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Fast growth was not associated with an increased incidence of soft flesh and gaping in two strains of Atlantic salmon (*Salmo salar*) grown under different environmental conditions

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Abstract

We tested the hypothesis that fast growth prior to harvest increased the incidence of soft flesh and gaping in Atlantic salmon (*Salmo salar* L.) fillets. Growth trials were conducted at Salar, South Uist Western Isles, Scotland and at the Gildeskål Research Station-Gifas, Northern Norway in duplicate 5 m × 5 m × 5 m net pen sea cages, and feeding commercial diets. Individual growth rate was measured as the thermal growth coefficient (TGC) and a range of flesh quality attributes were measured including fillet firmness using an instrumental texture analyser. The Uist trial comprised the offspring of seven families from the Stofnfiskur breeding programme (Stofnfiskur A/S, Iceland). Salmon from the Uist trial harvested in October 2003 had an average TGC of 2.1 (range 1.4 to 3.6) and showed a very minor but significant positive relationship between the work done (WD) (mJ) to shear a standardised fillet slab and TGC (R^2=0.041; degrees of freedom 160; P=0.01). In the Gifas trial 1200 PIT-tagged 03 input S1 smolt of the NLA strain were tightly graded and stocked into 4 net pens in June 2004 at a mean weight of 1447 g (16% coefficient of variation). In order to gain salmon with a wide spectrum of growth rates of comparable harvest weight the fish were fed in duplicate cages either to satiation or restricted ration to target a lower growth rate whilst maintaining the same feed conversion rate. In September 2004 104 fish were harvested, selected for high growth rates (TGC=3.7±0.06, mean±SE; range 2.6 to 5.0) and 106 lower growth rate fish (TGC=2.7±0.04, mean±SE; range 1.7 to 3.6) were harvested in November 2004. For the September harvest there was no relationship between TGC and WD whereas for the November harvest there was a very minor but significant negative correlation between TGC and WD (R^2=0.046; degrees of freedom 102; P=0.04). There was no relationship between TGC and the incidence of gaping 3d post-*rigor* as measured by the length (cm) gapes m^{-2} fillet cross-sectional area (Uist trial) or gaping score (0=no gaping to 4=severe gaping) (Gifas trial). In practical terms it was concluded that there was no evidence that fast growing fish had a materially higher incidence of soft flesh and gaping than slow growing fish for the stocks and sites studied.

Keywords: Atlantic salmon; Growth rate; Flesh quality; Gaping and soft flesh

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1. Introduction

At various stages of the value chain from fish farm to final seafood product there can be an economic loss due to sub-optimal raw material characteristics of the flesh, reflecting a complex mixture of factors related to genetics, production and harvesting conditions (Johnston, 1999; Michie, 2001; Johnston et al., 2006). In Atlantic salmon (*Salmo salar*) downgrading losses during primary processing (evisceration, cleaning and weighing) are mostly caused by maturation, spinal deformity and disease whilst monetary loss during secondary processing (filleting, curing, smoking and preparing the final consumer product) mainly arise due to variations in colour, bloodspotting, gaping of the fillet, lacing and soft texture (Michie, 2001). There has been speculation that the high growth rates achieved by genetic selection, improved diets and production techniques have led to an increased incidence of soft flesh and gaping and hence more downgrading losses relative to the early days of the salmon farming industry. Although widely discussed within the industry this speculation has been based on anecdotal not scientific evidence. The aim of this study was therefore to test the hypothesis that growth rate influences fillet texture and gaping. Individual growth rate was assessed using the thermal growth coefficient (TGC) (Cho, 1992). In order to increase the robustness and generality of the hypothesis testing, two different strains of Atlantic salmon were studied in Scotland and Northern Norway that had been farmed under very different environmental conditions. A very wide range of individual growth rates were achieved ranging from 1.4 to 3.6 TGC for the Scottish trial and 1.8 to 5.0 TGC for the Norwegian trial. At the high latitude site we obtained TGC values that were amongst the highest values recorded for adult Atlantic salmon in the literature (Johnston et al., 2002; Morris et al., 2003; Ytrestøyl et al., 2006).

2. Materials and methods

2.1. Fish husbandry

The first growth trial was conducted at Salar, South Uist, Western Isles, Scotland in duplicate 5 m × 5 m × 5 m net pen sea cages. Each cage was initially stocked with approximately 2000 S1-smolts (60–80 g) comprising the offspring of seven families from the Stofnfiskur breeding program (Stofnfiskur A/s, Iceland) in April 2001. Prior to stocking fish were individually PIT tagged (Passive Induced Transponder, supplied by Fish Eagle, Gloucestershire, England) and freeze-branded. Fish were fed a commercial ration of the Ecolife® series (BioMar Ltd., Grangemouth, Scotland) consisting of 25/47 (oil/protein) for the 4.5 mm, 30/40 for 6.5 mm and 33/38 for 9 mm pellet sizes. The total feed input (energy input) was controlled using a computer-operated demand feeding system (AKVAsmart UK Ltd). The mass of each fish was measured starting on the 24th August 2001 (start weight). Fish were batch netted at random into a sample weigh bin, anaesthetized with Benzoak® (>30 mg benzocaine l^{-1} sea water), identified by PIT tag and mass and fork length recorded. A total of 40 fish were removed from each of the duplicate cages at the first harvest on the 1st July 2002, and 72 of the remaining fish were sacrificed on the 31st October 2002 (2nd harvest). In both cases, the first 6 fish identified per family from each of the sea cages were taken for sampling. Daily water temperature readings were taken throughout the trial.

The second growth trial was conducted at the Gildeskål Research Station-Gifas, Northern Norway. In June 2004, 1200 PIT-tagged 03 input S1 Atlantic salmon smolt (NLA strain) were tightly graded (average start body weight 1447 g, 16% coefficient of variation) and the selected fish were distributed between four 5 m × 5 m × 5 m net pen sea cages, with ~ 270 fish per pen. In order to gain salmon with a wide spectrum of growth rates at comparable harvest weight the fish were fed with a commercial ration of Bio-optimal® CPK 9 mm (BioMar AS) in duplicate cages either to satiation (cages 1 and 3) or a restricted ration equivalent to 70% appetite in order to achieve lower growth rates (cages 2 and 4) whilst maintaining the same feed conversion rate (FCR). This was achieved by calculating and adjusting feeding rate on a weekly basis by using the mean temperature from the previous week, biomass in each cage and the biomass increase based on recorded feed consumption and a target FCR of 1.0. In order to facilitate accurate calculations of feed intake and actual FCR, feed wastage was collected through a lift-up system and calculated. Daily measurements of water temperature at 1 and 3 m depth were recorded.

Fish were identified by PIT-tag and mass and length were measured at the start of the trial (24th May 2004) and at the end of the trial which was on the 16th–17th September 2004 or the 4th–5th November 2004 for the fish fed to appetite and 70% appetite respectively. Fish were batch netted into a sample weigh bin, anaesthetized with Benzoak® (>30 mg benzocaine l^{-1} sea water), to aid with handling. Approximately equal numbers of fish were sampled from the duplicate cages.

2.2. Fish processing

Fish were fasted for 4 degree days prior to harvest. The sample fish were killed by percussion stunning,

bled in ice-slurry (Uist trial) or in ambient sea water for 30 min then chilled in ice-slurry (Gifas trial), eviscerated, gill-tagged and packed on ice in polystyrene ice boxes. The boxes were transported to the fish processor (Uniq plc, Annan, Scotland) where the carcasses were left on ice for 3 d until post-*rigor*. One fresh fillet was then removed by hand for the assessment of gaping and the other was left on the skeleton, placed in fillet bags, packed on ice in polystyrene boxes and dispatched to the University of St Andrews for texture analysis. The position of the various samples taken is illustrated in Fig. 1. All texture, gaping and lipid measurements were taken post-*rigor* around 72 h after slaughter and were performed on all the fish sampled.

2.3. Instrumental texture analysis

Texture was evaluated by a shear test on all the fish using a TA-HDi Texture Analyzer controlled with Texture Expert Exceed 2.52 software from Stable Micro Systems, Surrey, England. To ensure the flesh temperature was kept constant during testing, each fish was kept on ice until the flesh samples were excised and the temperature of the muscle tissue was found to be 2–4 °C for a selection of individual fish chosen at random. Shear tests were performed in duplicate on each fish using two 4×4×2 cm blocks of fast muscle excised from the Flesh Quality Cut (FQC); epaxial myotomes anterior to the first dorsal fin ray (Uist trial) or from the Scottish Quality Cut (SQC); epaxial myotomes below the dorsal fin (Gifas trial) (Fig. 1). The probe used was a 60° knife edge blade (not sharpened) with a slotted blade insert located in a heavy duty platform. A 100 kg load cell was used and the test speed was set at 1 mm s^{-1} with the blade traveling perpendicular to the orientation of the muscle fibres. Each texture profile was analyzed using Texture Expert Exceed 2.52 software and fillet firmness was determined as work done (WD) in millijoules (mJ) during the shear test, calculated from the area under the curve during shearing.

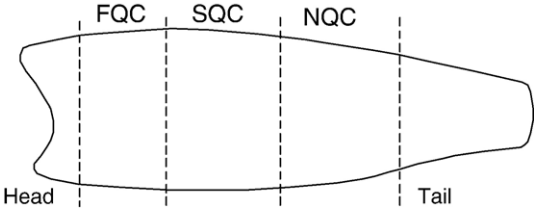

Fig. 1. Illustration of the Flesh Quality Cut (FQC), the Scottish Quality Cut (SQC) and the Norwegian Quality Cut (NCQ) used for sampling.

2.4. Flesh lipid content

A steak was cut from the posterior section of the Norwegian Quality Cut (NQC) (see Fig. 1), skin and bones were removed and a homogenate was made of the flesh using a knife mill for 7 s at 650 rpm (Grindomix GM200, Brinkman Instruments Inc, Westbury, New York, USA). Ten grams of homogenised flesh was analysed in duplicate by near infrared absorbance (NIR) spectroscopy. NIR for lipid content was carried out using an InfraAlyzer™ 500 (Bran+Luebbe, Brixworth, Northampton, UK) controlled by a Sesame v3 operating software (Bran+Luebbe). The NIR instrument was fully calibrated with lipid chemical analysis.

2.5. Assessment of gaping

For the Uist trial fillets were trimmed post-*rigor* at Uniq plc and the outline drawn on paper, scanned and the cross-sectional area digitized (Sigma Scan pro., Systat Inc, USA). The number and length of individual gapes were quantified and number or total length of gapes per m^2 of fillet was calculated for each fish. In the Gifas trial gaping was assessed in the processing factory using a commercial five point scale (0=no gaping, 1=slight gaping, 2=moderate gaping, 3=serious gaping and 4=fillet falling apart).

2.6. Statistical analysis and calculations

Thermal growth coefficient (TGC) (Cho, 1992) was calculated according to the formula: $TGC = [(W_2^{0.333} - W_1^{0.333}) \text{ (degree days)}^{-1} \times 1000]$, where W_1 and W_2 were the start and harvest body weights respectively. Degree day values are the sum of the °C values for each day of the growth trial. The results were analysed with a General Linear Model ANCOVA with a normal error structure, using sequential sum of squares (Minitab™ statistical software, Minitab Inc., State College, USA). Plots of residuals versus fitted values, the normal probability of residuals and histograms of residuals were performed to ensure the data fulfilled the assumptions of the ANOVA. The model had shear work (WD) and gape length m^{-2} fillet as the dependent variables, time of harvest nested, and cage nested within harvest as a fixed factors and thermal growth coefficient as a covariate. The correlation between TGC and WD was further investigated by fitting first order linear regressions with significance testing by ANOVA (Sigmaplot 8.0 software, SPSS in). Gaping scores were assessed qualitatively as no pattern with respect to TGC was discernable. Average gaping scores and

Table 1
Growth and flesh quality parameters for the Uist trial

Parameter	Units	1st July harvest		31st October harvest
		(n=71)	(n=9)	(n=72)
		Grilse	Salmon	Salmon
Start weight	g	265±6	272±34	273±6
Final weight	g	3498±62	2913±88	3807±83
Final fork length	cm	64.5±0.4	62.2±0.4	66.6±0.4
Condition Factor	–	1.30±0.01	1.21±0.03	1.27±0.01
Thermal Growth Coefficient		2.0±0.03	1.8±0.06	2.1±0.03
Flesh lipid content	%	10.0±0.2	8.9±0.6[a]	12.5±0.1[b]
Flesh firmness (Work done in an Instrumental Shear test)	mJ	446±9	396±15[a]	601±10[b]
Length gapes	cm. m^{-2} fillet	NA	83.6±16.8	212±29.7[a]
Flesh pH post-*rigor*	pH units	NA	NA	6.33±0.0.01

Values represent mean±SE. The number of fish sampled (n) is shown in brackets. Parameters were measured on all the samples. Significant differences at the $P<0.05$ level are indicated by superscripts a and b representing respectively comparisons between grilse and salmon in the 1st harvest and salmon between harvests.

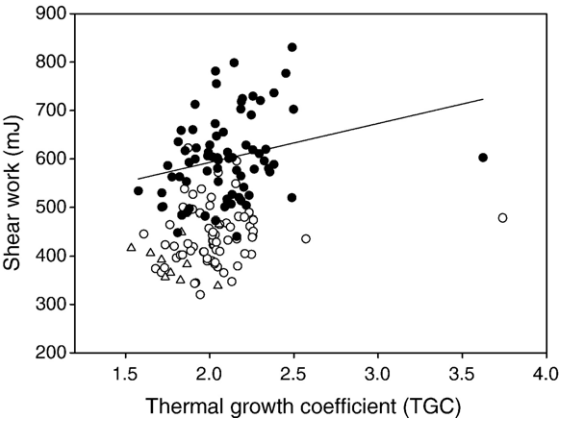

Fig. 2. The relationship between thermal growth coefficient (TGC) and the work required (WD) in mJ to shear a standardised slab of fillet for Atlantic salmon from the Uist trial. First order regressions were fitted to the data using a least squares method. The open circles represent grilse (n=71) and the open triangles immature salmon (n=9) harvested on the 1st July 2002 and the closed circles represent fish harvested on the 31st October 2002 comprising 72 immature salmon. The regression equation were as follows: First harvest (all fish): WD (mJ)=352.5+50.6. TGC; R^2=0.034; degrees freedom 77; $P>0.1$, not significant. First harvest (grilse only): WD (mJ)=386.0+27.3. TGC; R^2=0.015; degrees freedom 67; $P>0.1$, not significant. Second harvest: WD (mJ)=431.8+80.5. TGC; R^2=0.062; degrees freedom 71; $P<0.05$.

growth rate were compared using a non-parametric Mann–Whitney U test.

3. Results and discussion

3.1. Fillet firmness

Information on the growth and flesh quality parameters of fish in the Uist trial are summarized in Table 1. The 1st harvest on the 1st July comprised 71 grilse (maturing salmon) and 9 immature salmon (classified on the basis of gonad somatic index and external visual assessment) whereas the 2nd harvest on the 31st October comprised 72 immature salmon. An ANOVA (all fish analysed) showed a significant difference between harvests in fillet texture measured as the work required to shear a standardized fillet slab (WD, mJ), with a firmer texture observed in the immature fish from the second harvest ($F_{1,\ 144}$=38.4; $P<0.05$) (Fig. 2). WD for the immature fish from harvest 2 was 601±10 mJ (mean±SE, n=72), compared with 396±15 mJ (mean±SE, n=9) for immature salmon and 446±9 mJ (mean±SE, n=71) for the maturing salmon (grilse) in harvest 1. Although the number of immature salmon that had reached 4–5 kg in July was small the results are consistent with season being the most important factor accounting for the observed difference in fillet texture. Roth et al. (2005) also found a similar relationship with season, where 1+ or 0+ input Atlantic salmon had significantly higher texture (WD) in October compared to June. Season was also reported to affect the maximum shear force in salmon, particularly in the tail region of the fish (Espe et al., 2004). In the present study, there was also a small but statistically significant cage effect in texture ($F_{2,\ 148}$=3.82; $P<0.05$), and post-hoc tests

Table 2
Growth and flesh quality parameters for the Gifas trial

Parameter	Units	September harvest (n=101)	November harvest (n=106)
Start weight	g	1385±20	1516±23
Final weight	g	3659±33	3770±24
Final fork length	cm	65.7±0.2	65.8±0.2
Condition Factor	–	1.29±0.011	1.33±0.013
Thermal Growth Coefficient		3.66±0.056	2.65±0.036[a]
Flesh lipid content	%	11.18±0.30	10.60±0.22
Flesh firmness (Work done in an Instrumental Shear test)	mJ	314±4	343±7[a]
Gaping score	0–4	0.8±0.1	1.6±0.1[a]
Flesh pH post-*rigor*	pH units	6.27±0.042	6.27±0.006

Values represent mean±SE. The number of fish sampled (n) is shown in brackets. Parameters were measured on all the samples. The superscript a denotes a significant difference between harvests at the $P<0.05$ level.

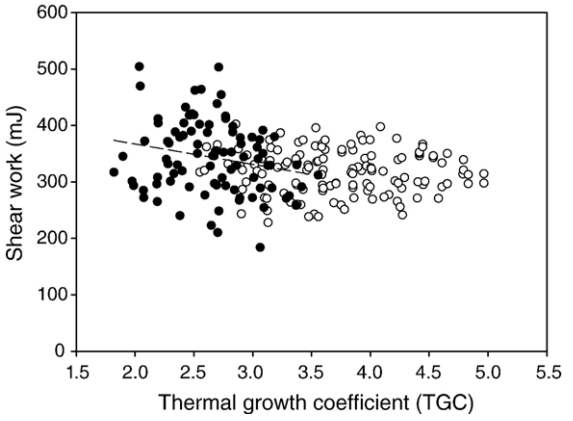

Fig. 3. The relationship between thermal growth coefficient (TGC) and the work required (WD) in mJ to shear a standardised slab of fillet for Atlantic salmon from the GIFAS trial. First order regressions were fitted to the data using a least squares method. The open circles represent fish harvested in September and the closed circles fish harvested in November. First harvest: No significant correlation. Second harvest: WD (mJ) — −36.1+439.3. TGC; R^2=0.046; degrees freedom 89; P=0.04.

revealed this was due to the immature salmon from the second harvest (cage 1, 627±15 and cage 2, 574±12 mJ; mean±SE; equivalent to an 8% difference between cages).

There was no significant correlation between TGC and fillet firmness measured as WD for harvest 1 both for all fish and the grilse only (Fig. 2). For harvest 2, comprising immature salmon, there was a significant positive correlation between TGC and WD, but the relationship was weak and could only explain 6.2% of the total variation (Fig. 2).

Information on the growth and flesh quality parameters of salmon in the GIFAS trial are summarised in Table 2. For fish harvested in September with TCGs between 2.5 and 5.0 there was a statistically significant, but very minor negative correlation between WD and TGC (R^2=0.046; P=0.04) (Fig. 3). However, for the slower growing fish harvested in November with TGCs between 1.7 and 3.6 there was no significant relationship between WD and TCG (Fig. 3). WD showed a very minor, but significant cage effect across the trial ($F_{6,\ 187}$=7.61; P<0.01). For both harvests there were no significant correlations between the post-*rigor* pH of the flesh and WD (not shown). Espe et al. (2004) also found no significant correlation between post-*rigor* pH and fillet firmness (Shear Force) in farmed salmon harvested at different seasons. In the present study, there was only a very weak correlation or no correlation between WD and flesh lipid obtained respectively for fish harvested on the 1st July and 31st October in the Uist trial (Fig. 4A). In contrast, for the GIFAS trial significant negative correlations were found between flesh lipid content and WD within each harvest which when combined, explained 25% of the total variation (Fig. 4B). Whilst there was a positive relationship between lipid content and harvest weight there was no correlation between lipid content and growth rate measured as TCG (not shown). Mørkøre et al., 2002, also found a significant inverse relationship between fat content and fillet firmness in farmed rainbow trout, measured as resistance to compression. Genetic and also particularly environmental factors are likely to influence the relationship between flesh lipid content and texture.

The texture of fresh and smoked salmon fillets has been positively correlated with muscle fibre density (Johnston et al., 2000) and the concentration of mature pyridinoline cross-links between collagen molecules (Li

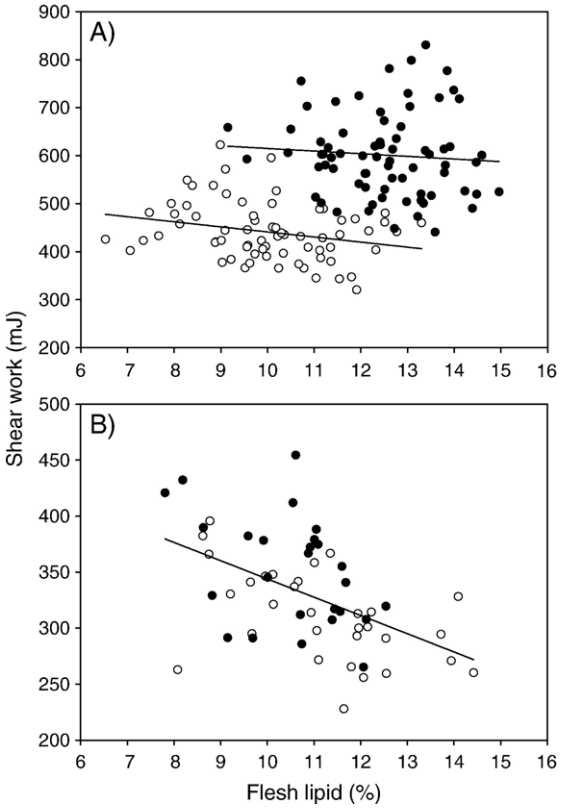

Fig. 4. The relationship between flesh lipid content (%) and fillet firmness (work done to shear a standardised slab of muscle (WD), mJ). 1st order regressions were fitted to the data with the following equations: A) (solid circles) 1st July harvest Uist trial; Fillet firmness=−10.6+546.8.WD; R^2=0.07, $F_{1,67}$=4.8; P=0.03; (open circles) 31st October harvest Uist trial; no significant correlation. B) GIFAS trial, open circles September harvest and closed circles November harvest; For the combined data Fillet firmness=−16.3+507.0 WD; R^2=0.25, $F_{1,55}$=18.6; P<0.001.

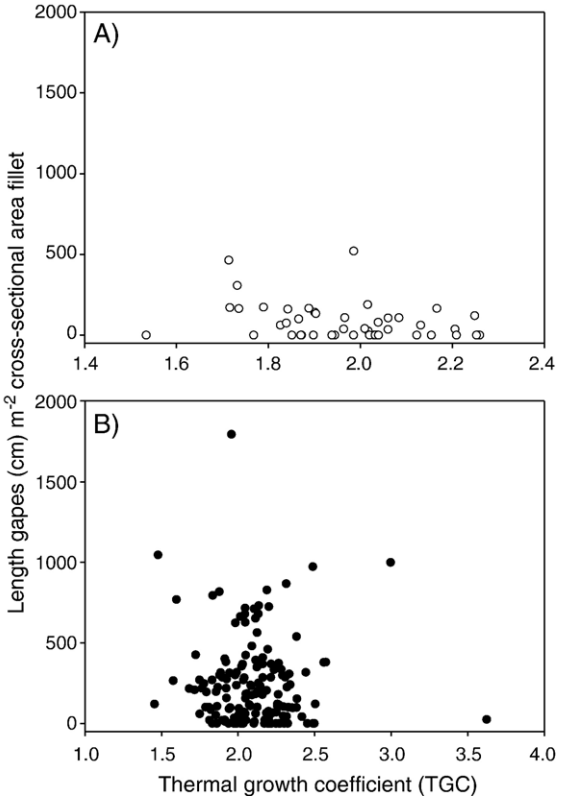

Fig. 5. The length gapes (cm) per m^{-2} fillet cross-sectional area in relation to thermal growth coefficient (TCG) for fish in the Uist trial (A) harvested on the 1st July and (B) 31st October.

et al., 2005) and can be influenced by environmental conditions during growth (Johnston, 2006), feed ration prior to slaughter (Einen and Thomassen, 1998; Einen et al., 1999), stress prior to slaughter (Roth et al., 2006), method of slaughter (Kiessling et al., 2004), filleting pre-or post-*rigor* (Einen et al., 2001), post-*mortem* storage time (Espe et al., 2004), fresh or frozen storage conditions (Mørkøre et al., 2002) and smoking procedures (Birkeland et al., 2004, Hultmann et al., 2004). However, the results in the present study did not support the hypothesis that fast growth within a population leads to a reduction in fillet firmness for the strains and farm sites studied.

3.2. Fillet gaping

The phenomenon of gaping is the result of the post-*mortem* rupture of the connective tissue matrix between muscle fibres resulting in tears appearing in the fillet that impede secondary processing and detract from the appearance of the product. Gaping is often but not always associated with a soft texture (Mørkøre and Rørvik, 2001). The mechanism(s) of gaping are poorly understood, but probably involve the weakening of structures connecting the connective tissue with the contractile filaments, causing acute tears to appear in the fillet following the development of rigor forces post-*mortem* which further develop with storage time on ice (Espe et al., 2004). The proximal causes of gaping are also obscure but may be influenced by slaughter method (Robb, 2001) and the intrinsic raw material characteristics of the flesh including muscle fibre density, collagen content and proteolytic enzyme activities (Ando et al., 1991; Johnston et al., 2002). In the present study, there were no significant effects of cage on the extent of fillet gaping. The average length (cm) of gapes m^{-2} fillet area was 83.6±16.8 for Uist harvest 1 (n=48) and 212.0±29.7 for Uist harvest 2 (n=70) (mean±SE) (ANOVA; $F_{1,\ 117}$=10.85: P<0.05). 43.8% of fillets in harvest 1 showed no gaping compared to just 20% for harvest 2. There was no significant relationship between the extent of gaping and the thermal growth coefficient (Fig. 5). Similar results were obtained for the number of gapes per fillet area (results not shown). Espe et al. (2004) found a similar relationship with season, where approximately 60% of salmon sampled in June had no or mild gaping 5 days post-slaughter compared to about 40% of fish sampled in September. In the GIFAS trial, fillet gaping was measured using a commercial 5-point scale in the processing factory. There was no apparent relationship between gaping score and TGC (Fig. 6), although it should be pointed out that none of the fish studied showed severe gaping. Kiessling et al. (2004) also found no significant relationship between gaping and either growth rate or body weight in Atlantic salmon slaughtered at an average weight of 5.5 kg. We found no

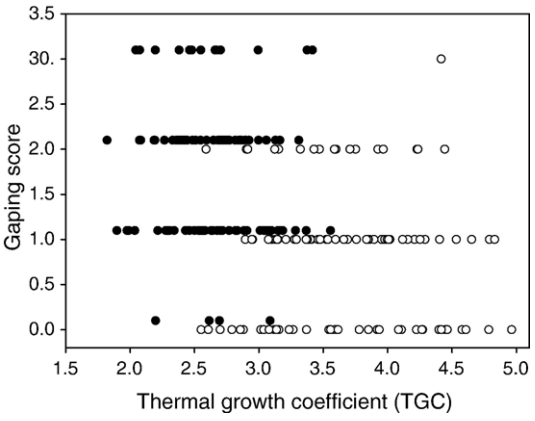

Fig. 6. Gaping score for Atlantic salmon in the GIFAS trial in relation to thermal growth coefficient (TCG) for fish fed to appetite and harvested in September (open circles) or 70% appetite and harvested in November (closed circles).

relationship between the final pH and the incidence of gaping in contrast to the results reported by Espe et al. (2004). However the pre-and post-slaughter procedures were carried out in a controlled manner to minimize any effects of such variables on flesh quality.

3.3. Conclusions

The present study with two strains of Atlantic salmon farmed under widely different environmental conditions did not support the hypothesis that growth rate was related to muscle texture and gaping. The generality of our conclusion is strengthened by the study of two different populations grown under very different environmental conditions in Scotland and Norway. Thus the suggestion that fast growth is a cause of soft flesh and gaping was not supported. The average TGC of fish in the Uist trial (2.0–2.1) was less than the 2.4–2.8 reported in another comparable growth trial in Scotland (Morris et al., 2003), but higher than growth reported for Atlantic salmon of comparable size under commercial production in Scotland (TGC = 1.9) (Morris et al., 2005). In contrast, the mean TGC of 3.7 for the September harvest at the high latitude site in Norway was higher than reported for most comparable studies in the literature e.g. 2.8 (Bailey et al., 2003) and 2.5 (Ytrestøyl et al., 2006). Thus we are confident that we achieved growth rates that encompass the full range observed under commercial conditions.

Since the early days of salmon farming the optimization of production techniques including the use of accelerated smolts, improved diets and treatments for sea lice infestation have reduced the time required to produce 4–5 kg salmon from around 4.5 to a little over 2 years. In other farm animals the concentration of mature collagen cross-links that gives skeletal muscle much of its mechanical strength increase with age (Purslow, 2005), and this is probably also true in fish muscle (I.A. Johnston and R. Bickerdike, unpublished results). It is therefore plausible that whilst commercial farming practices have gone a long way to improve flesh quality the increased incidence of soft texture and gaping reported since the early days of salmon farming reflect, at least in part, the fact that the fish are younger at harvest size.

Acknowledgements

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