DAFS (6 pp.).
DAFS, 1986. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1985. DAFS (8 pp.).
DAFS, 1987. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1986. Department of Agriculture and Fisheries for Scotland (8 pp.).
DAFS, 1988. Salmon and Trout Farming in Scotland — Report of Results of DAFS Annual Survey 1987. Department of Agriculture and Fisheries for Scotland (11 pp.).

DAFS, 1989. Report of the DAFS Annual Survey of Fish Farms for 1988. DAFS (11 pp.).
DAFS, 1990. Report of the DAFS Annual Survey of Fish Farms for 1989. DAFS (14 pp.).
Ellingsen, H., Aanondsen, S.A., 2006. Environmental impacts of wild caught cod and farmed salmon — a comparison with chicken. Int. J. Life Cycle Assess. 1, 60–65.
Ellis, T., Berrill, I., Lines, J., Turnbull, J., Knowles, T.G., 2012. Mortality and fish welfare. Fish Physiol. Biochem. 38, 189–199.
FAO, 2007. Aquaculture — the only way to fill the coming "fish gap": outcomes of the high level special event on aquaculture. FAO Aquacult. Newsl. 39, 4–5 (http://www.fao.org/docrep/014/i0148e/i0148e00.htm accessed 5 March 2015).
FAO, 2012. The State of World Fisheries and Aquaculture 2012 (Rome. 209 pp.).
FAO, 2014. The State of World Fisheries and Aquaculture 2014 (Rome. 223 pp.).
FAWC, 1992. Report on the Welfare of Broiler Chickens. Farm Animal Welfare Council, London (37 pp.).
FAWC, 1996. Report on the Welfare of Farmed Fish. Farm Animal Welfare Council, London (52 pp.).
FAWC, 2014. Opinion on the Welfare of Farmed Fish. Farm Animal Welfare Committee, London (40 pp.).
Forster, J., 2010. What can U.S. open ocean aquaculture learn from salmon farming? Mar. Technol. Soc. J. 44, 68–79.
Garnett, T., Appleby, M.C., Balmford, A., et al., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34.
Glover, K.A., Pertoldi, C., Besnier, F., Wennevik, V., Kent, M., Skaala, Ø., 2013. Atlantic salmon populations invaded by farmed escapees: quantifying genetic introgression with a Bayesian approach and SNPs. BMC Genet. 14, 74.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., et al., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.
Hall, S.J., Delaporte, A., Phillips, M.J., Beveridge, M., O'Keefe, M., 2011. Blue Frontiers: Managing the Environmental Costs of Aquaculture. The WorldFish Center, Penang, Malaysia (103 pp.).
Hastings, T.S., Smith, R.J., 2005. Scottish Fish Farms Annual Production Survey, 2003. Fisheries Research Services (53 pp.).
Hawkins, S.J., Firth, L.B., McHugh, M., et al., 2013. Data rescue and re-use: recycling old information to address new policy concerns. Mar. Policy 42, 91–98.
Jones, A.C., Mead, A., Kaiser, M.J., et al., 2015. Prioritization of knowledge needs for sustainable aquaculture: a national and global perspective. Fish Fish. 16, 668–683.
Kristensen, T., Haugen, T.O., Rosten, T., Fjellheim, A., Atland, A., Rosseland, B.O., 2012. Effects of production intensity and production strategies in commercial Atlantic salmon smolt (*Salmo salar* L.) production on subsequent performance in the early sea stage. Fish Physiol. Biochem. 38, 273–282.
Lymbery, P., 2002. In Too Deep — the Welfare of Intensively Farmed Fish. Compassion in World Farming Trust, Hampshire (56 pp.).
Main, D.C.J., Mullan, S., Atkinson, C., Bond, A., Cooper, M., Fraser, A., Browne, W.J., 2012. Welfare outcomes assessment in laying hen farm assurance schemes. Anim. Welf. 21, 389–396.
Marine Scotland, 2014. An Assessment of the Benefits to Scotland of Aquaculture. Marine Scotland (164 pp. http://www.gov.scot/Topics/marine/Publications/publicationslatest/farmedfish/AqBenefits accessed 5 March 2015).
Maxime, V., 2008. The physiology of triploid fish: current knowledge and comparison with diploid fish. Fish Fish. 9, 67–78.
McGinnity, P., Prodöhl, P., Ferguson, A., et al., 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proc. R. Soc. Lond. B 270, 2443–2450.
McVicar, A.H., 1997. Disease and parasite implications of the coexistence of wild and cultured Atlantic salmon populations. ICES J. Mar. Sci. 54, 1093–1103.
Munro, A.L.S., Gauld, J.A., 1994. Scottish Fish Farms Annual Production Survey, 1993. SOAFD (32 pp.).
Munro, A.L.S., Gauld, J.A., 1995. Scottish Fish Farms Annual Production Survey 1994. Marine Laboratory Aberdeen (35 pp.).
Munro, A.L.S., Gauld, J.A., 1996. Scottish Fish Farms Annual Production Survey 1995. Marine Laboratory Aberdeen (36 pp.).
Munro, A.L.S., Gauld, J.A., 1997. Scottish Fish Farms Annual Production Survey 1996. Marine Laboratory Aberdeen (35 pp.).
Munro, A.L.S., Wadell, I.F., 1981. Annual Report for 1980 on the Production of the Scottish Salmon and Trout Farming Industry. DAFS (4 pp.).
Munro, L.A., Wallace, I.S., 2013. Scottish Fish Farm Production Survey 2012. Marine Scotland Science (54 pp.).
Munro, L.A., Wallace, I.S., 2015. Scottish Fish Farm Production Survey 2014. Marine Scotland Science (53 pp.).
Munro, A.L.S., Wadell, I.F., Elso, K.G.R., 1980. Report on the Growth of Scottish Salmonid Fish Farms and their Production and Manpower in 1979. DAFS Marine Lab (8 pp.).
Munro, L.A., Warwick, A.L., Wallace, I.S., 2014. Scottish Fish Farm Production Survey 2013. Marine Scotland Science (48 pp.).
NASCO, 2014. Report of the thirty-first annual meeting of the council, Saint-Malo, France, 3–6 June 2014. (CNL(14)58, 291 pp. http://www.nasco.int/reports_annual.html accessed 5 March 2015).
Naylor, R., Burke, M., 2005. Aquaculture and ocean resources: raising tigers of the sea. Annu. Rev. Environ. Resour. 30, 185–218.
Oglend, A., 2013. Recent trends in salmon price volatility. Aquac. Econ. Manag. 17, 281–299.
Pelletier, N., Tyedmers, P., 2007. Feeding farmed salmon: is organic better? Aquaculture 272, 399–416.
Pelletier, N., Tyedmers, P., Sonesson, U., et al., 2009. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. Environ. Sci. Technol. 43, 8730–8736.
Robertsen, R., Andreassen, O., Iversen, A., 2012. Havbruksnæringens ringvirkninger i Troms. Rapport/Report 28/2012. Nofima (52 pp. [In Norwegian]. http://www.nofima.no/filearchive/Rapport%2028–2012.pdf accessed 5 March 2015).
Scottish Executive, 2002. Review and Synthesis of the Environmental Impacts of Aquaculture. Scottish Executive Central Research Unit (62 pp. http://www.gov.scot/Resource/Doc/46951/0030621.pdf accessed 5 March 2015).
Seafish, 2011. Market based questions (as at April 2011). What is the most popular fish in the UK? (http://www.seafish.org/media/486918/faqs%20web%20version%20010711.pdf accessed 5 March 2015).
Seafish, 2012. Responsible Sourcing Guide: Farmed Atlantic Salmon. http://www.seafish.org.uk/media/Publications/SeafishResponsibleSourcingGuide_Atlanticsalmon_201208.pdf (accessed 5 March 2015).
Shepherd, J., 2012. Aquaculture: are the criticisms justified? Feeding fish to fish. World Agric. 3 (2), 11–18.
Shepherd, C.J., Jackson, A.J., 2013. Global fishmeal and fish-oil supply: inputs, outputs and markets. J. Fish Biol. 83, 1046–1066.
Shepherd, C.J., Little, D.C., 2014. Aquaculture: are the criticisms justified? II — aquaculture's environmental impact and use of resources, with specific reference to farming Atlantic salmon. World Agric. 4 (2), 37–52.
Shepherd, J., Monroig, O., Tocher, D.R., 2015. Production of high quality, healthy farmed salmon from a changing raw material base, with special reference to a sustainable Scottish industry. Scottish Aquaculture Research Forum (159 pp. http://www.sarf.org.uk/cms-assets/documents/216181-554802.sarfsp007.pdf accessed 8 February 2016).
Smith, R.J., 2006. Scottish Fish Farms Annual Production Survey, 2005. Fisheries Research Services (53 pp.).
Smith, R.J., 2007. Scottish Fish Farms Annual Production Survey, 2006. Fisheries Research Services (53 pp.).
Smith, R.J., 2008. Scottish Fish Farms Annual Production Survey, 2007. Fisheries Research Services (53 pp.).
Smith, R.J., Bland, M.D., Hastings, T.S., 2005. Scottish Fish Farms Annual Production Survey, 2004. Fisheries Research Services (53 pp.).
SOAFD, 1991. Annual Survey of Fish Farms — 1990 (Revised). DAFS (16 pp.).
SOAFD, 1992. Report of the SOAFD Annual Survey of Fish Farms for 1991. SOAFD (14 pp.).
SOAFD, 1993. Report of the SOAFD Annual Survey of Fish Farms for 1992. SOAFD (15 pp.).
SSPO, 2015. Fish health management report October to December 2014. http://scottishsalmon.co.uk/wp-content/uploads/2015/02/Fish-Health-Management-report-Q4-2014.pdf (accessed 5 March 2015).
Stagg, R.M., Allan, C.E.T., 1999. Scottish Fish Farms Annual Production Survey 1998. Fisheries Research Services (36 pp.).
Stagg, R.M., Allan, C.E.T., 2000. Scottish Fish Farms Annual Production Survey 1999. Fisheries Research Services (36 pp.).
Stagg, R.M., Allan, C.E.T., 2001. Scottish Fish Farms Annual Production Survey 2000. Fisheries Research Services (36 pp.).
Stagg, R.M., Allan, C.E.T., 2002. Scottish Fish Farms Annual Production Survey, 2001. Fisheries Research Services (53 pp.).
Stagg, R., Gauld, J.A., 1998. Scottish Fish Farms Annual Production Survey 1997. Fisheries Research Services (40 pp.).
Stagg, R.M., Smith, R.J., 2003. Scottish Fish Farms Annual Production Survey, 2002. Fisheries Research Services (53 pp.).
Telechea, F., Fontaine, P., 2014. Levels of domestication in fish: implications for the sustainable future of aquaculture. Fish Fish. 15, 181–195.
Tilseth, S., Hansen, T., Møller, D., 1991. Historical development of salmon culture. Aquaculture 98, 1–9.
Torrissen, O., Jones, S., Asche, F., et al., 2013. Salmon lice — impact on wild salmonids and salmon aquaculture. J. Fish Dis. 36, 171–194.
Tveteras, R., 2002. Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industry growth. Mar. Resour. Econ. 17, 121–132.
Walker, A.J., 2009. Scottish Fish Farms Annual Production Survey 2008. Marine Scotland (53 pp.).
Walker, A.J., 2010. Scottish Fish Farm Production Survey 2009 Report. Marine Scotland Science (58 pp.).
Walker, A.J., McAlister, J.M., 2011. Scottish Fish Farm Production Survey 2010 Report. Marine Scotland Science (56 pp.).
Walker, A.J., Wallace, I.S., Munro, L.A., 2012. Scottish Fish Farm Production Survey 2011. Marine Scotland Science (58 pp.).
Ytrestøyl, T., Aas, T.S., Berge, G.M., Hatlen, B., Sørensen, M., Ruyter, B., Thomassen, M., Hognes, E.S., Ziegler, F., Sund, V., Åsgård, T., 2011. Resource utilisation and eco-efficiency of Norwegian salmon farming in 2010. Nofima Report 53/2011 (65 pp.).