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# Factors influencing production loss in salmonid farming

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ABSTRACT

Using a unique dataset, this paper investigates factors influencing production loss in Norwegian salmonid farming. The factors can be grouped into fish-specific factors (e.g. species, genetics, and generation), input factors (e.g. vaccines and smolt quality), environmental factors (e.g. geographical location), and managerial factors (e.g. ownership). The most important result is most likely that production losses to a large extent are explainable, as our best model has an $R^2$ as high as 0.826. This implies that it is possibile to reduce production losses significantly. For the specific factors, vaccines reduce production loss, but their effect varies by production site. Production loss also varies with which smolt plant is providing juvenile fish, indicating that there is systematic quality variation among the providers of smolt. There is also significant variation in production loss between companies and production sites, and on average production losses are lower for larger companies and sea sites holding larger numbers of fish. An important point is that while some factors explaining production loss are controlled by the individual company, others are beyond their control. Some of these external factors are related to the regulatory system.

## 1. Introduction

Loss in production is undesirable for any biological industry, not only because it is economically negative, but also because production losses such as diseases may cause unintended environmental externalities and facilitate infestations and transmission of diseases. Production loss can be defined as individuals where the rearing process is started but not completed, and is part of all animal production process (Mellor and Stafford 2004). It is mostly associated with mortality due to diseases and injuries, but can also be due to other events such as individuals escaping from the plant. Production loss is also a challenge in aquaculture, where the production process takes place in an aquatic environment. In this paper, factors influencing production loss for farmed salmonid production in Norway will be investigated. Salmonids are one of the most successful aquaculture species and are globally the second largest species by production value (Garlock et al. 2020), with Norway as the largest producer (Iversen et al. 2020). It is also a particularly interesting industry since salmonid aquaculture in several dimensions from breeding, veterinary and nutritional aspects to governance and supply chains are among the most advanced farmed species (Smith et al. 2010; Kumar and Engle 2016; Asche and Smith 2018; Bergesen and Tveterås, 2019). Salmonids are also the aquatic species where the production system is closest to that of modern animal production such as chicken (Asche et al. 2018a).

Farming of salmonids is mostly conducted in open net-pens, giving an environment that cannot be fully controlled, and it exposes the activity to several production risks that can lead to production losses.[1] In particular, the interactions between the production process and the

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[1] There is a rapid development towards new production technologies that may increase the control with the production process such as land-based farming (Bjørndal and Tusvik 2019), or where the consequences are reduced such as with offshore farms (Bjørndal and Tusvik 2020). This is largely due to the challenges directly and through the governance system of the parasite sea lice (Abolofia et al. 2017; Osmundsen et al., 2020a, b), but it is also a trend at the technological frontier in most animal production systems (Asche, Cojocaru and Roth, 2018). Alam and Guttormsen (2019) and Kumar et al. (2019) provide more general overviews of production risk in aquaculture.

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surrounding environment facilitates the transmission of disease-causing pathogens. This is one of the main causes for production loss directly, or indirectly due to prophylactic or palliative treatments and handling of the fish undertaken to reduce direct losses (Brun et al. 2003; Hammell and Dohoo, 2005a, b; Ausnmo et al., 2008; Jensen and Kristoffersen 2015). Production losses also have significant economic consequences. For instance, producers in Chile experienced severe disease outbreaks from 2009 to 2012 as well as algae blooms in 2016 that led to high mortality and significant market impacts (Asche et al., 2009a; Fischer et al. 2016; Torrissen et al., 2011; Asche et al. 2018b; Dresdner et al. 2019). In the Norwegian aquaculture industry, the disease impacts have not been quite as significant after the introduction of oil-based vaccines with high efficacy in 1992, but some contagious viral diseases (e.g. infectious pancreatic necrosis (IPN), pancreas disease (PD), infectious salmon anemia (ISA) and cardiomyopathy syndrome (CMS)) and parasite infestation, particularly salmon lice (*Lepeophtheirus salmonis*), have impacted productivity, production costs and profitability throughout the industry's history (Asche 1997; Asche, 2008; Abolofia et al. 2017; Rocha Aponte and Tveterås 2019; Roll 2019; Iversen et al. 2020). Sea lice is still impacting the Norwegian industry's development significantly due to regulations intended to limit transmission of sea lice to from farms to wild salmonid stocks (Misund 2019; Osmundsen et al. 2020b). In particular, the main indicator for permitting increase or forcing reduction in production in each Norwegian production region is directly associated with sea lice infestation in the area. Production losses in the form of mortality and escapes are also influencing the public perception of the industry sustainability and is an indicator in several environmental certification systems (Amundsen et al. 2019; Thlusty et al., 2019; Osmundsen et al., 2020a).

Fig. 1 shows the loss rate as a percentage of the number of smolts stocked together with total salmonids production in Norway from 1998 to 2019. The production has increased rapidly, while the loss rate has remained stable at roughly 13%.[2] This suggests little improvement in terms of reducing production losses over time, and with the rapid production increase, the total production loss has increased at the same rate.

In this paper, access to a unique dataset allows us to investigate the impact of several factors believed to influence production losses at the farm level in the Norwegian salmonid industry. The data used in the analysis is based on a nationwide survey conducted by the Norwegian Food Safety Authority (Mattilsynet) covering the two generations of Atlantic salmon (*Salmo salar L.*) and rainbow trout (*Oncorhynchus mykiss*) transferred to a production site in the sea in the fall of 2010, spring of 2011 and fall of 2011. The data were collected retrospectively after all the fish were harvested and endpoint biological data were available (Bleie and Skrudland 2014). As such, the data are independent of the production loss data that are reported by the Norwegian Fisheries Directorate. Moreover, as total production loss measured in number of individuals is computed as the difference between the number of individuals transferred to the sea and the number of individuals harvested, there is little scope for misreporting.

The dataset contains several factors that are not available from public sources such as smolt provider and vaccination, that may influence production losses. The explanatory factors can be grouped into four main categories: fish-specific factors (e.g. species and generation), input factors (e.g. vaccines and smolt quality), production site-specific factors (e.g. geographical location and temperature), and managerial factors (e.g. date of transfer to sea, company size and ownership). The impact of the various factors will be investigated in four different regression models, that differ by how heterogeneity between smolt plants, companies, and production sites are modeled. To what extent the variation in production losses can be explained is important as it determines to what degree the losses can be reduced. Which factors are casuing the losses influence which measures and policies may be most useful for reducing production losses.

The paper is organized as follows: In the next section, the data set is presented in more detail together with the empirical approach. In section 3 the empirical results are reported before concluding remarks offered in section 4.

## 2. Data and empirical approach

The data were obtained using a questionnaire for each group of fish stocked at each farm. A fish group is defined as smolt from a single smolt plant with a uniform genetic origin and identical vaccine status transferred to sea at a specific production site during a short period of time (typically less than two weeks).[3] A total of 1066 groups were covered, representing 318 out of a total of 402 production sites in operation in Norway from fall 2010 and through 2011. These production sites are owned by 59 independent companies, stocked with juvenile fish from 139 smolt plants, and a total of 307 million individual fish.

Total production loss for a fish group was recorded as the total number of smolt transferred to the production site at the start of the production cycle minus the number of fish harvested at the end of the production cycle. The data set do not contain any mortality or discards during the harvesting process since it was not part of the biological production cycle. The factors that may influence production losses were grouped into four main categories; fish-specific factors, input factors, environmental factors, and managerial factors, and the variables will be discussed by these categories.

Salmonides farming in Norway is conducted with two species, Atlantic salmon and rainbow trout. The two different species produced under the same management system, and farmers are allowed to stock the species of their preference using the same license.[4,5] Of the 318 production sites, 288 (91%) stocked salmon and 30 (9%) stocked rainbow trout. Of the 1066 groups, 87 (8.1%) consisted of rainbow trout and 979 (91.9%) were salmon. Over time, the share of rainbow trout in Norwegian salmonid production has been declining (Norwegian Directorate of Fisheries, 2020), and a higher loss rate may be one explanation. Species (salmon or trout) and generation (1 - fall of 2010, 2 - spring of 2011, or 3 - fall of 2011) are included as fish-specific factors influencing losses.

Input factors is an important category in that farmers can influence their use and thereby the probability of loss. We investigate two types of input factors; smolt providers and vaccines. Which smolt plant the stocked juveniles originates from will account for a combination of the genetics of the smolts as well as the environmental conditions specific for a smolt plant, and these factors may account for the quality of smolts. For example, the susceptibility to IPN is largely determined by the genetics of the salmon (Houston et al., 2009), though it is also known that IPN may exist as site specific 'house strains" at the smolt plants (Kristoffersen et al., 2018). Without knowing the genetics, the hatchery effect will account for both these factors. In addition, sourcing and mixing smolt from different smolt plants (from 1 to up to 6 suppliers) offering different smolt qualities may also affect the loss in production.

Vaccines are another input category where the farmers have to make

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[2] It is of interest to note that compared to a number of terrestrial animal production process reported by Mellor and Stafford (2004), this rate is in the lower range.

[3] A production site normally operates 4–8 pens, and while smolt from different smolt providers are never mixed in the same pen, there may be smolt from different providers in different pens at the same production site.

[4] The large trout produced in sea pens primarily in Chile and Norway is also known as salmon trout to distinguish it from the much larger volumes of portion sized trout produced in continental Europe and a number of other countries (Nielsen et al. 2016; Guillen et al. 2019).

[5] An overview of the Norwegian management system can be found in Hersoug et al., (2019).

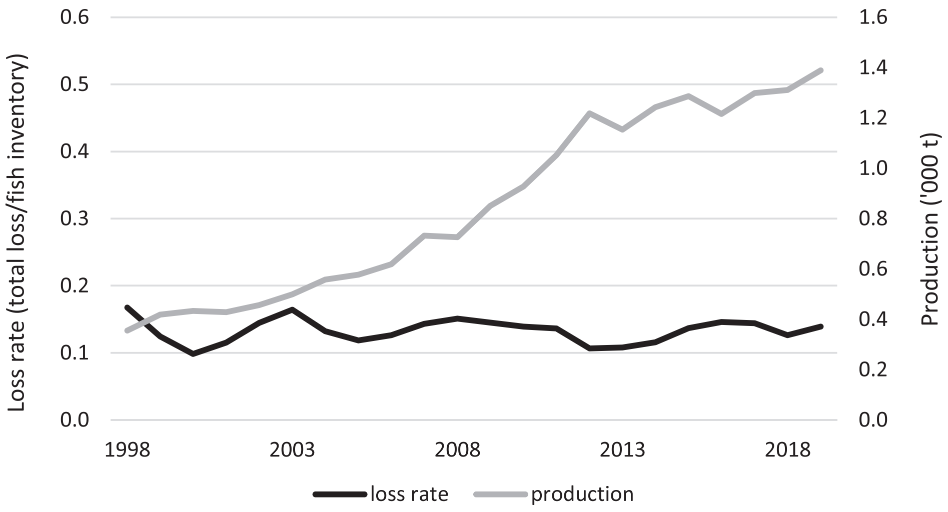

**Fig. 1.** Loss rate (black line) and total production ('000 t; gray line) in Norwegian salmonids farming from 1998 to 2019. Source: Norwegian Fisheries Directorate (2020)

decisions that can influence production loss. In the dataset, farmers used 13 different types of basic mandatory vaccines (including one undisclosed category) that protect against bacterial diseases such as vibriosis, cold water vibriosis, and furunculosis. Some farmers also used one of eight supplementary vaccine products as a secondary vaccine for reducing the impact of other disease-related production losses. The use of these different vaccines allows a test of whether their efficacies differ with respect to mortality.

Environmental factors, such as sea temperature and the length of daylight, influence growth rates, and may influence production losses (Hammell and Dohoo, 2005a, b; Jensen and Kristoffersen 2015). Two different approaches will be used as indicators to control for the environmental factors. The first is at which latitude interval the production site is located, indicating changes in average seawater temperatures and daylengthdegrees as one is moving northwards. This effect does not need to be negative as there is an optimal growth temperature range for any farmed fish species. Hermansen and Heen (2012) discuss how the industry has moved northward partly in response to climate change induced temperature increases. A weakness with the latitude measure is that it is continuous and does not allow for site-specific factors to influence the loss rate. A more flexible approach is to capture this effect with site-specific fixed effects, which is a set of dummy variables that takes the value of one for each specific location and zero for all other sites.[6]

Managerial factors that can influence production loss investigated here are the total number of smolt released, the calendar-day of the smolt transfer (as day 1 for January 1st to 365 for December 31st), and the length in time the smolt transfer occured counted as number of days from first to last transfer of a fish group. Moreover, specific aspects of the firms, such as whether the companies are small or large, may influence how the production is carried out. Two approaches are used to account for these aspects. In the first, the number of production sites per company was used as a proxy for company size. The firms were divided into three groups: companies with <5 production sites, companies with between 5 and 20 sites, and companies with >20 sites represented in the dataset. The second approach was to account for the heterogeneity using firm fixed effects, which includes company size, but also capture other individual firm characteristics such as firm culture.

Given the available variables, four regression models were estimated. In all models, the logarithm of total loss in production (*TL*) in each fish group (*c*) owned by a company (*f*) at a production site (*l*) was regressed on the logarithm of calendar-day of the smolt transfer (*STD*), the logarithm of transfer time (*STT*) and the logarithm of number of smolts in a group of fish (*S*) and dummy variables for the fish species (*FS*), generation (*G*), which basic vaccines (*BV*) and additional supplementary vaccines (AV) were applied to the fish. These explanatory dummy variables used salmon, the first generation, the vaccine T1, and no other vaccines as a base.

For model 1 no individual effects for the hatcheries, location or firms were used and the model contains dummy variables for the site latitude interval (*LAT*, base interval being 58-59 N), company size in terms of the number of production sites (*CS*, base size is the companies with less than 5 locations), and the number of smolt plants supplying each production site for the generation in question (*SS*, base is one smolt supplier):

$$TL_{flc} = \beta_0 + \beta_1 FS_{flc} + \beta_2 G_{flc} + \boldsymbol{\beta}_3 \boldsymbol{BV}'_{flc} + \boldsymbol{\beta}_4 \boldsymbol{AV}'_{flc} + \beta_5 STD_{flc} + \beta_6 STT_{flc} + \beta_7 S_{flc} + \boldsymbol{\beta}_8 \boldsymbol{LAT}'_{fl} + \beta_9 CS_f + \beta_{10} SS_{flc} \tag{1}$$

Model 2 uses fixed effects for which smolt plant (*H*) supplied the fish instead of the number of smolt suppliers:

$$TL_{flc} = \beta_0 + \beta_1 FS_{flc} + \beta_2 G_{flc} + \boldsymbol{\beta}_3 \boldsymbol{BV}'_{flc} + \boldsymbol{\beta}_4 \boldsymbol{AV}'_{flc} + \beta_5 STD_{flc} + \beta_6 STT_{flc} + \beta_7 S_{flc} + \boldsymbol{\beta}_8 \boldsymbol{H}'_{fl} \tag{2}$$

Model 3 contains firm fixed effects ($\beta_f$) instead of the company size:

$$TL_{flc} = \beta_0 + \beta_1 FS_{flc} + \beta_2 G_{flc} + \boldsymbol{\beta}_3 \boldsymbol{BV}'_{flc} + \boldsymbol{\beta}_4 \boldsymbol{AV}'_{flc} + \beta_5 STD_{flc} + \beta_6 STT_{flc} + \beta_7 S_{flc} + \beta_f \tag{3}$$

Finally, Model 4 uses production site fixed effects to account not only the specific environmental factors related to the site ($\beta_l$), but also firm and other time-invariant characteristics:

$$TL_{flc} = \beta_0 + \beta_1 FS_{flc} + \beta_2 G_{flc} + \boldsymbol{\beta}_3 \boldsymbol{BV}'_{flc} + \boldsymbol{\beta}_4 \boldsymbol{AV}'_{flc} + \beta_5 STD_{flc} + \beta_6 STT_{flc} + \beta_7 S_{flc} + \beta_l \tag{4}$$

A challenge with the three types of fixed effects is that they are highly correlated. For instance, most farms have only one owner, and many smolt suppliers only deliver to one company (presumably the owner). Multicollinearity, therefore, prevent the estimation of a model with more than one set of fixed effects.

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[6] To avoid the dummy trap, one production site is arbitrarily assigned to be the base and is measured by the constant term, while the estimated parameters on the dummies for the other locations measure the deviation from this base.

## 3. Empirical results and discussion

Table 1 presents the parameters estimated for the four different models. All the three models with fixed effects explained more of the variation in production losses than Model 1, which has an $R^2$ of 0.584. This suggests that the variables latitude interval, company size, and number of smolt plants supplying a production site do not capture all heterogeneity associated with their category. With the differences in explanatory power in the models, it is not surprising that $F$ tests of the null hypothesis that the fixed effects are all equal were rejected with $p$-values $<0.001$. Model 4 with the most detailed fixed effects, the production site effects, explained most of the variation in production losses with an $R^2$ of 0.826.

For all the models, the null hypothesis that production loss is independent of species cannot be rejected. Hence, production losses are not a cause for the declining share of rainbow trout in Norwegian aquaculture.

Spring transferred smolt are found to have higher losses compared to the fall generation. Diseases have been shown to affect spring and autumn stocked smolts differently (Jensen and Kristoffersen 2015). Furthermore, the spring and autumn smolts are stocked under contrasting environmental factors such as temperature, daylength, salinity, and parasite burden (especially sea lice) that affect the transferred smolt and may influence the total mortality. It has for instance been shown that PD-mortality is significantly associated with the environmental conditions during the period of diagnosis, more than only the temperature alone (Stormoen et al. 2013). The model with the production site fixed effects also suggests that the third cohort in the dataset did better than the first cohort, presumably because of more favourable biophysical conditions.

Most of the coefficients related to the basic vaccines are statistically significant, indicating variation in the effect of the vaccines. Hence, vaccine suppliers and products influence the survival of farmed

**Table 1**
Parameter estimates.

| | Model 1 | | Model 2 | | Model 3 | | Model 4 | |
|---|---|---|---|---|---|---|---|---|
| | Coeff | St. Err. | Coeff | St. Err. | Coeff | St. Err. | Coeff | St. Err. |
| Species farmed (base = salmon) | | | | | | | | |
| Trout | 0.0892 | (0.137) | −0.0810 | (0.178) | −0.113 | (0.152) | −0.364 | (0.227) |
| Fish generation (base =1): | | | | | | | | |
| Fish generation 2 | 0.249*** | (0.062) | 0.144* | (0.063) | 0.199** | (0.062) | 1.934*** | (0.523) |
| Fish generation 3 | 0.0685 | (0.041) | 0.0417 | (0.040) | −0.0438 | (0.041) | −0.808* | (0.382) |
| Basic vaccine (base = T1): | | | | | | | | |
| Basic vaccine: T2 | −0.298 | (0.181) | −0.207 | (0.284) | −0.825*** | (0.207) | −1.219*** | (0.258) |
| Basic vaccine: T3 | −0.0292 | (0.268) | 0.441 | (0.358) | −0.326 | (0.272) | −0.485 | (0.331) |
| Basic vaccine: T4 | −0.531** | (0.179) | −0.231 | (0.280) | −0.954*** | (0.207) | −1.400*** | (0.262) |
| Basic vaccine: T5 | −0.374* | (0.163) | −0.0852 | (0.251) | −0.701*** | (0.187) | −1.219*** | (0.217) |
| Basic vaccine: T6 | −0.378 | (0.526) | 0.212 | (0.540) | −0.877 | (0.517) | −1.353** | (0.455) |
| Basic vaccine: T7 | −0.117 | (0.184) | −0.0499 | (0.286) | −0.785*** | (0.216) | −1.466*** | (0.266) |
| Basic vaccine: T8 | −0.301 | (0.183) | −0.0761 | (0.282) | −0.818*** | (0.207) | −1.172*** | (0.266) |
| Basic vaccine: T9 | −0.878*** | (0.236) | −0.840** | (0.324) | −1.398*** | (0.265) | −1.357*** | (0.295) |
| Basic vaccine: T10 | −0.107 | (0.146) | 0.0293 | (0.199) | −0.466** | (0.162) | −0.485** | (0.162) |
| Basic vaccine: T11 | −0.229 | (0.207) | −0.00550 | (0.302) | −0.957*** | (0.245) | −1.583*** | (0.282) |
| Basic vaccine: T12 | −0.0613 | (0.199) | −0.0505 | (0.290) | −0.345 | (0.220) | −1.438*** | (0.278) |
| Basic vaccine: T13 | −1.047** | (0.343) | −1.045* | (0.416) | −1.716*** | (0.382) | −1.862*** | (0.359) |
| Supplementary vaccines (base = no other vaccines): | | | | | | | | |
| Supplementary vaccines: | −0.0418 | (0.071) | −0.372*** | (0.078) | −0.0971 | (0.052) | −0.133 | (0.094) |
| Supplementary vaccines: T14 | −0.133 | (0.149) | −0.00218 | (0.195) | 0.133 | (0.143) | 0.137 | (0.143) |
| Supplementary vaccines: T15 | −1.324*** | (0.234) | −0.829* | (0.332) | −0.961*** | (0.225) | −0.976*** | (0.248) |
| Supplementary vaccines: T16 | −0.0495 | (0.214) | −0.580** | (0.208) | −0.120 | (0.225) | −0.196 | (0.244) |
| Supplementary vaccines: T17 | 0.117 | (0.218) | −0.0355 | (0.230) | 0.239 | (0.228) | −2.497*** | (0.602) |
| Supplementary vaccines: T18 | 0.945** | (0.355) | −0.307 | (0.502) | 0.541 | (0.434) | 2.282*** | (0.477) |
| Supplementary vaccines: T19 | −0.481 | (0.356) | −0.654 | (0.351) | −0.882* | (0.345) | −0.604* | (0.295) |
| Smolt suppliers (base = one supplier) | | | | | | | | |
| Several smolt suppliers | 0.117** | (0.036) | | | −0.0134 | (0.039) | 2.880*** | (0.372) |
| Latitude (base = 58-59 N) | | | | | | | | |
| 59-60 N | −0.0259 | (0.101) | | | | | | |
| 60-61 N | −0.223* | (0.101) | | | | | | |
| 61-62 N | −0.543*** | (0.117) | | | | | | |
| 62-63 N | −0.684*** | (0.116) | | | | | | |
| 63-64 N | 0.162 | (0.118) | | | | | | |
| 64-65 N | −0.238 | (0.129) | | | | | | |
| 65-66 N | −0.213 | (0.150) | | | | | | |
| 66-67 N | −0.511*** | (0.133) | | | | | | |
| 67-68 N | −0.716*** | (0.146) | | | | | | |
| 68-69 N | −0.832*** | (0.118) | | | | | | |
| 69-70 N | 0.0994 | (0.119) | | | | | | |
| 70-71 N | 0.309** | (0.114) | | | | | | |
| Calendar-day of the smolt transfer | 0.194** | (0.071) | 0.114 | (0.074) | 0.0863 | (0.071) | 0.155* | (0.071) |
| Smolt transfer time | −0.00146 | (0.007) | 0.0141 | (0.008) | 0.0124 | (0.008) | 0.0163* | (0.008) |
| Smolt released number | 1.177*** | (0.028) | 1.146*** | (0.031) | 0.982*** | (0.034) | 1.100*** | (0.037) |
| Company size (base $\leq$ 5 locations): | | | | | | | | |
| Companies with 5–20 farm locations | −0.0660 | (0.046) | | | | | | |
| Companies with >20 farm locations | −0.315*** | (0.056) | | | | | | |
| Constant | −4.842*** | (0.542) | −5.122*** | (0.642) | −2.373*** | (0.635) | −4.767*** | (0.735) |
| Hatchery FE | no | | yes | | no | | no | |
| Firm FE | no | | no | | yes | | no | |
| Location FE | no | | no | | no | | yes | |
| N | 3144 | | 3144 | | 3144 | | 3144 | |
| $R^2$ | 0.584 | | 0.671 | | 0.626 | | 0.826 | |

salmonids. Moreover, the number of statistically significant effects are higher and the magnitudes of the coefficients larger for the models with production site or firm-specific effects. This suggests that factors associated with the production practices or biophysical factors at the specific production site may influence the efficacy of a particular vaccine. For the additional supplementary vaccines, there are relatively fewer statistically significant parameters in all models except the model with site-specific fixed effects, again underlining that production site-specific factors influence the efficacy of any particular vaccine.

Using smolts from more than one smolt plant increase the total losses in model 1 (without any fixed effects) and in model 4 (with production site fixed effects), while it is not statistically significant in the other two models. However, the data show that most farms do not mix smolts from different suppliers. The fixed effects for the smolt plants from Model 2 sorted by production loss magnitude are shown in Fig. 2. They show a large variation in production losses associated with the different smolt plants, indicating significant differences in smolt quality between different suppliers of smolt. It is of particular interest to note that there are a few smolt plants which are associated with much higher losses independent of which production sites the smolt were stocked at. While the data do not provide any information about why this may be the case, it may be attributed to fish already carrying a disease or to generally poor physiological quality of the smolt. To investigate whether the size of the smolt plant has any effect on the survival of fish after it is transferred to the production site, the correlation coefficient between the fixed effects for the smolt plants and their estimated annual output is computed. The coefficient is estimated to be −0.22, and accordingly, there is a systematic variation in smolt quality by the size of the smolt plant in that production losses on average are lower for smolts supplied by plants with a larger production capacity.

In Model 1, dummies for the different latitude intervals are used to account for temperature and light profile. There are no monotonic pattern here, as there is a band with lower production loss in the two latitude intervals between 61° and 63° N, and another span with the lowest production loss in the three intervals between 66° and 69° N. The highest loss in production is found in the northernmost latitude interval between 70° and 71° N. This region, Finnmark, which also has the lowest degree of smolt self-sufficiency and a high degree of dependency on transport of smolt from far away regions. The variation in the pattern suggests that there are factors related to the production sites that influence production losses. This helps to explain why the model with site-specific fixed effects is performing better in terms of explanatory power.

Managerial related factors, such as the calenderday of the smolt transfer and the length in time the transfer took have a weak influence on production loss. The further into the calendar-year and the longer the transfer time, the higher the loss. In addition, an increasing total number of smolts released in any one production cycle increases the production loss. This is in line with what is reported in Jensen and Kristtofersen (2015) with respect to the timing of the smolt release influencing mortality rates.

Model 1 cannot reject the null hypothesis that companies with between 5 and 20 production sites have the same production loss as the smallest companies. However, the largest companies with more than 20 locations have significantly lower production losses. When accounting for firm heterogeneity (Model 3, Fig. 3) and site heterogeneity (Model 4, Fig. 4), there is a large variation in losses between production sites and companies. However, it is worthwhile to note in Fig. 4 that almost two-thirds of the production sites have very low production losses, while it increases rapidly for the remaining sites, largely due to fish health issues (Bleie and Skrudland 2014). Model 4 accounting for production site-specific fixed effects has the highest $R^2$ suggesting that there are significant differences between specific production sites. Whether this is associated with the environmental characteristics of the production site, proximity to other salmon farms or farm-specific managemental factors is not possible to assert with the available data. However, this result suggests that the companies themselves as well as the regulatory authorities may reduce losses by targeting the worst performing production sites. For instance, it is possible to reduce production by reducing the number of smolts released or to give the company incentives to move the geographical location of the site.

The correlations between the fixed effects and company size are also computed for these models. For Model 3 (Firms FE), the correlation coefficient is −0.13, and for model 4 (Production site FE) it is −0.09. These correlation coefficients support the result from Model 1 indicating that the losses are smaller for larger multi-site companies. Larger companies also tend to have their sea farming operations in a variety of geographical regions, hence spreading the risk of negative events like algal blooms, contagious diseases and mandatory culling on the order of the veterinary authorities due to listed pathogens at any one site (Asche et al., 2009b; Oglend and Tveteras 2009).

In addition, the correlation between the production site fixed effects from Model 4 and site-specific production quantity is −0.37. This indicate that the production sites with higher production also are the ones with lower losses. This is an interesting result as the regulations limits how much fish can be kept at a single site of environmental reasons. As such, there seems to be a trade-off between local environmental

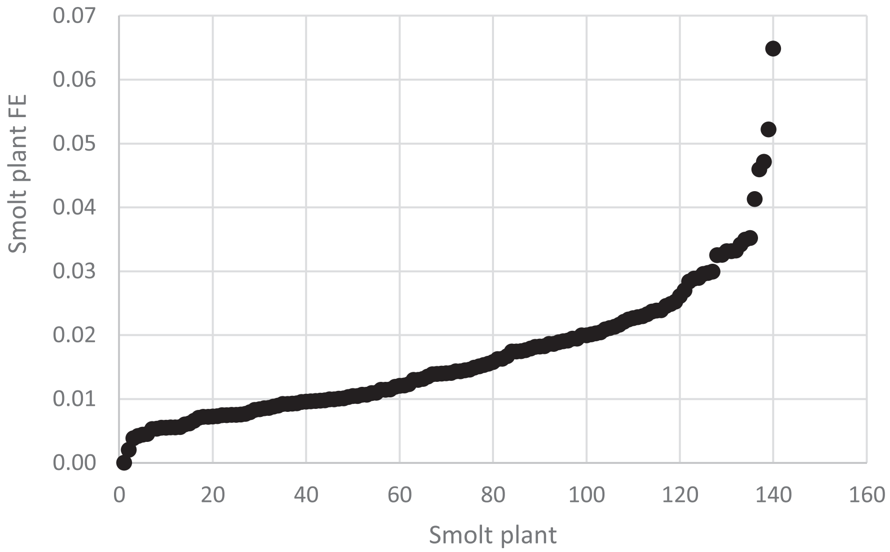

**Fig. 2.** Smolt plant fixed effects from model 2 sorted by production loss.

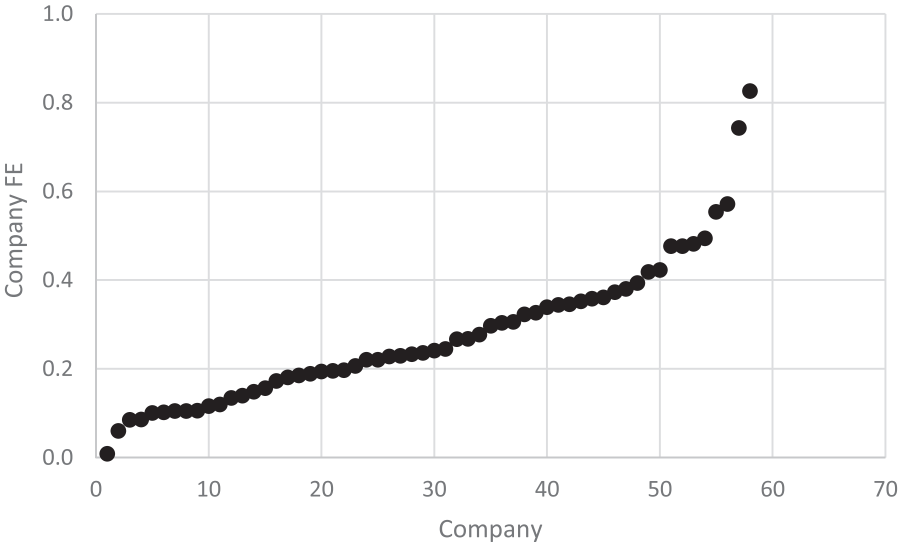

**Fig. 3.** Company Firm fixed effects from model 3 sorted by production loss effects.

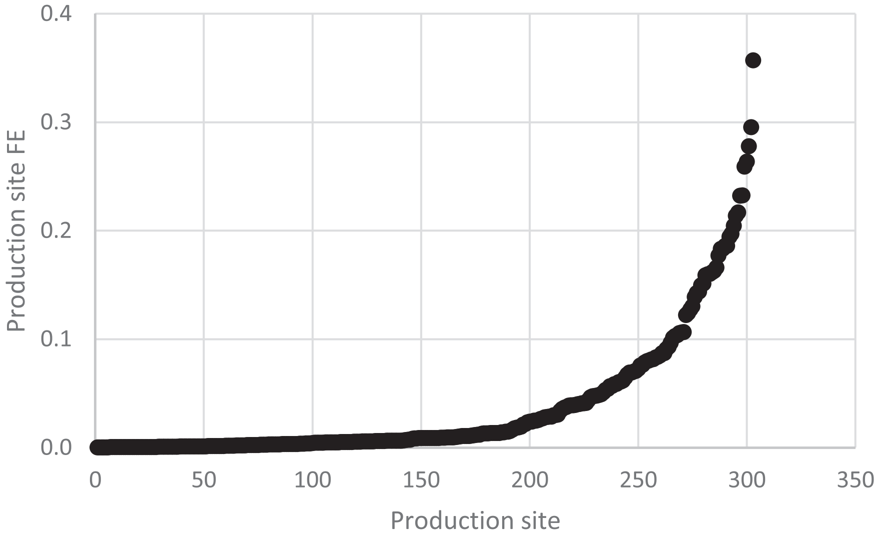

**Fig. 4.** Production site fixed effects from model 4 sorted by production loss effects.

considerations and health and fish welfare. There exists evidence that occurrences such as escape events are larger in terms of number of individuals lost when they take place at a large site (Pincinato et al. 2020), but the negative correlation here indicates that on average production losses are smaller at large sites presumably because events are less frequent.

While larger companies and sites tended to do better in terms of production losses on average, it is worthwhile to note that the smaller companies constitute a much more heterogeneous group. The best-performing companies and sites in our dataset can be found in the group with the smallest companies. Hence, these results should not be interpreted as larger sites and companies necessarily performing better even though they do so on average. Rather, it is important to address the heterogeneity among smaller companies and the challenge represented by poor performers if one aims to reduce production loss.

## 4. Concluding remarks

This paper has investigated potential factors influencing production losses in Norwegian salmonid farming production using a unique dataset that captures several variables that are not available from public collected data such as smolt supplier and vaccine use. The most important result is most likely that production losses to a large extent are explainable, as our best model had an $R^2$ as high as 0.826. This implies that it is possible to reduce production losses significantly. However, while it is possible, it is far from obvious that the producers have incentives to do so as it is in general costly. Also, many factors influencing mortality are beyond the individual farmer's direct control, but rather constitute direct or indirect effects of the management or biophysical system in which the farms operate.

Not unexpectedly, vaccines, in general, have a positive impact on survival, but the effect varies with the vaccine product used. Moreover, as the impact of the vaccines, and particularly the more multivalent vaccines, is strongest in the model with production site-specific effects, this suggests that different vaccine products are more or less effective depending on the characteristics of a specific production site. Production loss varies systematically with smolt suppliers, indicating that some smolt plants provide smolt with better quality than others. However, for a farmer not too concerned with mortality or fish welfare, this may at least partly be justified by a lower smolt price.

There is systematic variation in the magnitude of production loss between companies and between production sites. For any production site and small companies this may be a consequence of both site-specific biophysical features and managerial characteristics of the company, while for larger companies, it is primarily an indication of a managerial issue at the company level. This does suggest that if production loss is a concern, regulators should consider giving incentives to or directly closing production at the worst sites and also target companies with the worst production practices. It also suggests that the current regulatory system with large multi-site production zones that target one source of production loss (sea lice) where all firms within the same zone are treated equally is inefficient as a tool to reduce production loss. Recent cases where the Food Safety Authority temporarily has reduced how many smolts a specific company can release at a production site is targeting such issues more precisely, as it gives incentives for specific production sites and companies. That larger companies and production sites on average have lower production losses poses an interesting trade-off as the regulatory system limits how much fish can be kept at a site and the government has also prioritized small companies when awarding licenses (Hersoug et al., 2019).

## CRediT authorship contribution statement

**Ruth B.M. Pincinato:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Frank Asche:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Hogne Bleie:** Conceptualization, Data curation, Writing - review & editing. **Aud Skrudland:** Conceptualization, Data curation, Writing - review & editing. **Marit Stormoen:** Conceptualization, Data curation, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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