Aquaculture 396–399 (2013) 43–50

Contents lists available at SciVerse ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Future challenges for the maturing Norwegian salmon aquaculture industry: An analysis of total factor productivity change from 1996 to 2008

Frank Asche [a], Atle G. Guttormsen [b,*], Rasmus Nielsen [c]

[a] *Department of Industrial Economics, University of Stavanger, Ullandhaug N-4036, Stavanger, Norway*
[b] *UMB school of Economics and Business, Norwegian University of Life Sciences, P.O. Box 5003, N-1432, Aas, Norway*
[c] *Institute of Food and Resource Economics, University of Copenhagen, DK-1958 Frederiksberg C, Denmark*

ARTICLE INFO

Article history:
Received 4 November 2011
Received in revised form 22 August 2012
Accepted 13 February 2013
Available online 27 February 2013

Keywords:
Salmon aquaculture
Total factor productivity
Data envelopment analysis
Malmquist index

ABSTRACT

In this paper, we analyze total factor productivity change in the Norwegian salmon aquaculture sector from 1996 to 2008. During this period, the production has on average been growing with 8% per year. At the same time, the price of salmon has stabilized indicating that an increase in demand is driving the production growth rather than increasing productivity in the sector.

A Malmquist index approach is used to calculate total factor productivity change applying data envelopment analysis to construct the underlying production frontier. Furthermore, the bootstrap approach has been applied to construct confidence intervals for the Malmquist change indices. The results show a total factor productivity change of 1–2% a year, where the contribution from technical efficiency change is between 0.2 and 1.2% and technological change is between 0.6 and 0.8%.

The results show that productivity growth has slowed down over the years indicating that demand growth is the main driver of production growth. Furthermore, as productivity growth is slowing down production growth can only happen when the production area is increased. The scarcity of suitable production sites can potentially be the most limiting factor to future production growth in the salmon aquaculture industry.

1. Introduction

Aquaculture has been the world's fastest growing animal food producing industry during the last decades (Food and Agriculture Organisation of the United Nations, 2009). The main factor causing this development is widely recognized to be that control with the biological production process has led to a tremendous growth in productivity (Anderson, 2002; Asche, 2008; Smith et al., 2010). The control with the production process has allowed systematic R&D at all levels in the supply chain from input providers (Asche, 2008; Tveteras and Heshmati, 2002), production and quality control (Forsberg and Guttormsen, 2006) and downstream due to improvements in logistics and sales (Asche et al., 2007b; Kvaløy and Tveteras, 2008; Larsen and Asche, 2011). However, the main focus when studying productivity growth in aquaculture has been on the production plants or farms (Sharma and Leung, 2003), as this is the key element in the successful aquaculture industry.

Salmon is one of the most successful aquaculture species, and productivity growth has been the main engine for the production growth (Asche, 2008). Productivity can be regarded as a performance measure, as more efficient firms produce more output with a set of inputs. Innovations increase productivity by influencing the output/input ratio. For instance, better breeds lead to increased productivity because they have better growth for the same input mix. In the case of Norwegian salmon production there is increasing evidence that the productivity growth is slowing down. An indication of this feature is shown in Fig. 1. While the real price of salmon was rapidly declining until the late 1990s, indicating that productivity growth was faster than demand growth, the price of salmon stabilized in the late 1990s (Fig. 2). The relatively constant price during the last decade is an indication that productivity grows at a similar pace as demand. However, the production growth, which is the volume of output produced relative to the year before, has on average been growing with 8% per year from 1996 to 2008. With a fairly constant price, this implies a demand growth of 8%, which is very close to what is reported by Asche et al. (2011).

This raises two interesting questions. Is it the demand growth that has picked up pace or is it productivity growth that has slowed down? Moreover, if productivity growth is slowing down, the only way for production to increase is by the use of more inputs. That is

---

* Corresponding author. Tel.: +47 64965691.
E-mail addresses: frank.asche@uis.no (F. Asche), atle.guttormsen@umb.no (A.G. Guttormsen), rn@foi.dk (R. Nielsen).

0044-8486/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.aquaculture.2013.02.015

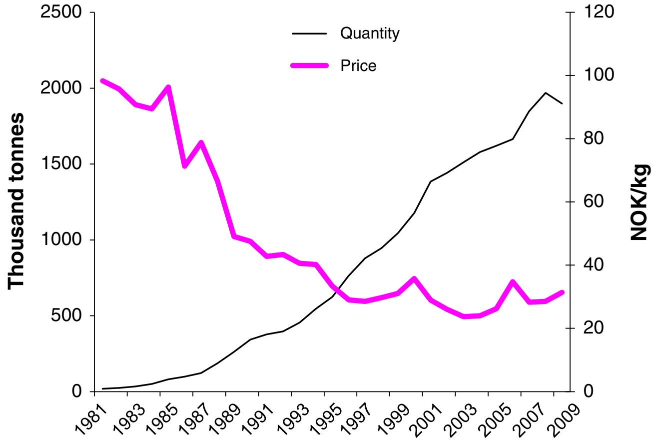

Fig. 1. Global salmon production and real Norwegian export price, 1981–2009 (2009 = 1).

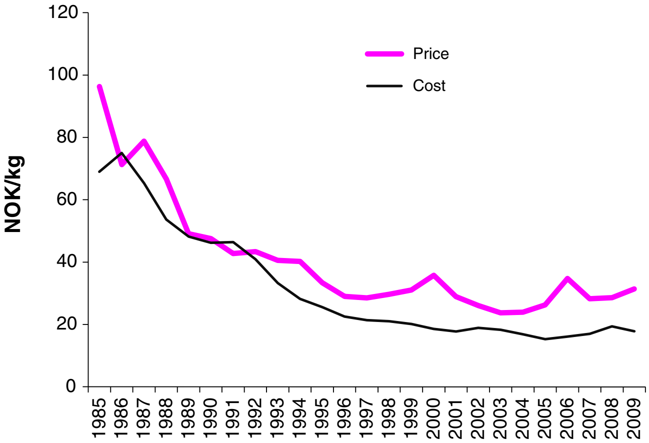

Fig. 2. Real Norwegian export price and production cost, 1985–2009 (2009 = 1).

straightforward if the inputs are available. However, in salmon farming, the main input is production sites, a factor that might be a limit to further growth.[1] More than 95% of all farmed salmon is currently produced in four countries (Canada, Chile, Norway and the UK), and in all countries the access to production sites is tightly regulated.

A number of studies have investigated productivity growth in Norwegian salmon farming (Andersen et al., 2008; Asche et al., 2007a; Guttormsen, 2002; Tveteras, 2002). Other studies focus on more specific element such as agglomeration (Tveteras, 2002; Tveteras and Battese, 2006), production risk (Kumbhakar and Tveteras, 2003), inefficiency (Asche et al., 2009b) and learning by doing (Nilsen, 2010) using a parametric approach. This studies report productivity growth in the range of 3–15%, that technical change has been non-neutral, and that productivity growth is less when accounting for inefficiency, as reduced inefficiency shows up as productivity growth when not modeled explicitly.

In this study, we are using a Malmquist index to calculate total factor productivity (TFP) growth using data envelopment analysis (DEA) to construct the underlying production frontier. Even though, the Malmquist index and DEA are often used for productivity analysis, the application to aquaculture is still limited (Cinemre et al., 2006; Hassanpour et al., 2010; Vassdal and Holst, 2011; Vassdal and Roland, 1998) and with the exception of the early study by Vassdal and Roland (1998) and the recent study of Vassdal and Holst (2011), this approach has not been used to investigate productivity development in salmon aquaculture.[2] The advantage of using the Malmquist index is that the TFP growth can be divided into both technical efficiency change and technological change. Our approach will add to the information provided by Vassdal and Holst (2011) as we calculate pure technical and scale efficiency and use the approach of Simar and Wilson (1999) to obtain standard errors. Moreover, we also explicitly account for the smolt input and the area used for production. Furthermore, the TFP growth and related change indices are calculated in two ways; first using a balanced data set estimating the year to year change; secondly by using a balanced data set only including firms operating in both 1996 and 2008 to estimate the change for the whole period. Finally, by assuming that the price has been varying around a constant mean since the late 1990s, we can separate the part of the production growth that is due to productivity change from the part that is due to increased input factor use.

The paper is organized as follows: We start by introducing the readers to the methodology, focusing on the Malmquist index and DEA. In Section 3, the data for the analysis are described together with some descriptive statistics before we present the results from our analysis, in Section 4. At last we conclude and discuss some possible policy implications.

2. Methodology

The Malmquist index can be used to estimate changes in total factor productivity (TFP) for a firm or an industry over time. The TFP index is defined (Coelli et al., 2005) as an index of the ratio of all output produced to all input used in the production. The Malmquist index is often used when price and cost data are not readily available. The index is based on non-parametric distance functions, which allows for a description of a multi-input and multi-output production technologies without the need to specify a behavioral objective function (Coelli et al., 2005). Furthermore, the index has the advantage that TFP changes can be separated into technical efficiency change (EFFCH) and technological change (TECHCH). The EFFCH can further be divided into pure technical efficiency change (PURE EFFCH) and scale efficiency change (SCALE EFFCH). Data envelopment analysis (DEA) can be applied to estimate the distance functions used to obtain the results of the Malmquist TFP index (Fare et al., 1994). The distance functions measure how far a firm is from its optimal production relative to other firms in a sample given the observed input and output.

An advantage of using the non-parametric methods, such as DEA and TFP indices, is that these do not require specification of a functional form for the production frontier. Furthermore, it is relatively easy to handle multiple inputs and outputs in these methods. On the other hand, the non-parametric approaches do not take statistical noise into account and all deviations from the frontier are considered as inefficiency. However, using the bootstrap technique suggested by Simar and Wilson (1998, 1999, 2000a), which can be used to analyze the sensitivity of nonparametric efficiency scores to sampling variation, it is possible to address this problem.

In this paper, the Malmquist TFP index is applied to estimate TFP changes in the Norwegian salmon aquaculture sector from 1996 to 2008.

Fare et al. (1994) specified an output oriented Malmquist productivity change index m_o as follows:

$$m_o(y_t, x_t, y_{t+1}, x_{t+1}) = \left[\frac{d_{oc}^{t}(y_{t+1}, x_{t+1})}{d_{oc}^{t}(y_t, x_t)} \&z.ccirf; \frac{d_{oc}^{t+1}(y_{t+1}, x_{t+1})}{d_{oc}^{t+1}(y_t, x_t)}\right]^{1/2}. \quad (1)$$

Where d_{oc} represents the distance function. The subscript o indicates the output-oriented approach and c refers to the use of constant returns to scale (CRS) technology. The index m_o estimates the productivity change of a firm producing (y_{t+1}, x_{t+1}) in period $(t + 1)$ relative

---

[1] Asche (2008) provides a discussion of how food production can increase due to productivity growth or due to use of more inputs, and provides several examples of both types of growth in agriculture.

[2] It should be noted that the approach has been used in the gray literature.

Table 1
Descriptive statistics of Norwegian aquaculture firms 1996–2008.
Source: Norwegian Directorate of Fisheries Aquaculture Statistics 1996–2008.

Year	Firms	Output 1000 tons	Feed 1000 Tons	Smolt 1000 tons	Labor 1000 h	Area million cubic meters	Capital million NOK real value	% of total production of salmon and trout	Average use of input per kilo of output				
		Y1	X1	X2	X3	X4	X5		X1/Y1	X2/Y1	X3/Y1	X4/Y1	X5/Y1
1996	291	209	238	6	2378	6	1099	65	1.14	0.027	0.011	0.029	5.25
1997	239	258	303	6	2526	7	1491	71	1.18	0.023	0.010	0.027	5.78
1998	200	306	372	7	2274	9	1797	75	1.21	0.023	0.007	0.030	5.87
1999	198	331	391	8	2459	10	1881	70	1.18	0.026	0.007	0.030	5.69
2000	182	390	459	10	2386	10	2496	80	1.18	0.025	0.006	0.026	6.40
2001	162	364	426	8	2192	13	2604	72	1.17	0.022	0.006	0.037	7.16
2002	142	339	401	7	1827	13	2156	62	1.18	0.022	0.005	0.039	6.36
2003	137	313	390	7	1656	14	1832	54	1.24	0.022	0.005	0.044	5.85
2004	126	364	440	8	1989	17	2117	58	1.21	0.023	0.005	0.046	5.81
2005	124	527	631	11	2490	25	3514	82	1.20	0.022	0.005	0.048	6.66
2006	117	590	689	12	2780	30	3527	85	1.17	0.020	0.005	0.051	5.98
2007	102	600	723	12	2546	36	4308	73	1.21	0.020	0.004	0.060	7.18
2008	103	634	795	13	2913	44	4830	77	1.25	0.021	0.005	0.069	7.61

to the firm production (y_t, x_t) in period (t). A value greater than one indicates a positive TFP growth from period (t) to period (t + 1).

Eq. (1) can be reorganized to demonstrate that the productivity index is equal to the product of the EFFCH index and TECHCH index.

$$m_o(y_t, x_t, y_{t+1}, x_{t+1}) = \frac{d_{oc}^{t+1}(y_{t+1}, x_{t+1})}{d_{oc}^{t}(y_t, x_t)} \cdot \left[\frac{d_{oc}^{t}(y_{t+1}, x_{t+1})}{d_{oc}^{t+1}(y_{t+1}, x_{t+1})} \cdot \frac{d_{oc}^{t}(y_t, x_t)}{d_{oc}^{t+1}(y_t, x_t)}\right]^{1/2}. \tag{2}$$

The first part of the index estimates the EFFCH, where as the second part estimates the TECHCH. To separate EFFCH into measures of local PURE EFFCH and SCALE EFFCH (EFFCH = PURE EFFCH ∗ SCALE EFFCH), the distance functions also have to be estimated assuming VRS.[3] PURE EFFCH can as such be calculated as (Coelli et al., 2005):

$$\text{Pure technical effeciency change} = \frac{d_{ov}^{t+1}(y_{t+1}, x_{t+1})}{d_{ov}^{t}(y_t, x_t)}. \tag{3}$$

d_{ov} represents the output orientated distance function where the subscribed v represents the use of VRS technology in the DEA models. Finally, the SCALE EFFCH can be calculated as (Coelli et al., 2005):

$$\text{Scale effeicency change} = \left[\frac{d_{ov}^{t+1}(y_{t+1}, x_{t+1})/d_{oc}^{t+1}(y_{t+1}, x_{t+1})}{d_{ov}^{t+1}(y_t, x_t)/d_{oc}^{t+1}(y_t, x_t)} \cdot \frac{d_{ov}^{t}(y_{t+1}, x_{t+1})/d_{oc}^{t}(y_{t+1}, x_{t+1})}{d_{ov}^{t}(y_t, x_t)/d_{oc}^{t}(y_t, x_t)}\right]^{1/2}. \tag{4}$$

To solve Eqs. (1)–(4) eight DEA distance functions must be estimated. DEA was first introduced by Charnes et al. (1978, 1979). A general introduction to DEA can be found in Cooper et al. (2000) and Coelli et al. (2005). The output-oriented DEA model can formally be written as (Coelli et al., 2005):

$$\left[d_o^t(y_t, x_t)\right]^{-1} = \quad \max_{\phi,\lambda}\phi \qquad \text{st.}: \tag{5}$$

$$\phi y_{(t)f,k} \le \sum_{n=1}^{F} \lambda n \cdot y_{(t)n,k} \qquad k = 1, \ldots, K \tag{6}$$

$$x_{(t)f,m} \ge \sum_{n=1}^{F} \lambda n \cdot x_{(t)n,m} \qquad m = 1, \ldots, M \tag{7}$$

$$\lambda n \ge 0, \quad \sum_{n=1}^{F} \lambda n = 1 \qquad n = 1, \ldots, F. \tag{8}$$

The subscript f (f = 1,…, F) represents the f'th farm, where F is the total number of farms. $y_{f,k}$ is the k'th (k = 1,…, K) output for the f'th farm, $x_{f,m}$ is the m'th (m = 1,…, M) input for the f'th farm. The scalar ϕ measures the radial expansion in the output necessary to make the farm technically efficient. If ϕ equals 1, the farm is technically efficient. Finally, λ is a vector of F weights, which identifies the extent to which the technically efficient observations are used to construct that part of the piecewise linear frontier approximation that envelops the f'th data point. The restrictions imposed by Eqs. (6)–(7) ensure that the farm stays within the production possibility set for the sector when expanding the output y. Eq. (8) imposes VRS on the underlying technology, whereas CRS can be imposed by eliminating Eq. (8).

In this study, the bootstrap technique suggested by Simar and Wilson (1998, 1999, 2000a,b) is applied. Using this method, it is possible to address the problem of measurement errors estimating confidence intervals for DEA scores and Malmquist indices. The "smoothed" bootstrap procedure outlined in Simar and Wilson (1999) is performed 1000 times, which results in a sample of 1000 estimates of the Malmquist index and change indices for each individual firm. The smoothing parameter suggested by Silverman (1986) for the bivariate data is used in the present context. From these samples a confidence interval can be constructed. This makes it possible to evaluate whether the Malmquist TFP changes and decomposed change indices of a firm are subject to significant changes during the time period investigated, and if the reason for these changes can be allocated to EFFCH, TECHCH, PURE EFFCH or SCALE EFFCH.

For detection of outliers, which can have large influence on the estimated DEA frontier, the super efficiency test developed by Andersen and Petersen (1993) is used. The reason for removing outliers in this study is that the aim is to obtain representative average TFP changes that are not heavily influenced by a few extreme observations. For a more thorough evaluation on detection of outliers using the super efficiency test, see Wilson (1995), Banker and Chang (2006).

3. Data

The data used in the present analysis is based on a profitability survey for Norwegian aquaculture collected by the Norwegian Directorate of Fisheries. The survey collects annual account data at the firm level

---

[3] In general the Malmquist index should be solved under the assumption of a CRS technology to obtain measures of global EFFCH, because measures of productivity changes may not be calculated correctly assuming a variable returns to scale (VRS) technology (Coelli et al., 2005; Ray and Desli, 1997).

Table 2
Selected data for the year to year analysis 1996–2008.
Source: Norwegian Directorate of Fisheries Aquaculture Statistics 1996–2008.

Firm	Year	Output 1000 tons	Feed 1000 tons	Smolt 1000 tons	Labor 1,000 h	Area million cubic meters	Capital million NOK real value	% of total production of salmon and trout	Average use of input per kilo of output				
		Y	X1	X2	X3	X4	X5		X1/Y	X2/Y	X3/Y	X4/Y	X5/Y
173	1996_1	124	142	3	1463	4	738	39	1.15	0.024	0.012	0.030	5.95
173	1997_1	165	198	4	1736	5	1119	45	1.20	0.024	0.011	0.029	6.78
161	1997_2	148	175	4	1487	4	898	40	1.18	0.027	0.010	0.028	6.07
161	1998_2	184	219	4	1434	6	1055	45	1.19	0.022	0.008	0.032	5.73
148	1998_3	197	235	5	1526	6	1114	48	1.19	0.025	0.008	0.031	5.65
148	1999_3	218	261	6	1655	7	1280	46	1.20	0.028	0.008	0.031	5.87
143	1999_4	241	287	6	1869	8	1480	51	1.19	0.025	0.008	0.031	6.14
143	2000_4	300	354	8	1919	8	1902	61	1.18	0.027	0.006	0.028	6.34
128	2000_5	247	290	7	1542	7	1546	51	1.17	0.028	0.006	0.028	6.26
128	2001_5	273	320	6	1645	11	2013	54	1.17	0.022	0.006	0.039	7.37
116	2001_6	248	290	5	1456	10	1900	49	1.17	0.020	0.006	0.039	7.66
116	2002_6	276	330	6	1490	11	1849	51	1.20	0.022	0.005	0.039	6.70
106	2002_7	258	304	6	1388	10	1695	47	1.18	0.023	0.005	0.038	6.57
106	2003_7	255	322	5	1326	11	1565	44	1.26	0.020	0.005	0.045	6.14
104	2003_8	247	312	5	1286	11	1465	43	1.26	0.020	0.005	0.044	5.93
104	2004_8	272	330	7	1426	13	1603	43	1.21	0.026	0.005	0.049	5.89
100	2004_9	300	370	7	1643	15	1822	48	1.23	0.023	0.005	0.049	6.07
100	2005_9	359	431	8	1693	18	1900	56	1.20	0.022	0.005	0.050	5.29
95	2005_10	409	488	9	1881	20	2637	63	1.19	0.022	0.005	0.049	6.45
95	2006_10	502	588	10	2290	25	3041	72	1.17	0.020	0.005	0.050	6.06
81	2006_11	425	511	9	2110	23	2419	61	1.20	0.021	0.005	0.055	5.69
81	2007_11	523	626	11	2207	33	3618	64	1.20	0.021	0.004	0.063	6.92
87	2007_12	558	669	11	2332	34	3959	68	1.20	0.020	0.004	0.060	7.09
87	2008_12	597	756	12	2717	42	4577	73	1.27	0.020	0.005	0.070	7.67

together with production data. Each firm account contains information on production, cost, earnings and balance sheet. For companies producing both salmon and salmon trout, cost data is aggregated so it is impossible to trace the cost to species. However, the production of the two species is quite similar and salmon trout only account for 10% of the total production. Furthermore, firms with no registration of hours of labor used in production, no purchase of smolts for production in the year, zero value of tangible assets, and observation with unusual feed conversion rates were excluded from the dataset.

To describe the production process of salmon, the following input variables were selected for the analysis: Feed measured in weight, labor measured in hours, smolts measured in weight, area used for production in cubic meters and capital cost measured as tangible fixed assets in real value. The output produced is the total production of salmon and trout in the year measured in weight. The output includes the fish sold, stored, and the growth in live fish stock. In Table 1, the descriptive statistics for input and output variables are shown for the total unbalanced sample of firms selected by the Norwegian Directorate of Fisheries.

In Table 2, the balanced dataset used for the year to year analysis is presented. The selection of this dataset is based on the same criteria as the data presented in Table 1 and is a subset of this dataset.

In Table 3, the balanced dataset only including the firms operating in 1996 and 2008 is presented. The selection of this dataset is based on the same criteria as the data presented in Table 1 and is a subset of this dataset.

As can be seen from Tables 1–3, the average use of input per kilo of output is quite similar in the three samples. Even in the smallest sample with 57 firms data cover 12% of the total production and 18% of the total numbers of firms in 1996 and 22% of the total production and 54% of the total numbers of firms in 2008. Furthermore, all samples contain a mix of small, medium and large size firms. Altogether, this indicates that the samples are relative representative for the industry as a whole.

4. Empirical results

In this section, a general description of the development and the influence of the selected input variables are presented based on the data presented in Table 1. Furthermore, the estimated results from the calculation of the Malmquist index and the bootstrap analysis are presented.

Feed is one of the most important inputs in salmon production (Guttormsen, 2002). In the period 1996–2008 the use of feed has been relatively constant, as shown in Fig. 3. The area used for production has increased, which to some extent can be explained by the implementation of legislation on the use of production sites and the volume of fish in the cages. The regulation is introduced to control the volume of production and to protect the environment. Capital invested in tangible fixed assets has been increasing, due to investment in larger cages and feeding-boats using more advanced technology, such as, computer systems to monitor feeding, oxygen levels in the water and the growth in the cages (Asche and Bjørndal, 2011). The increased use of feed, area and capital for production of one kilo of fish indicates a decrease in productivity from 1996 to 2008.

Table 3
Selected data for the analysis of 1996 and 2008.
Source: Norwegian Directorate of Fisheries Aquaculture Statistics 1996–2008.

Firm	Year	Output 1,000 tons	Feed 1,000 tons	Smolt 1,000 tons	Labor 1,000 h	Area million cubic meters	Capital million NOK real value	% of total production of salmon and trout	Average use of input per kilo of output				
		Y	X1	X2	X3	X4	X5		X1/Y	X2/Y	X3/Y	X4/Y	X5/Y
57	1996	37	43	1	469	1	239	12	1.14	0.026	0.013	0.025	6.38
57	2008	178	224	4	815	12	1143	22	1.26	0.023	0.005	0.066	6.43

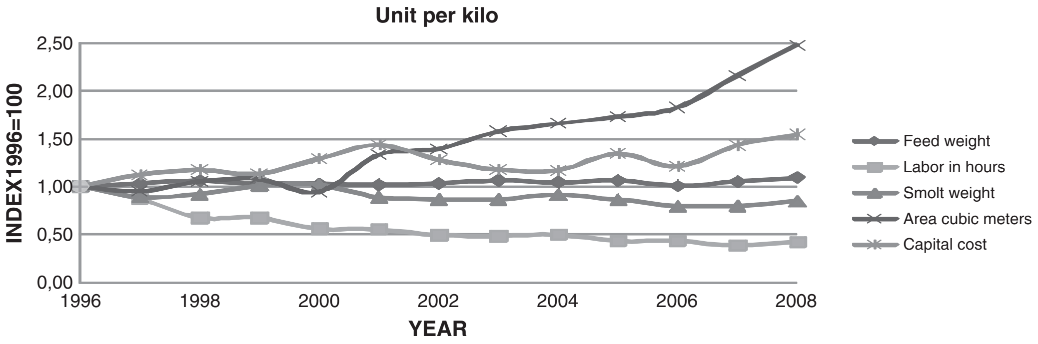

Fig. 3. Selected input used for the production of one kilo of salmon from 1996–2008 (index 1996 = 100).

On the other hand, the average use of smolts has decreased from an average of 0.025 in 1996–2000 to an average of 0.021 in 2001–2008 per kilo produced. The reason for this change can be explained by the fact that the smolts released in the pens are larger than in the beginning of the period, and that the vaccines and antibiotics have been improved in lowering the mortality rate. The average use of labor in terms of hours has been reduced by more than 50% from 1996 to 2008. The decreased input of smolts and labor indicates an increase in productivity.

In Fig. 4, a real price index for the selected input is shown from 1996 to 2008 for production of one kilo of fish. Only capital cost has increased over the period, whereas feed, labor, and smolts have decreased. The sum of the selected input cost decreased until 2005, but since then, the cost per kilo increased to a level just below the cost in 1996.

Table 4 shows the results from the calculation of the Malmquist index. The results show that the TFP changes have been positive in most years, except for 2008. Overall, the average yearly growth has been 1.9% from 1996 to 2008. However, the TFP change has been stagnating or falling since 2005. In the year to year analysis, the most important component has been the EFFCH with an average yearly growth of 1.2%, whereas TECHCH has contributed with an average yearly growth of 0.6%. The PURE EFFCH has been positive with an average growth of 1.4% a year, whereas the average SCALE EFFCH has been close to zero. Hence, the constant return to scale assumption of Vassdal and Holst (2011) does not seem to influence the results, despite the fact that increasing returns are reported in recent parametric studies (Asche et al., 2009b; Nilsen, 2010).

In general, the results seem plausible and are in line with those in Vassdal and Holst (2011), which also find a decline in the TFP growth from 2005. In contrast to these studies, Vassdal and Roland (1998), analyzed the years 1992–1995 and found an annual productivity improvement of 15–20%, which mostly could be attributed to TECHCH. Growth rates of that magnitude are not found in this analysis. In our analysis, the contribution to TFP growth from TECHCH has been negative in most years since 2002, which is also in line with the results in Vassdal and Holst (2011). This indicates that the most obvious technological improvements have been integrated by the industry and that the industry is becoming more mature. With TFP growth at 1.9%, productivity growth is lagging far behind a production growth at 8%, and increased input factor use do accordingly seem to be the main reason why salmon production continues to increase.

In order to test the result found in the year to year analysis the Malmquist index is calculated for a sample of 57 firms operating both in 1996 and 2008. Using this approach we are able to study the development for each individual firm operating in the whole period instead of looking at a year to year development. This way we can obtain more detailed information on the TFP changes at firm level and the importance of EFFCH and TECHCH. On the other hand, the sample is reduced due to the facts that firm stops operating and new ones are starting up. The exclusion of firm leaving or entering the sector over the time period can bias the results, because the ones leaving may be expected to have low productivity and the ones entering might have the opportunity to invest in new technology and have high productivity. This has to be born in mind when evaluating the results from the two analyses. Furthermore, to investigate if the changes are significant, confidence intervals are constructed using the bootstrap procedure suggested by Simar and Wilson (1999).[4]

In Table 5, the average result for the 57 firms is presented. The calculation of the Malmquist index shows a different trend than the results obtained by the year to year calculation. The average annual TFP growth is estimated to 1%, which is 0.9% less than the results from the year to year analysis. The contribution from EFFCH is 1% lower at a level of 0.2% a year, whereas the TECHCH has become slightly more important increasing from 0.6 to 0.8%.

An explanation for these differences could be that the firms that have managed to stay in the sector for the whole period of time have been close to the frontier from the beginning, due to good management, therefore, the catching up effect has been smaller than for other firms. However, this seems not to be the case here, because the average EFFCH is the same for the selected 57 firms as for the whole sample in both years.

Another explanation could be that within an industry characterized by a high rate of innovation, the producers tend to employ several different technologies at the same time, which can contribute to technical inefficiency. In other words, even though, the average producer experiences growth they are not catching up with the best using state of the art technology, and the distance to the frontier (inefficiency) decreases at a slower rate than if there have been no technical innovations. Furthermore, firms entering an industry which have a high rate of innovation may be able to leapfrog already established firms by avoiding large investments in older technologies, and taking advantage of best practice technologies that were previously unavailable (Nilsen, 2010).

In Table 6, the change index score is shown for the 57 selected firms in the sample. 38 experienced a positive TFP growth, whereas only 19 had negative growth. Using the bootstrap method 28 firms could be identified as having a significant positive growth, whereas only 12 had a significant negative growth. Furthermore, the most important contribution to TFP growth comes from TECHCH where 42 firms experienced positive growth (20 significant) and only 15 had negative growth (3 significant). Looking at EFFCH 32 firms had positive growth (9 significant) and 25 had negative growth (7 significant). These results are in line with Vassdal and Roland (1998) in

---

[4] The original DEA estimates have not been bias corrected, because the bias corrected estimator had a higher standard deviation than the original estimator (Simar and Wilson, 1999). Furthermore, the analysis was also performed using "the normal reference rule" for the calculation of bandwidth (Simar and Wilson, 2000a). The changed bandwidth had no effect on the estimated confidence intervals (Simar and Wilson, 1998, 1999).

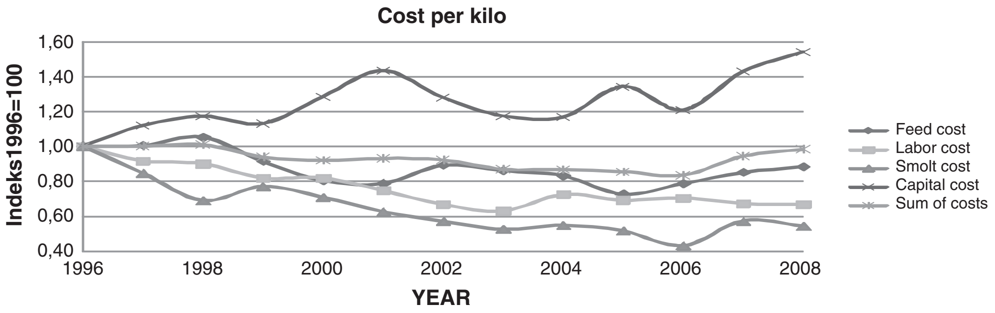

Fig. 4. Selected input used for production real price development from 1996 to 2008 (index 1996 = 100).

which they concluded that TECHCH was the most important driver of TFP growth. Furthermore, the results can also be related to the agriculture sector, where Rasmussen (2010) investigated TFP growth for three kinds of agricultural farming in Denmark. The overall result showed an average yearly growth of 2.1–3.3% from 1985 to 2006. TECHEFF was the most important factor with a yearly growth of 1.0–1.6%, whereas EFFCH was close to zero.

In Table 7, the average growth in input and output parameters from 1996 to 2008 is shown for the selected 57 firms divided into groups with a positive, neutral and negative changes in the Malmquist index, EFFCH and TECHCH indices at a 10% level of significance.

The firms experiencing a positive TFP change increased production 4.7 times, which equals the average level, but they used a lower than average input. For the firms that experienced positive EFFCH the output increased more than 6 times using a little more input than the average firm except for the input of labor hours and area. For the firms experiencing positive TECHCH the output increased 4.9 times using less input than the average firm except for the input of feed.

The overall average growth in production shows an increase in output of 4.8.

Of the 57 firms, 11 have a combined production of salmon and salmon trout. There is no indication that a combined production of salmon and salmon trout has any influence on TFP, thus, the firms having a combined production are represented in both the positive, neutral and negative groups above.

5. Concluding remarks

The results in this paper show that the yearly growth in the Norwegian salmon production has slowed down from yearly growth rates of 15–20% in 1992–1995 (Vassdal and Roland, 1998) to yearly growth rates of 1–2% over the period 1996–2008. The decomposition of the Malmquist index into EFFCH and TECHCH shows that the average chance in EFFCH has been between 1.2 and 0.2%, whereas the TECHCH has been between 0.6 and 0.8%. Moreover, in contrast to what is the case in parametric studies, there is no evidence of increasing returns to scale. This may then be an artifact of the functional form.

Table 4
Malmquist index.

Year	Firm's	EFFCH	TECHCH	TFPCH	PURE EFFCH	SCALE EFFCH
1996–1997	173	1.00	1.00	1.01	1.01	0.99
1997–1998	161	0.99	1.04	1.03	0.99	1.01
1998–1999	148	1.02	1.01	1.02	1.04	0.98
1999–2000	143	0.98	1.09	1.06	0.99	0.99
2000–2001	128	1.02	0.98	1.00	1.00	1.02
2001–2002	116	1.02	1.03	1.05	1.02	1.00
2002–2003	106	1.02	0.98	1.01	1.01	1.02
2003–2004	104	1.03	0.98	1.01	1.05	0.98
2004–2005	100	1.05	1.01	1.05	1.02	1.03
2005–2006	95	0.98	1.02	1.00	0.98	1.00
2006–2007	81	1.04	0.96	1.00	1.02	1.03
2007–2008	87	0.99	0.99	0.99	1.05	0.95
Average yearly growth %		1.2	0.6	1.9	1.4	0.0

This analysis clearly illustrates the development of a maturing industry; from an infant industry with high growth rates and technological development to a more mature industry with lower growth rate. Lower growth rate also means limited possibilities to increase productivity growth through technical development and more efficient production. The industry is then becoming more dependent upon external factors, such as demand and regulation, which they have less control over. With the limited productivity growth, this indicates that most of the production growth from the late 1990s has been possible primarily due to higher input use. This is also an indication that production sites have not been a strongly limiting factor. In Norway, this is partly due to more licenses and partly due to larger plants at each location (Asche and Bjørndal, 2011). Whether this can continue is a different question as production licenses are tightly regulated in all the large salmon producing countries, and environmental concerns are increasingly leading to regulations that can limit plant size.

The use of the main input, feed, has been slightly increasing from 1996 to 2008, which indicates a decrease in productivity. On the other hand, the cost and the relative importance of feed to other inputs in production have been decreasing, which is in contrast to the development from 1986 to 1998, where Guttormsen (2002) showed that the cost share and importance of feed were increasing even though the price was falling. Guttormsen (2002) also showed that there was evidence of very limited short-run substitution possibilities between feed and capital and feed and labor. A productivity increase in feed should, therefore, either be driven by a decrease in the consumption of feed or lower prices. Since the consumption of feed seems to have reached its minimum level, increased productivity is depending on lower prices. So far, the feed producing industry has been able to substitute between the more expensive fish meal and oil and cheaper vegetable alternatives to proteins, to cut prices, and this development is expected to continue. On the other hand, consumers demand for a more “healthy” product that can limit the substitution possibilities and possible price decrease, because the vegetable alternatives do not contain the healthy omega 3 and 6 fatty acids.

That the area used for production has been the input factor that has increased the most, this indicates a reduction in productivity over the period investigated. The spatial issue is important for several reasons. First, as the production has expanded in Norway the availability of good production sites has become more limited and the

Table 5
Malmquist index for the 57 selected firms operating in both 1996 and 2008.

Year	Firm's	EFFCH	TECHCH	TFPCH	PURE EFFCH	SCALE EFF
1996–2008	57	1.02	1.10	1.12	1.02	0.99
Average annual growth %		0.2	0.8	1.0	0.2	−0.1

Table 6
Results from the bootstrap analysis of 57 individual firms.

Firm nr.	TFPCH	EFFCH	TECHCH	PURE EFFCH	SCALE EFF
36	0.616^{***}	0.686^{***}	0.897^{*}	0.700^{***}	0.980^{*}
28	0.702^{***}	0.813^{***}	0.864^{***}	0.950	0.856
4	0.722^{***}	0.720^{***}	1.003	0.701^{***}	1.028
47	0.739^{***}	0.700^{***}	1.055	0.848	0.826^{**}
14	0.744^{***}	0.775^{***}	0.960	1.056	0.734
46	0.796^{***}	0.677^{***}	1.175	0.680	0.997
26	0.830^{***}	0.874^{***}	0.950	0.893	0.979
49	0.838^{***}	0.880^{**}	0.953	0.986	0.892^{*}
38	0.861^{***}	0.762^{***}	1.130^{**}	0.753^{***}	1.012
7	0.868^{***}	0.928	0.935	0.988	0.940
51	0.871^{**}	1.000	0.871^{**}	1.000	1.000
45	0.878^{***}	0.985	0.892	1.029	0.956
48	0.943	0.988	0.955	1.000	0.988
17	0.954	0.852^{**}	1.120^{*}	0.821^{***}	1.038
6	0.957	0.812^{***}	1.179^{**}	0.941	0.863
5	0.958	0.864^{**}	1.109^{**}	0.935	0.924*
32	0.978	0.888	1.102	1.000	0.888
24	0.983	1.056	0.931	1.000	1.056
3	0.998	0.931	1.072	0.890	1.046
1	1.013	0.941	1.077	1.000	0.941
41	1.019	1.034	0.985	1.083	0.955
2	1.034	1.111	0.931	1.000	1.111
40	1.035	0.892^{***}	1.161^{*}	1.000	0.892
53	1.040	1.059	0.981	1.000	1.059
15	1.050	0.944	1.113	0.956	0.987
22	1.061	1.036	1.024	1.052	0.985
33	1.077	0.982	1.097	1.000	0.982
52	1.079	1.057	1.021	1.096	0.964
44	1.089	0.973	1.119	0.977	0.996
39	1.121^{***}	0.863^{***}	1.299^{***}	1.105	0.781^{***}
16	1.140^{*}	1.104	1.033	0.884^{*}	1.249^{***}
12	1.143^{***}	0.996	1.147	1.000	0.996
27	1.146^{***}	1.063	1.078	1.073	0.990
20	1.162^{**}	0.972	1.195^{**}	1.000	0.972
42	1.181^{***}	1.072	1.102	1.065	1.007
21	1.186^{***}	1.045	1.135^{**}	1.038	1.007
19	1.190^{***}	1.182^{**}	1.007	1.168	1.012
43	1.212^{***}	1.000	1.212^{**}	0.980	1.020
50	1.245^{***}	1.126	1.105	0.989	1.139^{**}
23	1.262^{***}	1.287^{***}	0.980	1.291^{***}	0.997
34	1.272^{***}	1.000	1.272^{***}	1.000	1.000
10	1.281^{***}	1.104	1.160	1.127	0.980
25	1.281^{***}	1.023	1.252^{***}	1.000	1.023
30	1.297^{***}	1.130	1.148	1.129	1.001
8	1.306^{***}	1.121	1.165^{*}	1.101	1.019
13	1.356^{***}	1.375^{***}	0.986	1.316^{***}	1.045^{*}
37	1.357^{***}	1.326^{***}	1.024	1.400^{***}	0.947
9	1.364^{***}	1.251^{***}	1.090	1.205^{***}	1.038
18	1.366^{***}	1.135	1.204^{**}	1.157	0.981
57	1.382^{***}	1.108	1.248^{***}	1.000	1.108
11	1.397^{***}	1.321^{*}	1.058	1.308^{*}	1.010
31	1.417^{***}	1.117	1.269^{**}	1.000	1.117
56	1.491^{***}	1.238	1.204^{***}	1.000	1.238
55	1.513^{***}	1.285^{***}	1.178^{**}	1.288^{***}	0.998
29	1.564^{***}	1.220^{***}	1.282^{***}	1.155^{**}	1.057
35	1.572^{***}	1.267^{**}	1.241^{***}	1.203	1.053
54	1.737^{***}	1.000	1.737^{***}	1.000	1.000

'*', '**' and '***' indicate that the index is significantly different from unity at the 10%, 5% and 1% level.

Table 7
Average growth in output and input from 1996 to 2008 for the selected 57 firms.

Firms	Index changes	Output	Feed	Smolt	Hours	Area	Capital
28	Positive TFP	4.7	4.9	3.8	1.4	9.7	4.3
17	Neutral TFP	5.9	6.1	4.4	2.6	15.4	6.3
12	Negative TFP	3.5	4.4	4.5	1.5	14.6	4.1
9	Positive EFFCH	6.1	5.7	4.8	1.7	9.7	5.2
34	Neutral EFFCH	4.6	5.0	3.8	1.6	12.6	4.3
14	Negative EFFCH	4.3	5.7	4.8	2.2	13.9	5.9
20	Positive TECHCH	4.9	5.5	4.0	1.6	10.1	4.6
34	Neutral TECHCH	4.9	5.3	4.4	1.9	13.9	5.3
3	Negative TECHCH	3.0	3.5	3.5	1.4	13.3	1.7
57	Overall average	4.8	5.3	4.2	1.7	12.4	4.8

aquaculture producers are competing for space with other users, such as fishermen and recreational use of the water. The same feature is important also in Chile as production is moving south, and lack of new sites has largely stopped the production growth in Canada and Scotland (Asche and Bjørndal, 2011). Secondly, agglomeration of the aquaculture industry can have positive effects on productivity, but a higher density of fish farms can have negative effects, because it increases the risk of spreading diseases between farms, and the negative effect seems to dominate (Asche et al., 2009a; Nielsen, 2011; Tveteras, 2002).

With more than 95% of the world's salmon production located in only four countries, the limited productivity growth in the last decade raises questions with respect to how long farmed salmon production can continue to grow. It is certain that it is limited how much production can continue to grow if it can only happen with more sites. As technology is globally available (Asche and Bjørndal, 2011), our results can also go a long way to explain why production has not increased in Canada and Scotland, as new sites are not available in these countries. It also goes a long way to explain why price volatility has increased (Oglend and Sikveland, 2008). This development also gives stronger incentives for more radical technology development, where genetic modification may be the strongest candidate (Smith et al., 2010).

References

Andersen, P., Petersen, N.C., 1993. A procedure for ranking efficient units in data envelopment analysis. Management Science 39, 1261–1264.

Andersen, T.B., Roll, K.H., Tveteras, S., 2008. The price responsiveness of salmon supply in the short and long run. Marine Resource Economics 23 (4), 425–438.

Anderson, J.L., 2002. Aquaculture and the future: why fisheries economist should care. Marine Resource Economics 17, 133–151.

Asche, F., 2008. Farming the sea. Marine Resource Economics 23 (4), 527–547.

Asche, F., Bjørndal, T., 2011. The Economics of Salmon Aquaculture. Wiley-Blackwell, Chichester.

Asche, F., Kumbakhar, S., Tveteras, R., 2007a. Testing cost versus profit functions. Applied Economics Letters 14, 715–718.

Asche, F., Roll, K.H., Tveteras, R., 2007b. Productivity growth in the supply chain — another source of competitiveness for aquaculture. Marine Resource Economics 22, 329–334.

Asche, F., Hansen, H., Tveteras, R., Tveteras, S., 2009a. The salmon disease crisis in Chile. Marine Resource Economics 24 (4), 405–411.

Asche, F., Roll, K.H., Tveteras, R., 2009b. Economic inefficiency and environmental impact: an application to aquaculture production. Journal of Environmental Economics and Management 58, 93–105.

Asche, F., Dahl, R.E., Gordon, D.V., Trollvik, T., Aandal, P., 2011. Demand growth for salmon in the European market. Marine Resource Economics 26 (4), 255–265.

Banker, R.D., Chang, H., 2006. The super-efficiency procedure for outlier identification, not for ranking units. European Journal of Operational Research 175, 1311–1320.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. European Journal of Operational Research 2, 429–444.

Charnes, A., Cooper, W.W., Rhodes, E., 1979. Short communication: measuring efficiency of decision making units. European Journal of Operational Research 3, 339.

Cinemre, H.A., Ceyhan, V., Bozoğlu, M., Demiryürek, K., Kılıç, O., 2006. The cost efficiency of trout farms in the Black Sea Region, Turkey. Aquaculture 251 (2–4), 324–332.

Coelli, T.J., Rao, D.S.P., O'Donnel, C.J., Battese, G.E., 2005. An Introduction to Efficiency and Productivity Analysis, Second edition. Springer, New York.

Cooper, W.W., Seiford, L.M., Tone, K., 2000. Data Envelopment Analysis. Kluwer Academic Publishers, Boston.

Fare, R., Grosskopf, S., Norris, M., Zhang, Z., 1994. Productivity growth, technical progress and efficiency changes in industrialised countries. American Economic Review 84, 66–83.

Food and Agriculture Organisation of the United Nations, 2009. The State of World Fisheries and Aquaculture 2008. (Available at: www.fao.org/.FisheriesandAquacultureInformationandStatisticsService-04/05/2011).

Forsberg, O.I., Guttormsen, A.G., 2006. Modeling optimal dietary pigmentation strategies in farmed Atlantic salmon: application of mixed-integer non-linear mathematical programming techniques. Aquaculture 261, 118–124.

Guttormsen, A.G., 2002. Input factor substitutability in salmon aquaculture. Marine Resource Economics 17, 91–102.

Hassanpour, B., Ismail, M.M., Mohammed, Z., Kamarulzaman, N.H., 2010. Source of productivity growth in rainbow trout aquaculture in Iran: technical efficiency change or technological progress? Aquaculture Economics and Management 14, 218–234.

Kumbhakar, S.C., Tveteras, R., 2003. Risk preferences, production risk and firm heterogeneity. The Scandinavian Journal of Economics 105, 275–293.

Kvaløy, O., Tveteras, R., 2008. Cost structure and vertical integration between farming and processing. Journal of Agricultural Economics 59, 296–311.

Larsen, T.A., Asche, F., 2011. Contracts in the salmon aquaculture industry: an analysis of Norwegian salmon exports. Marine Resource Economics 26 (2), 141–149.

Nielsen, R., 2011. Green and technical efficient growth in Danish fresh water aquaculture. Aquaculture Economics and Management 15, 262–277.

Nilsen, O.B., 2010. Learning-by-doing or technical technological leapfroging: production frontiers and efficiency measurement in Norwegian salmon aquaculture. Aquaculture Economics and Management 14, 97–119.

Oglend, A., Sikveland, M., 2008. The behaviour of salmon price volatility. Marine Resource Economics 23, 507–526.

Rasmussen, R., 2010. Scale efficiency in Danish agriculture: an input distance-function approach. European Review of Agriculture Economics 37 (3), 335–367.

Ray, S.C., Desli, E., 1997. Productivity growth, technical progress, and efficiency change in industrialized countries. American Economic Review 87, 1033–1039.

Sharma, K.R., Leung, R.S., 2003. A review if production frontier analysis for aquaculture management. Aquaculture Economics and Management 7, 15–34.

Silverman, B.W., 1986. Density Estimation for Statistics and Data Analysis. Chapman and Hall, London.

Simar, L., Wilson, P.W., 1998. Sensitivity analysis of efficiency scores: how to bootstrap in nonparametric frontier models. Management Science 44 (1), 49–61.

Simar, L., Wilson, P.W., 1999. Estimating and bootstrapping Malmquist indices. European Journal of Operational Research 115, 459–471.

Simar, L., Wilson, P.W., 2000a. A general methodology for bootstrapping in nonparametric frontier models. Journal of Applied Statistics 27 (6), 779–802.

Simar, L., Wilson, P.W., 2000b. Statistical inference in nonparametric frontier models: the state of the art. Journal of Productivity Analysis 13, 49–78.

Smith, M.D., Asche, F., Guttormsen, A.G., Wiener, J.B., 2010. Genetically modified salmon and full impact assessment. Science 330, 1052–1053.

Tveteras, R., 2002. Industrial agglomeration and production costs in Norwegian aquaculture. Marine Resource Economics 17 (1), 1–22.

Tveteras, R., Battese, G.E., 2006. Agglomeration externalities, productivity and technical inefficiency. Journal of Regional Science 46, 605–625.

Tveteras, R., Heshmati, A., 2002. Patterns of productivity growth in the norwegian salmon farming industry. International Review of Economics and Business 49 (3), 367–393.

Vassdal, T., Holst, H.M.S., 2011. Technical progress and regress in Norwegian salmon farming: a Malmquist index approach. Marine Resource Economics 26, 329–341.

Vassdal, T., Roland, B.E., 1998. Technical change in the Norwegian salmon aquaculture sector: a Malmquist index approach. In: Eide, A., Vassdal, T. (Eds.), Proceedings of the 9th International Conference of the International Institute of Fisheries Economics and Trade, Tromsø, July 8–11, 1998, pp. 404–415.

Wilson, P.W., 1995. Detecting influential observation in data envelopment analysis. Journal of Productivity Analysis 6, 27–45.