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RESEARCH ARTICLE

Long-term fasting in the anadromous Arctic charr is associated with downregulation of metabolic enzyme activity and upregulation of leptin A1 and SOCS expression in the liver

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SUMMARY

The life strategy of the anadromous Arctic charr (*Salvelinus alpinus*) includes several months of voluntary fasting during overwintering in freshwater, leading to emaciation prior to seawater migration in spring. In this study we compared changes in condition, substrate utilization and liver metabolism between captive anadromous charr subjected to food deprivation during late winter and spring, and conspecifics fed in excess. In March, nine out of the 10 sampled fed fish had not eaten, indicating that they were in a voluntary anorexic state. In June, the fed fish were eating and all had higher body mass, condition factor and adiposity than in March. In fasted fish there were only small decreases in body mass, condition factor and adiposity between March and May, but all these parameters decreased markedly from May to June. The fasted fish were depleted in fat and glycogen in June, had suppressed activity of hepatic enzymes involved in lipid metabolism (G6PDH and HOAD) and seemed to rely on protein-derived glucose as a major energy source. This was associated with upregulated liver gene expression of *leptin A1*, *leptin A2*, *SOCS1*, *SOCS2* and *SOCS3*, and reduced *IGF-I* expression. In an *in vitro* study with liver slices it was shown that recombinant rainbow trout leptin stimulated *SOCS1* and *SOCS3* expression, but not *SOCS2*, *IGF-I* or genes of enzymes involved in lipid (*G6PDH*) and amino acid (*AspAT*) metabolism. It is concluded that liver leptin interacts with SOCS in a paracrine fashion to suppress lipolytic pathways and depress metabolism when fat stores are depleted.

Supplementary material available online at http://jeb.biologists.org/cgi/content/full/216/17/3222/DC1

Key words: *Salvelinus alpinus*, seasonal fasting, emaciation, liver metabolism, leptin, SOCS, IGF-I.

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INTRODUCTION

The anadromous life strategy of Arctic charr [*Salvelinus alpinus* (Linnaeus 1758)] is characterized by substantial seasonal changes in food intake, growth and adiposity. Most of the annual growth and energy accumulation occurs during a short summer seawater residence, whereas overwintering in freshwater is characterized by anorexia and depletion of energy reserves (Dutil, 1986; Boivin and Power, 1990; Jørgensen et al., 1997; Jobling et al., 1998). Captive offspring of anadromous Arctic charr also exhibit pronounced seasonal changes in food intake and growth when held at constant temperature and given food in excess (Tveiten et al., 1998), showing that the seasonal cycle of food intake and growth is under physiological control. In captive offspring of anadromous charr, feeding commences in May (Tveiten et al., 1996; Bottengård and Jørgensen, 2008; Aarseth et al., 2010). In wild anadromous charr, appetite seems to return in early May (Aas-Hansen et al., 2005), whereas seaward migration takes place 3 to 4 weeks later (Aas-Hansen et al., 2005; Jensen et al., 2012). During the pre-migratory period the fish apparently find little food, and their condition factor continues to decrease until the time of downstream migration, when it may be as low as 0.70 (Nilssen et al., 1997; Aas-Hansen et al., 2005). Hence, the anadromous life strategy of Arctic charr incorporates a prolonged, voluntary anorexia with emaciation, indicating high tolerance to food deprivation. As such, the anadromous charr represents an interesting model for investigation of mechanisms associated with long-term regulation of appetite and energy homeostasis.

Since the first identification of a gene encoding a cDNA homologue to mammalian leptin (Lep) in pufferfish (*Takifugu rubripes*) (Kurokawa et al., 2005), *Lep* genes have been identified in many fish species, including the Arctic charr (Frøiland et al., 2010). In contrast to mammals, in which Lep is produced mainly in adipose tissue (Masuzaki et al., 1995), Lep is produced in numerous tissues in fish, including the liver (Wong et al., 2007; Kurokawa and Murashita, 2009; Rønnestad et al., 2010; Tinoco et al., 2012; Trombley et al., 2012). Hepatic *LepA1* and *LepA2* expression increased towards the end of a 7 week period of feed restriction in Atlantic salmon (*Salmo salar*) (Trombley et al., 2012) and during the latter part of a 75 day period of feed deprivation in Arctic charr (Frøiland et al., 2012). Increased liver *LepA1* expression was observed without any change in plasma Lep concentrations (Frøiland et al., 2012; Kling et al., 2012), indicating a paracrine role for Lep in nutrient processing and regulation of endogenous energy reserves in the liver. A paracrine role for Lep in the fish liver is

also supported by the presence of the *Lep receptor* (*LepR*) gene in this organ in several fish species (Liu et al., 2010; Rønnestad et al., 2010; Tinoco et al., 2012; Trombley et al., 2012).

We have studied the metabolic responses of the liver to long-term fasting in the Arctic charr, and have investigated whether Lep and the suppressor of cytokine stimulation (SOCS) may play a role in regulating these responses. Examination of *SOCS* gene expression was included in the study because SOCS is known to modulate the signalling of hormones regulating energy homeostasis such as growth hormone (GH) and Lep in mammals (Fujimoto and Naka, 2003).

MATERIALS AND METHODS

Experiment 1: fish, experimental setup and sampling

The experiment was carried out at Tromsø Aquaculture Research Station (TARS), Tromsø, Norway (69°N), with hatchery-reared offspring of anadromous Arctic charr derived from a broodstock captured in Lake Vårfluesjøen, Svalbard (79°N), in 1990. The eggs hatched in winter 2008 and juveniles were held in freshwater at 6°C under continuous light until July 2009, and thereafter at ambient water temperature and natural light (transparent roof) conditions until the start of the experiment. On 8 and 9 March 2010, a total of 360 individually tagged (Floy FTF-69 fingerling tags; MGF, Seattle, WA, USA) fish with an average body mass of 146 g were taken from a stock tank, anaesthetised in benzocaine (60 p.p.m.) and randomly distributed among four 300 litre circular tanks. The tanks were subjected to simulated natural light conditions (69°N) and were supplied with freshwater at *ca.* 5°C (ranging between 4.7 and 6.3°C). The fish were provided with commercial dry-pellet feed (Nutra Parr; Skretting, Stavanger, Norway) in excess until 24 March, after which the fish in two tanks were feed deprived until the end of the experiment in June (FU fish). The fish in the other two tanks continued to be fed in excess throughout the experiment (FF fish). The experiment was terminated on 17 June, when the condition factor [(mass/length^3)×100] of the fasted fish was approaching that (0.70) of wild, anadromous Arctic charr when they descend to the sea.

On 25 March, 6 May and 17 June, a total of five randomly selected fish were quickly netted from each tank and killed with an overdose of benzocaine (120 p.p.m.). Blood was collected from the caudal vein using 2 ml, lithium-heparinized (30 USP units) vacutainers and held on ice until plasma was separated by centrifugation (6000 ***g*** for 10 min). Plasma was stored at −80°C until analyses of cortisol and glucose concentrations were carried out. Thereafter, body mass (M_b; g) and fork length (FL; cm) of the fish were measured before each fish was dissected. Liver masses were noted and three small pieces were removed. One piece was put in a tube with RNAlater (Ambion, Life Technologies, Carlsbad, CA, USA) and stored at −20°C until analysis of *LepA1*, *LepA2, IGF-I* and *SOCS1–3* gene expression, and the other two were wrapped in aluminium foil and frozen at −80°C for later analysis of glycogen and enzyme activities. The fish were then examined for feed in the stomach, sex and maturity status before the body was wrapped in aluminium foil and stored at –80°C for later analysis of proximate chemical composition. After the sampling in March and May, the remainder of the fish in each tank were anaesthetized in benzocaine for body mass and length measurement.

For the FF fish, one out of the 10 fish sampled in March had eaten and in May, four fish had eaten, whereas six had empty stomachs. In June, seven out of the 10 sampled fish had well-filled stomachs. The FF fish were intended to simulate the seasonal feeding cycle of wild, anadromous Arctic charr, so the fish that was recorded as eating in March and those that were anorexic in June were excluded from the analyses. The FF fish sampled in May were also excluded because of the low number of feeding fish and the heterogeneity of feeding behaviour within the group.

The experiment was approved by the Norwegian Committee on Ethics in Animal Experimentation (ID 2442).

Plasma cortisol and glucose, and liver glycogen and enzyme analyses

Plasma cortisol concentration was determined by radioimmunoassay, using an established protocol (Schulz, 1985) validated for Arctic charr (Tveiten et al., 2010). The detection limit for the assay was 3.0 ng ml^{-1}. Plasma glucose concentration, given as nmol l^{-1}, was measured spectrophotometrically using a commercial enzymatic kit (HL 1611, Randox Laboratories, Crumlin, UK). Liver glycogen concentration was determined by glucose measurements, using the same kit as for plasma glucose measurements, before and after hydrolysis of glycogen with amyloglucosidase (Keppler and Decker, 1974) and expressed as μmol g^{-1} protein. Liver enzyme activities were measured as described in Aas-Hansen et al. (Aas-Hansen et al., 2005) and expressed as μmol min^{-1} g^{-1} protein. Enzyme activities determined were alanine aminotransferase (AlaAT) (EC 2.6.1.2), aspartate aminotransferase (AspAT) (EC 2.6.1.1), glucose-6-phosphate dehydrogenase (G6PDH) (EC 1.1.1.49), 3-hydroxyacylcoenzyme A dehydrogenase (HOAD) (EC 1.1.1.35), lactate dehydrogenase (LDH) (EC 1.1.1.27), phosphoenolpyruvate carboxykinase (PEPCK) (EC 4.1.1.32) and pyruvate kinase (PK) (EC 2.7.1.40).

Whole-body proximate composition analysis

Whole fish were homogenized by passing them three times through a mincer (Sirman TC22F, Marsango, Italy). Duplicate samples of *ca.* 10 g homogenate were weighed (±0.1 g), dried for 24 h at 105°C and then re-weighed to calculate water content. Fat extraction was carried out as described by Johansen et al. (Johansen et al., 2002), using a Behrotest extraction system (Behr Labor-technik, Düsseldorf, Germany) and ether (Merck, Darmstadt, Germany) as the solvent. Following fat extraction, the extraction thimbles with tissue samples were dried and weighed. Fat content was calculated as mass loss during extraction, and fat concentration was calculated in relation to sample wet mass and expressed as a percentage of body mass. Finally, samples were ashed at 500°C for 12 h to estimate the percentage of ash in the sample. Protein was estimated as the difference between the dry sample mass and the combined masses of fat and ash, under the assumption of negligible carbohydrate content. The full data set for these results and calculations is given in supplementary material Table S1.

Experiment 2: *in vitro* study of liver leptin treatment

The *in vitro* study was performed in January 2013, with liver slices obtained from one Arctic charr (345 g) of the same strain as those used in Experiment 1. The fish were not eating at the time of sampling, but had a higher condition factor (1.06) than the fasted fish used in Experiment 1. The fish was killed by a sharp blow to the head and then decapitated. Thereafter the fish was dissected and the liver was perfused with ice-cold PBS *via* the hepatic portal vein until it turned white. The liver was then excised and placed in ice-cold L15 medium. A liver piece of *ca.* 0.7×0.7×0.5 cm was then taken and sliced (250 μm thickness) with a Leica VT1200 (Leica Microsystems, Wetzlar, Germany).

Nine liver slices were incubated individually under gentle shaking for 24 h in a 24-well plate at 5°C. Three wells contained 0.5 ml L15

medium with recombinant rainbow trout Lep dissolved in 5 µl phosphate buffered saline (PBS), resulting in a Lep concentration in the medium of 50 nmol l^{-1} (PBS + Lep). The choice of concentration was based on results from treatment of grass carp (*Ctenopharyngodon idellus*) hepatocytes with recombinant grass carp leptin (Lu et al., 2012). The recombinant rainbow trout leptin with proven bioactivity was produced by the method described by Murashita et al. (Murashita et al., 2008). The purity of produced leptin was approximately 60%, determined by SDS-PAGE. Three wells contained 0.5 ml L15 medium with 0.5 µl PBS added (PBS) and the final three wells contained 0.5 ml L15 medium alone (untreated). After 24 h the slices were put in RNAlater and stored at −20°C until analysis of *SOCS1*, *SOCS2*, *SOCS3*, *G6PDH*, *AlaAT* and *IGF-I* gene expression. The choices of metabolic enzymes were made in order to investigate representatives of lipid metabolism (G6PDH) and gluconeogenesis (AspAT) that decreased and remained unchanged with fasting, respectively. Liver slice viability was estimated by LDH leakage, using a Cytotoxicity Detection Kit (LDH) from Roche (Roche Diagnostics, Mannerheim, Germany) and a Spetramax plus spectrophotometer (Molecular Devices, Sunnyvale, CA, USA) set at 490 nm.

Real-time quantitative PCR of liver *LepA1*, *LepA2*, *IGF-I*, *SOCS1*, *2* and *3*, *AspAT* and *G6PDH* mRNA expression

Reverse transcription of total RNA was performed using the QuantiTect Reverse Transcription Kit (Qiagen, Hilden, Germany) with 1000 ng of RNA per 20 µl cDNA reaction according to the manufacturer's instructions. This kit includes an initial step of gDNA removal, and a reverse transcription test on a selection of samples showed that this was effective. Quantitative real-time PCR (qPCR) was performed, using the comparative C_T method (Applied Biosystems, Warrington, UK), on an ABI 7500 Fast Real-Time PCR System. For real-time estimations, cDNA corresponding to 25 ng RNA was amplified for 40 cycles in a 20 µl PCR mix (Fast SYBR Green Master Mix, Applied Biosystems, Foster City, CA, USA) containing a final concentration of 500 nmol l^{-1} of each primer (PrimerDesign Ltd, The Mill Yard, Southampton, UK; Table 1). Cycling conditions were as follows: 95°C for 20 s, 40 cycles at 95°C for 3 s, and 60°C for 30 s including melt curve analysis. Duplicate PCR analyses were performed on each cDNA sample; the absence of gDNA was confirmed by performing a no-reverse-transcriptase control for every RNA sample, and absence of contamination was confirmed by including a no-template control in every run. The $\Delta\Delta C_T$ method (Livak and Schmittgen, 2001) was used to determine the relative amount of target gene, normalizing against the average expression of the two reference genes *EF1α* and *β-Actin* in Experiment 1 and against *EF1α* in Experiment 2. The primer sequences used for RTqPCR analyses are listed in Table 1.

Data treatment and statistics

All data from Experiment 1 are presented as means ± s.e.m. *LepA1* and *LepA2* expression are given as relative values in comparison with the mean liver *LepA1* expression in FF fish in March. *SOCS* genes expression are given relative to the mean *SOCS1* expression in FF fish in March, and *IGF-I* gene expression is given relative to the mean liver *IGF-I* expression in FF fish in March. Only values normalized against EF1α are given for the *in vitro* data. Condition factor (CF) and hepatosomatic index (HSI) were calculated as $(M_b \times FL^{-3}) \times 100$ and (liver mass×100)×M_b^{-1}, respectively. The masses of body fat and protein present in the fish were calculated by combining the body fat and protein data for the fish sampled in March, May and June with those relating to changes in M_b over time for the fish sampled in May (only FU fish) and June. All data were log-transformed before statistical analyses, with 1 added to the CF, liver HOAD, PEPCK, PK enzyme activity and liver *Lep*, *IGF-I* and *SOCS* expression data in order to achieve positive log numbers. A two-way ANOVA was used to reveal possible effects of time and treatment (replicates pooled) on M_b, CF, percentage body fat and protein, HSI, plasma cortisol and glucose concentrations, liver glycogen concentration and enzyme activities and liver *LepA1*, *LepA2*, *SOCS1-3* and *IGF-I* gene expression. A *post hoc* (Tukey's HSD) test was used to reveal where significant differences occurred. Possible effects of Lep on the mRNA expression of liver *SOCS1-3*, *AspAT*, *G6PDH* and *IGF-I* genes in the *in vitro* study were tested using a non-parametric Kruskal–Wallis test. Results were considered significant at $P \leq 0.05$.

RESULTS

Experiment 1

M_b did not differ between treatments in March (Fig. 1A), but in June FF fish had a much higher M_b than FU fish ($P<0.001$). A similar pattern was seen for CF, which did not differ between the two treatment groups in March, but was much higher ($P<0.001$) in FF than in FU fish in June (Fig. 1B). The FF fish sampled in June had increased markedly in M_b ($P<0.01$) and CF ($P<0.01$) from March to June (supplementary material Table S2). There was no change in M_b between March and May in FU fish sampled in March, while those sampled in June had only a minor, insignificant decline in M_b

Table 1. Nucleotide sequences used in the qPCR analyses and accession numbers of the gene sequences they were constructed from

Gene symbol	Gene name	Accession number	Primer sequences
LepA1	*Leptin A1*	JQ615967	F: TCC TAG ACT GGG CAG ACC T; R: GCC TGG GCA GCG TGA TAT
LepA2	*Leptin A2*	AB490667	F: TGG CAC TAA ACA GAC TCA AGG; R: CTC AGT GAT GAT CTA TGT CAG TAA C
β-Actin	*Beta actin*	AF503211	F: GCC CCC CTG AAC CCC; R: GAA GGT CTC AAA CAT AAT CTG GGT C
EF1α	*Elongation factor*	AF498320	F: AGG CAT TGA CAA GAG AAC CATT; R: TGA TAC CAC GCT CCC TCT C
SOCS1	*Suppressor of cytokine signalling 1*	NM_001146166	F: TCA GCG TAC GCA TCG TCT AT; R: CGG TCA GGC TTT TCT TAG AGG
SOCS2	*Suppressor of cytokine signalling 2*	AM748722. 1	F: TCG GAT GAC TTT TGG CCT AC; R: CCG TTC TTC TCT CGT TTT CG
SOCS3	*Suppressor of cytokine signalling 3*	AM748723	F: ACC TCT GAC GAA GCA CAC AT; R: GCT GTA ATG GTT GAA TGG ATA GGA
IGF-1	*Insulin-like growth factor 1*	M95183	F: TGG ACA CGC TGC AGT TTG TGT GT; R: CAC TCG TCC ACA ATA CCA CGG T
AspAT	*Aspartate aminotransferase, cytoplasmic*	NM_001141739	F: TCC TTT CCT CAT CTC CTT CAT TAC; R: TTT CCT TGT GTC CTT CCC TCT
G6PDH	*Glucose-6-phosphate dehydrogenase*	EF551311.1	F: CAC TAC CTG GGC AAG GAG AT; R: TTG CTC ATC ATC TTG GCG TA

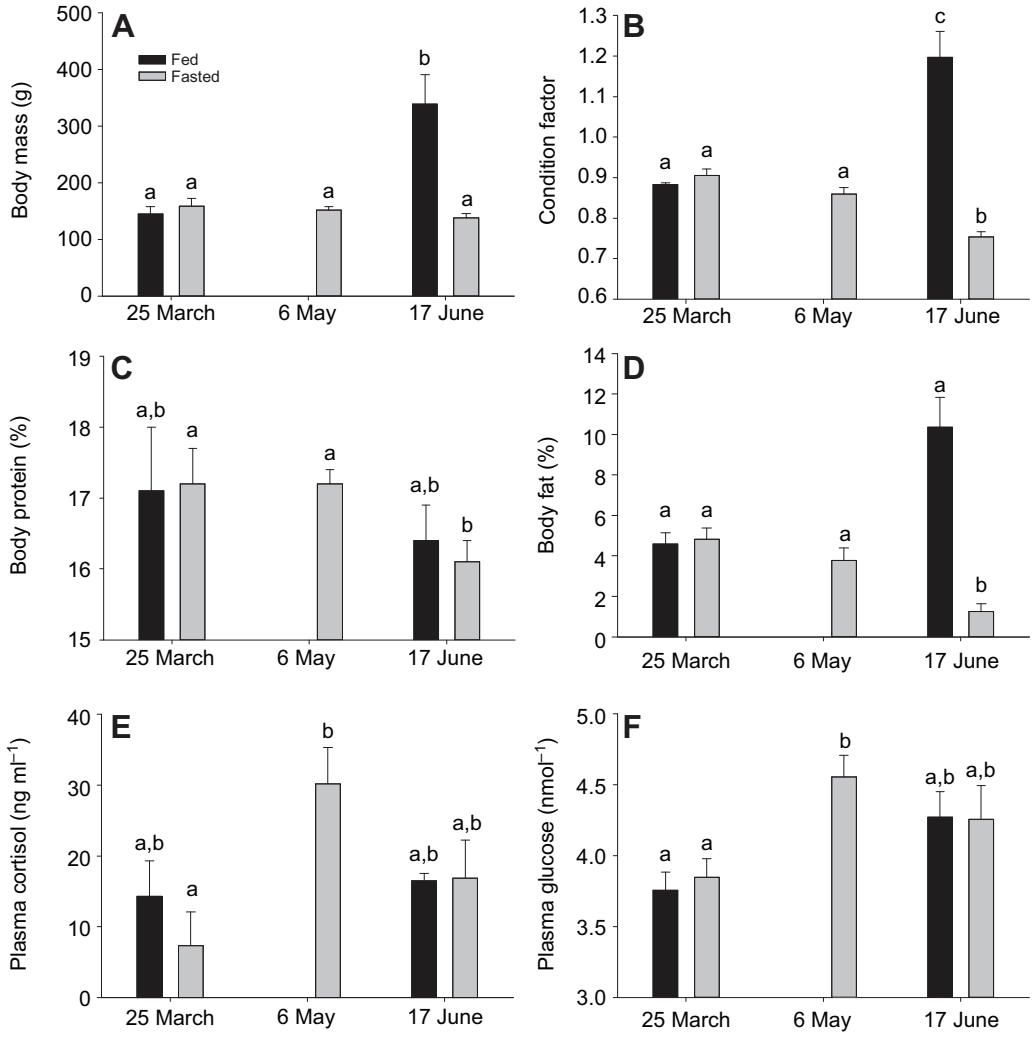

Fig. 1. Temporal changes in mean (±s.e.m.) body mass (A), condition factor (B), body protein (C) and fat (D) concentrations, and plasma cortisol (E) and glucose (F) concentrations in fed and fasted anadromous Arctic charr. Different letters denote significant differences between groups.

from March to June (from 155.4±9.3 to 138.1±7.5 g). The latter fish decreased in CF (P<0.001) from 0.88±0.01 to 0.75±0.01 (supplementary material Table S2).

There were no differences in the percentage of body protein between FF and FU fish sampled in March and June. The percentage of total body protein did not differ between FU fish sampled in March and May, but was slightly lower (P<0.05) in June than in March and May (Fig. 1C). There were no differences in the percentage of total body protein in FF fish sampled in March and June. The percentage of total body fat did not differ significantly between FF and FU fish in March (Fig. 1D). In FU fish, the percentage of total body fat did not differ significantly between March and May, but was much lower (P<0.01) in June than in May. In FF fish, the proportion of body fat was lower in March (4.5±0.5%) than in June (10.4±1.5%) and was higher than in FU fish (1.2±0.4%) in June (P<0.001). In mass terms, there was an almost total depletion of body fat in FU fish during the course of the experiment, and a greater loss of protein between May and June than between March and May (Fig. 2B). In FF fish, both total body fat and protein content were much higher in June than in March (Fig. 2A).

Plasma cortisol concentration did not differ between FF and FU fish in March and June (Fig. 1E), but was higher in FU fish in May than in March (P<0.05). The same trend was seen for plasma glucose concentrations (Fig. 1F), which also showed a transient increase in FU fish from March to May (P<0.05).

Liver *LepA1* mRNA expression did not differ between FF and FU fish in March (Fig. 3A) and for FF fish there was no change in expression between March and June. In FU fish there was a higher expression in both March and June than in May (P<0.05 and P<0.01, respectively). In June, *LepA1* expression was markedly lower in FF fish than in FU fish (P<0.05). The same general pattern was seen for *LepA2* expression (Fig. 3B), which was higher in FU fish than in FF fish in June (P<0.01). Liver *IGF-I* mRNA expression did not differ between FF and FU fish in March. There was no difference in *IGF-I* expression for FU fish sampled in March and May (Fig. 3C), but there was a decrease in expression from May to June (P<0.05). There was no difference in *IGF-I* expression in FF fish sampled in March and June.

Liver *SOCS* gene expression is shown in Fig. 4. There were no differences between FF and FU fish in *SOCS1*, *SOCS2* and *SOCS3* in March. In FF fish, *SOCS1* mRNA expression was higher in March than in June (P<0.05). There were no differences in *SOCS1* expression in FU fish sampled at different times, resulting in a tendency toward a higher *SOCS1* expression in FU fish than in FF

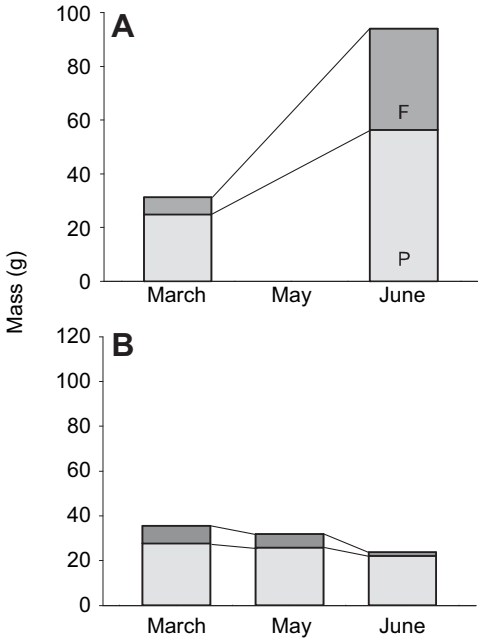

Fig. 2. Temporal change in masses of body protein (light grey, P) and fat (dark grey, F) of the fed (A) and fasted (B) fish sampled in June. Body fat and protein mass in March and May were calculated from the body mass in March and May of the fish sampled in June, and the data for percentage of body fat and protein of the fish sampled in March and May (see supplementary material Table S1 for more information).

fish in June (P=0.062). For *SOCS2*, expression was higher in FF fish sampled in March than in June (P<0.001), whereas the opposite was seen in FU fish (P<0.001). This resulted in a higher *SOCS2* expression in FU fish than in FF fish in June (P<0.001). *SOCS3* expression was higher in March than June in both FF (P<0.01) and FU fish (P<0.05), with a higher expression in FU than in FF fish in June (P<0.05).

HSI did not differ between FF and FU fish in March, after which there was a decrease in FU fish (P<0.05) and an increase in FF fish (P<0.001), resulting in a higher HSI in FF than in FU fish in June (P<0.001; Table 2). Liver glycogen concentration (Table 2) did not differ between FF and FU fish in March, but was higher in FF fish in June than in March (P<0.05) and lower in FU fish in June than in both March and May (P<0.001). This resulted in a marked difference in liver glycogen concentrations between FF (28.2±4.7 μmol g^{-1} protein) and FU fish in June (1.8±0.5 μmol g^{-1} protein; P<0.001).

There were no differences in any enzyme activities between FF and FU fish in March, nor between March and May in FU fish (Table 2). In FF fish, G6PDH (P<0.001), LDH (P<0.01), HOAD (P<0.001) and PEPCK (P<0.05) activities were higher in June than in March. In FU fish, G6PDH (P<0.01), LDH (P<0.01) and HOAD (P<0.01) activities were lower in June than in March. In June, there were higher Asp-AT, G6PDH, LDH, HOAD, PEPCK and PK activities in FF than in FU fish.

Experiment 2

There was significantly higher *SOCS1* (P<0.05) and *SOCS3* (P<0.05) gene expression in Lep-treated liver slices (PBS + Lep) than in untreated and sham (PBS) treated slices, but no effects of Lep were seen for *SOCS2*, *G6PDH*, *AspAT* and *IGF-I* gene expression (Fig. 5).

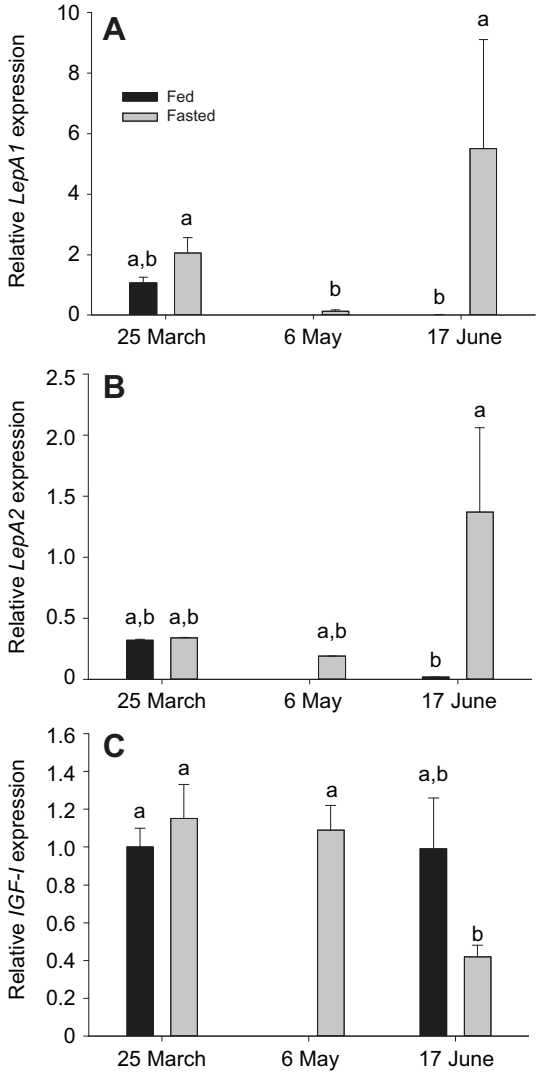

Fig. 3. Temporal changes in mean (±s.e.m.) liver *LepA1* (A), *LepA2* (B) and *IGF-I* (C) gene expression in fed and fasted anadromous Arctic charr. Different letters denote significant differences between groups.

DISCUSSION

The present study was designed to simulate the overwintering fast in wild, anadromous Arctic charr and the emaciation experienced by these fish during the latter part of their overwintering in freshwater. Because the CFs of the fish used in the present study (Fig. 1B) were similar to those of wild anadromous charr sampled in a previous study (Aas-Hansen et al., 2005), in which CF decreased from 0.84 in April to 0.77 in June, we consider this objective to have been achieved. In our study, only one fish sampled in March had food in its stomach, despite access to food, indicating that the fish were in a voluntary anorexic state. Some FF fish had consumed food when sampled on 6 May (see Materials and methods), which agrees with previous findings of a return of appetite in May in both captive anadromous Arctic charr (Tveiten et al., 1996; Bottengård and Jørgensen, 2008; Aarseth et al., 2010) and their wild conspecifics (Aas-Hansen et al., 2005).

Metabolic responses to fasting

In FU fish, fasting resulted in a decrease in M_b, CF, body fat and protein, particularly between the samplings in May and June,

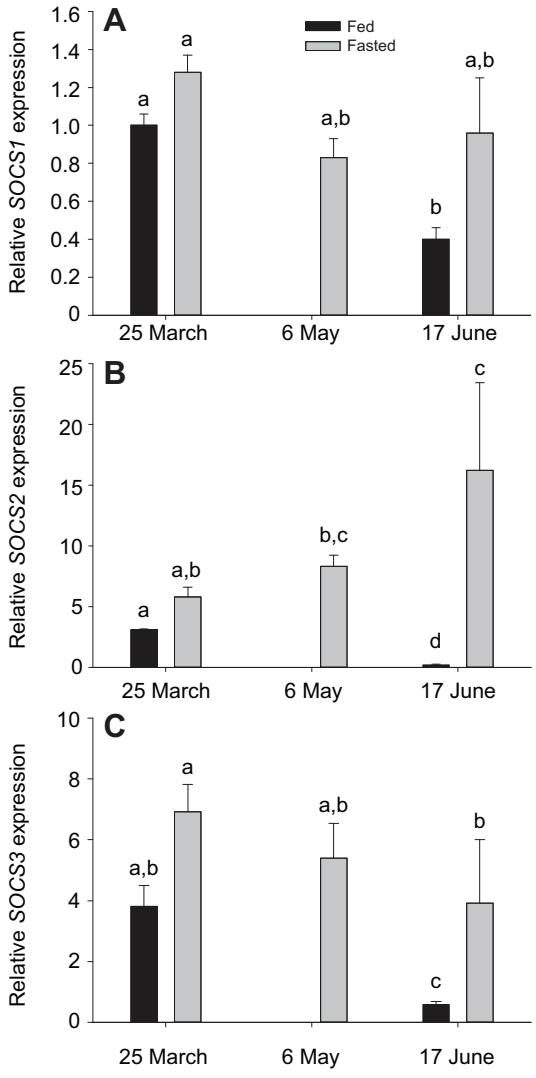

Fig. 4. Temporal changes in *SOCS1* (A), *SOCS2* (B) and *SOCS3* (C) gene expression in liver of fed and fasted Arctic charr. Different letters denote significant differences between groups.

whereas there were increases in M_b, CF, body fat and protein in FF fish between March and June (Fig. 1A,B,D, Fig. 2). The low percentage (1.2±0.4%) and low absolute amount (Fig. 2) of body fat in FU fish in June indicates that stored fat was severely depleted at this time. In a previous study, plasma triglyceride concentration was also found to decrease in anadromous Arctic charr deprived of food during late spring/early summer, concomitant with an increase in plasma glucose concentration (Frøiland et al., 2012). Thus it seems that the energy needed during the latter part of overwintering, as well as during migration, must be taken from the body protein store in the anadromous Arctic charr. This conclusion is supported by the reduction in body protein observed in the FU fish from May to June (Fig. 2).

Prolonged fasting in fish is generally associated with reduced plasma glucose, HSI, liver glycogen and liver metabolic capacity (Navarro et al., 1992; Foster and Moon, 1991; Bastrop et al., 1992; Navarro and Gutiérrez, 1995). The lack of any large change in these parameters in FU fish between March and May (Fig. 1F, Table 2) indicates that physiological responses may differ between voluntarily fasting fish and fish subjected to enforced feed deprivation. The reduction in liver glycogen and liver enzyme activities from May to June in FU fish (Table 2) supports the notion that these fish were voluntarily anorexic until May, and that they subsequently experienced starvation stress in the absence of food. The reduced metabolic capacity of the liver, together with the depletion of glycogen in FU fish from May onwards, indicates that they responded by entering a state of metabolic depression, i.e. reduced metabolism under adverse environmental conditions (Guppy and Withers, 1999). Nevertheless, FU fish had plasma glucose concentrations similar to those of FF fish (Fig. 1F). This glucose was probably derived from protein, as evidenced from the decrease in the body protein store from May to June (Fig. 2B) and the maintained activity of enzymes involved in gluconeogenesis and amino acid catabolism (PEPCK and AlaAT; Table 2). In support of this, FU fish had plasma cortisol concentrations similar to those of FF fish at the end of the experiment in June (Fig. 1E), in accordance with the accepted gluconeogenetic action of this hormone (Mommsen et al., 1999). The maintenance of a high *de novo* glucose synthesis in the liver, despite depleted liver glycogen levels, reflects the importance of this substrate during a long-term fast (Polakof et al., 2012).

A role of leptin in liver metabolism?

The changes in liver *LepA1* and *LepA2* expression during the course of the experiment resembled those previously reported for anadromous Arctic charr (Frøiland et al., 2012): a decrease in fed fish from March to July and higher *LepA1* and *LepA2* expression in FU than in FF fish at the end of the fasting period in June. An increase in liver *Lep* expression with fasting/feed restriction has also

Table 2. Mean ± s.e.m. hepatosomatic index (HSI; %), liver glycogen concentrations (μmol g^{-1} protein) and enzyme activities (μmol min^{-1} g^{-1} protein) in fed and fasted Arctic charr

	25 March		6 May	17 June	
	Fed (*N*=9)	Fasted (*N*=10)	Fasted (*N*=10)	Fed (*N*=7)	Fasted (*N*=10)
HSI	1.2±0.06^{a}	1.2±0.07^{a}	1.1±0.02^{a,b}	2.0±0.12^{c}	1.0±0.04^{b}
Glycogen	12.6±1.6^{a}	15.0±2.2^{a}	11.5±1.2^{a}	28.2±4.7^{b}	1.8±0.5^{c}
Ala-AT	20.0±1.6	21.6±2.0	21.8±1.6	20.7±2.1	18.6±1.5
Asp-AT	12.5±1.3^{a,b}	10.3±0.6^{a,c}	10.1±0.7^{a,c}	16.4±2.3^{b}	8.3±0.7^{c}
G6PDH	4.1±0.3^{a}	5.2±0.4^{a}	3.9±0.3^{a}	15.0±2.3^{b}	2.5±0.3^{c}
LDH	45.5±2.5^{a}	51.4±4.1^{a}	49.6±1.4^{a}	68.2±6.9^{b}	35.3±2.0^{c}
HOAD	0.47±0.02^{a}	0.48±0.02^{a}	0.45±0.01^{a}	0.76±0.1^{b}	0.33±0.03^{c}
PEPCK	0.18±0.02^{a}	0.19±0.02^{a,b}	0.19±0.02^{a,b}	0.27±0.04^{b}	0.16±0.02^{a}
PK	0.70±0.06^{a,b}	0.78±0.07^{a,b}	0.91±0.05^{a}	1.13±0.16^{a}	0.61±0.08^{b}

N denotes the number of fish analyzed.
Different letters indicate values that are significantly different.

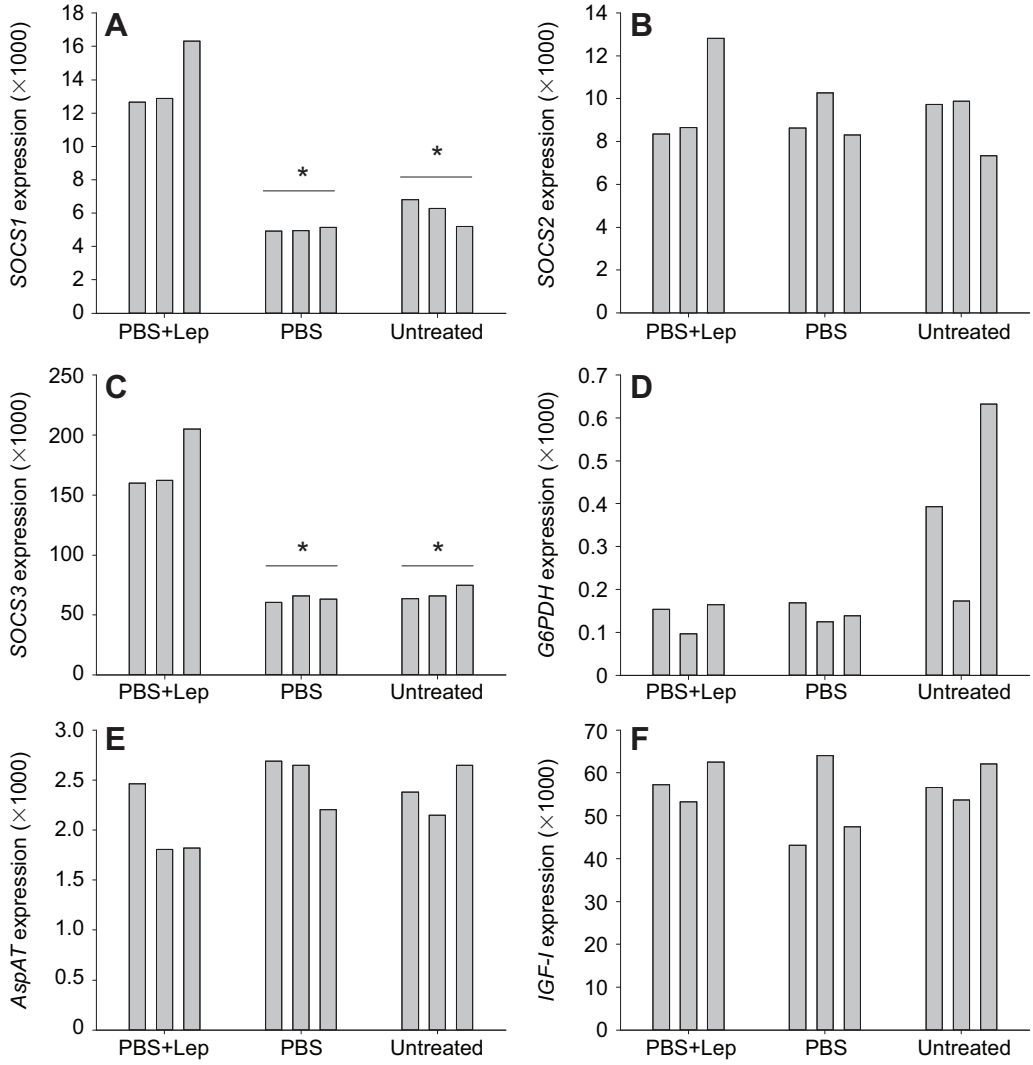

Fig. 5. *In vitro* effects of recombinant trout leptin on *SOCS1*, *SOCS2*, *SOCS3*, *G6PDH*, *AspAT* and *IGF-I* mRNA expression in liver slices from Arctic charr. Each column represents one liver slice. See Materials and methods for treatment descriptions. Asterisks denote those genes for which the expression was significantly different from that in the leptin-treated group.

been reported in Atlantic salmon (Rønnestad et al., 2010; Trombley et al., 2012), whereas a reduced liver *Lep* expression with fasting has been reported in goldfish (*Carassius auratus*) (Tinoco et al., 2012) and striped bass (*Morone saxatilis*) (Won et al., 2012), and no change with prolonged fasting in common carp (*Cyprinus carpio*) (Huising et al., 2006). The reason for these differences is not known, but they could relate to the degree of emaciation of the fish used in the different experiments, and interspecific differences in metabolic responses to an imposed fast.

In the present study, the activity of enzymes involved in lipid metabolism (G6PDH and HOAD) and glycolysis (PK) appeared to be inversely related to liver *LepA1* and *LepA2* expression in FU fish. In addition, the highest activity of these enzymes was recorded concurrently with low liver *LepA1* and *LepA2* expression in FF fish in June (Fig. 3A,B, Table 2). No such interrelationships were seen for enzymes involved in amino acid metabolism and gluconeogenesis; LDH activity decreased in FU fish and increased in FF fish, but there were no changes in liver AlaAT and AspAT activities with time (Table 2). These results suggest that Lep may be involved in the suppression of lipolytic pathways, but *in vitro* Lep treatment of liver slices did not affect the gene expression of *G6PDH* (Fig. 4D). This indicates that Lep was not directly responsible for the changes in liver enzyme activity.

A role of SOCS in liver metabolism?

In mammals, SOCS1, 2 and 3 are involved in attenuating GH and Lep signalling by downregulating post-receptor JAK/STAT-induced gene transcription (Fujimoto and Naka, 2003). *SOCS1–3* genes have been identified in several fish species (Jin et al., 2007; Xiao et al., 2010; Wang and Secombes, 2008; Studzinski et al., 2009) and their expression may be induced by cytokines in fish, as in mammals (Wang and Secombes, 2008). In the present study, *SOCS* gene expression was affected by the feeding regime (Fig. 4). The higher expression of the *SOCS* genes in FU fish than in FF fish in June coincided with a reduced expression of *IGF-I* in FU fish (Fig. 3C). This situation closely resembles the reduced *IGF-I* expression seen in fasted salmonid fish, as a result of downregulated hepatic GH signalling (Björnsson, 1997), and that in homozygotic GH transgenic zebrafish (*Danio rerio*), in which *SOCS1* and *SOCS3* seemed to be responsible for the downregulation of GH signalling in the liver (Studzinski et al., 2009). In common with the elevated plasma GH concentration in fasting salmonids (Björnsson, 1997), GH transgenic

zebrafish overexpress GH in comparison with their hemizygotic counterparts (de Azevedo Figueiredo et al., 2007).

It is interesting to note that liver *IGF-I* expression in the FU fish used in our study only decreased during the latter part of the enforced fasting period (i.e. from May onwards), despite the fact that the fish most likely had been fasting voluntarily for months when sampled in May. This resembles the situation seen in seasonal mammals, which differ in their responses when undergoing seasonal winter weight loss and when they are subjected to feed deprivation during summer (Adam and Mercer, 2004). The reduction in liver *IGF-I* expression with fasting seen in the present study (Fig. 3C) was probably not a direct result of the increase in *Lep* expression because *in vitro* Lep treatment did not affect liver *IGF*-I expression (Fig. 5F), but was more likely related to the elevated *SOCS1* and *SOCS3* expression (Fig. 4A,C). This would comply with the results obtained with GH-transgenic zebrafish, which indicated that reduced GH signalling was caused by SOCS1 and SOCS3 (Studzinski et al., 2009).

The present study showed that Lep stimulated hepatic *SOCS1* and *SOCS3* gene expression *in vitro* (Fig. 5A,C). This result provides evidence for a link between the higher liver *LepA1* and *LepA2* expression in FU fish than in FF fish in June (Fig. 3A,B) and the corresponding difference in liver *SOCS1* and *SOCS3* gene expression in FU and FF fish (Fig. 4A,C). The higher liver *SOCS2* expression in FU fish than in FF fish in June was probably not caused by Lep, which did not affect *SOCS2* expression in the *in vitro* experiment (Fig. 5B). Another candidate could be cortisol, which was recently shown to stimulate *SOCS2* expression in rainbow trout hepatocytes *in vitro* (Philip et al., 2012). However, we did not find differences in plasma cortisol concentrations between FU and FF fish in June (Table 2), even though the FU fish may have been suffering from starvation stress during the latter part of the fasting period.

In summary, the present study has revealed a metabolic suppression in anadromous Arctic charr subjected to fasting after they had entered their natural summer feeding period. Upregulated *Lep* and *SOCS* genes and downregulated *IGF-I* expression in the liver are suggested to be a part of the mechanisms that suppress lipolytic pathways and depress metabolism when fat stores are depleted. We have demonstrated that Lep stimulated hepatic *SOCS1* and *SOCS3* expression *in vitro*, and this stimulation may be responsible for downregulation of GH signalling and, consequently, reduced *IGF-I* expression in the liver. Further studies are needed to elucidate how Lep and SOCS interact to regulate intermediary metabolism in fish that display seasonal feeding cycles.

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AUTHOR CONTRIBUTIONS

E.H.J. and M.J. are largely responsible for the conception and design of the study, and took the lead in the interpretation of the findings and in the writing of the manuscript. M.M. and V.S. carried out most of the practical work and data analysis and contributed to the interpretation of the results. K.E.R.H. and C.S.R. were responsible for the establishment and validation of the molecular analyses, *in vitro* experiment, data treatment and interpretation of results. N.G. was responsible for the production of recombinant trout leptin and contributed to the writing of the manuscript.

COMPETING INTERESTS

No competing interests declared.

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REFERENCES

Aarseth, J. J., Frøiland, E. and Jørgensen, E. H. (2010). Melatonin implantation during spring and summer does not affect seasonal rhythms of feeding and maturation in anadromous Arctic charr (*Salvelinus alpinus*). *Polar Biol.* **33**, 379-388.

Aas-Hansen, Ø., Vijayan, M. M., Johnsen, H. K., Cameron, C. and Jørgensen, E. H. (2005). Re-smoltification in wild, anadromous Arctic char (*Salvelinus alpinus*): a survey of osmoregulatory, metabolic and endocrine changes preceding annual seawater migration. *Can. J. Fish. Aquat. Sci.* **62**, 195-204.

Adam, C. L. and Mercer, J. G. (2004). Appetite regulation and seasonality: implications for obesity. *Proc. Nutr. Soc.* **63**, 413-419.

Bastrop, R., Jürss, K. and Wacke, R. (1992). Biochemical parameters as a measure of food availability and growth in immature rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol.* **102A**, 151-161.

Björnsson, B. T. (1997). The biology of salmon growth hormone: from daylight to dominance. *Fish Physiol. Biochem.* **17**, 9-24.

Boivin, T. G. and Power, G. (1990). Winter condition and proximate composition of anadromous Arctic charr (*Salvelinus alpinus*) in eastern Ungava Bay, Quebec. *Can. J. Zool.* **68**, 2284-2289.

Bottengård, L. and Jørgensen, E. H. (2008). Elevated spring temperature stimulates growth, but not smolt development, in anadromous Arctic charr (*Salvelinus alpinus*). *Comp. Biochem. Physiol.* **151A**, 596-601.

de Azevedo Figueiredo, M., Lanes, C. F. C., Almeida, D. V., Proietti, M. C. and Marins, L. F. (2007). The effect of GH overexpression on GHR and IGF-I gene regulation in different genotypes of GH-transgenic zebrafish. *Comp. Biochem. Physiol.* **2D**, 228-233.

Dutil, J.-D. (1986). Energetic constraints and spawning interval in the anadromous Arctic charr (*Salvelinus alpinus*). *Copeia* **1986**, 945-955.

Foster, G. D. and Moon, T. W. (1991). Hypometabolism with fasting in the yellow perch (*Perca flavescens*): a study of enzymes, hepatocyte metabolism, and tissue size. *Physiol. Zool.* **64**, 259-275.

Frøiland, E., Murashita, K., Jørgensen, E. H. and Kurokawa, T. (2010). Leptin and ghrelin in anadromous Arctic charr: cloning and change in expressions during a seasonal feeding cycle. *Gen. Comp. Endocrinol.* **165**, 136-143.

Frøiland, E., Jobling, M., Björnsson, B. T., Kling, P., Ravuri, C. S. and Jørgensen, E. H. (2012). Seasonal appetite regulation in the anadromous Arctic charr: evidence for a role of adiposity in the regulation of appetite but not for leptin in signalling adiposity. *Gen. Comp. Endocrinol.* **178**, 330-337.

Fujimoto, M. and Naka, T. (2003). Regulation of cytokine signaling by SOCS family molecules. *Trends Immunol.* **24**, 659-666.

Guppy, M. and Withers, P. (1999). Metabolic depression in animals: physiological perspectives and biochemical generalizations. *Biol. Rev. Camb. Philos. Soc.* **74**, 1-40.

Huising, M. O., Geven, E. J. W., Kruiswijk, C. P., Nabuurs, S. B., Stolte, E. H., Spanings, F. A., Verburg-van Kemenade, B. M. and Flik, G. (2006). Increased leptin expression in common carp (*Cyprinus carpio*) after food intake but not after fasting or feeding to satiation. *Endocrinology* **147**, 5786-5797.

Jensen, A. J., Finstad, B., Fiske, P., Hvidsten, N. A., Rikardsen, A. H. and Saksgård, L. (2012). Timing of smolt migration in sympatric populations of Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), and Arctic char (*Salvelinus alpinus*). *Can. J. Fish. Aquat. Sci.* **69**, 711-723.

Jin, H.-J., Xiang, L.-X. and Shao, J.-Z. (2007). Identification and characterization of suppressor of cytokine signaling 1 (SOCS-1) homologues in teleost fish. *Immunogenetics* **59**, 673-686.

Jobling, M., Johansen, J. S., Foshaug, H., Burkow, I. C. and Jørgensen, E. H. (1998). Lipid dynamics in anadromous Arctic charr, *Salvelinus alpinus* (L.): seasonal variations in lipid storage depots and lipid class composition. *Fish Physiol. Biochem.* **18**, 225-240.

Jørgensen, E. H., Johansen, S. J. S. and Jobling, M. (1997). Seasonal patterns of growth, lipid deposition and depletion in anadromous Arctic charr. *J. Fish Biol.* **51**, 312-326.

Johansen, S. J. S., Ekli, M. and Jobling, M. (2002). Is there lipostatic regulation of feed intake in Atlantic salmon *Salmo salar* L.? *Aquac. Res.* **33**, 515-524.

Keppler, D. and Decker, K. (1974). Glycogen: determination with amyloglucosidase. In *Methods of Enzymatic Analysis* (ed. H.-U. Bergmeyer), pp. 1127-1131. Weinheim: Verlag Chemie.

Kling, P., Jönsson, E., Nilsen, T. O., Einarsdottir, I. E., Rønnestad, I., Stefansson, S. O. and Björnsson, B. T. (2012). The role of growth hormone in growth, lipid homeostasis, energy utilization and partitioning in rainbow trout: interactions with leptin, ghrelin and insulin-like growth factor I. *Gen. Comp. Endocrinol.* **175**, 153-162.

Kurokawa, T. and Murashita, K. (2009). Genomic characterization of multiple leptin genes and a leptin receptor gene in the Japanese medaka, *Oryzias latipes*. *Gen. Comp. Endocrinol.* **161**, 229-237.

Kurokawa, T., Uji, S. and Suzuki, T. (2005). Identification of cDNA coding for a homologue to mammalian leptin from pufferfish, *Takifugu rubripes*. *Peptides* **26**, 745-750.

Liu, Q., Chen, Y., Copeland, D., Ball, H., Duff, R. J., Rockich, B. and Londraville, R. L. (2010). Expression of leptin receptor gene in developing and adult zebrafish. *Gen. Comp. Endocrinol.* **166**, 346-355.

Livak, K. J. and Schmittgen, T. D. (2001). Analysis of relative gene expression data using real-time quantitative PCR and the $2^{-\Delta\Delta C_T}$ method. *Methods* **25**, 402-408.

Lu, R.-H., Liang, X.-F., Wang, M., Zhou, Y., Bai, X.-L. and He, Y. (2012). The role of leptin in lipid metabolism in fatty degenerated hepatocytes of the grass carp *Ctenopharyngodon idellus*. *Fish Physiol. Biochem.* **38**, 1759-1774.
Masuzaki, H., Ogawa, Y., Isse, N., Satoh, N., Okazaki, T., Shigemoto, M., Mori, K., Tamura, N., Hosoda, K., Yoshimasa, Y. et al. (1995). Human obese gene expression. Adipocyte-specific expression and regional differences in the adipose tissue. *Diabetes* **44**, 855-858.
Mommsen, T. P., Vijayan, M. M. and Moon, T. W. (1999). Cortisol in teleosts: dynamic, mechanisms of action, and metabolic regulation. *Rev. Fish Biol. Fish.* **9**, 211-268.
Murashita, K., Susumu, U., Yamamoto, T., Rønnestad, I. and Kurokawa, T. (2008). Production of recombinant leptin and its effect on food intake in rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol.* **150B**, 377-384.
Navarro, I. and Gutiérrez, J. (1995). Fasting and starvation. In *Metabolic Biochemistry* (ed. P. W. Hochachka and T. P. Mommsen), pp. 393-434. Amsterdam: Elsevier Science B. V.
Navarro, I., Gutiérrez, J. and Planas, J. (1992). Changes in plasma glucagon, insulin and tissue metabolites associated with prolonged fasting in brown trout (*Salmo trutta fario*) during two different seasons of the year. *Comp. Biochem. Physiol.* **102A**, 401-407.
Nilssen, K. J., Gulseth, O. A., Iversen, M. and Kjøl, R. (1997). Summer osmoregulatory capacity of the world's northernmost living salmonid. *Am. J. Physiol.* **272**, R743-R749.
Philip, A. M., Daniel Kim, S. and Vijayan, M. M. (2012). Cortisol modulates the expression of cytokines and suppressors of cytokine signaling (SOCS) in rainbow trout hepatocytes. *Dev. Comp. Immunol.* **38**, 360-367.
Polakof, S., Panserat, S., Soengas, J. L. and Moon, T. W. (2012). Glucose metabolism in fish: a review. *J. Comp. Physiol. B* **182**, 1015-1045.
Rønnestad, I., Nilsen, T. O., Murashita, K., Angotzi, A. R., Gamst Moen, A. G., Stefansson, S. O., Kling, P., Thrandur Björnsson, B. and Kurokawa, T. (2010). Leptin and leptin receptor genes in Atlantic salmon: cloning, phylogeny, tissue distribution and expression correlated to long-term feeding status. *Gen. Comp. Endocrinol.* **168**, 55-70.
Schulz, R. (1985). Measurement of five androgens in the blood of immature and maturing male rainbow trout, *Salmo gairdneri* (Richardson). *Steroids* **46**, 717-726.
Studzinski, A. L. M., Almeida, D. V., Lanes, C. F. C., Figueiredo, M. A. and Marins, L. F. (2009). SOCS1 and SOCS3 are the main negative modulators of the somatotrophic axis in liver of homozygous GH-transgenic zebrafish (*Danio rerio*). *Gen. Comp. Endocrinol.* **161**, 67-72.
Tinoco, A. B., Nisembaum, L. G., Isorna, E., Delgado, M. J. and de Pedro, N. (2012). Leptins and leptin receptor expression in the goldfish (*Carassius auratus*). Regulation by food intake and fasting/overfeeding conditions. *Peptides* **34**, 329-335.
Trombley, S., Maugars, G., Kling, P., Björnsson, B. T. and Schmitz, M. (2012). Effects of long-term restricted feeding on plasma leptin, hepatic leptin expression and leptin receptor expression in juvenile Atlantic salmon (*Salmo salar* L.). *Gen. Comp. Endocrinol.* **175**, 92-99.
Tveiten, H., Johnsen, H. K. and Jobling, M. (1996). Influence of maturity status on the annual cycles of feeding and growth in Arctic charr reared at constant temperature. *J. Fish Biol.* **48**, 910-924.
Tveiten, H., Mayer, I., Johnsen, H. K. and Jobling, M. (1998). Sex steroids, growth and condition of Arctic charr broodstock during an annual cycle. *J. Fish Biol.* **53**, 714-727.
Tveiten, H., Bjørn, P. A., Johnsen, H. K., Finstad, B. and McKinley, R. S. (2010). Effects of the sea louse *Lepeophtheirus salmonis* on temporal changes in cortisol, sex steroids, growth and reproductive investment in Arctic charr *Salvelinus alpinus*. *J. Fish Biol.* **76**, 2318-2341.
Wang, T. and Secombes, C. J. (2008). Rainbow trout suppressor of cytokine signalling (SOCS)-1, 2 and 3: molecular identification, expression and modulation. *Mol. Immunol.* **45**, 1449-1457.
Won, E. T., Baltzegar, D. A., Picha, M. E. and Borski, R. J. (2012). Cloning and characterization of leptin in a Perciform fish, the striped bass (*Morone saxatilis*): control of feeding and regulation by nutritional state. *Gen. Comp. Endocrinol.* **178**, 98-107.
Wong, M. M. L., Yu, R. M. K., Ng, P. K. S., Law, S. H. W., Tsang, A. K. C. and Kong, R. Y. C. (2007). Characterization of a hypoxia-responsive leptin receptor (omLepR_L) cDNA from the marine medaka (*Oryzias melastigma*). *Mar. Pollut. Bull.* **54**, 797-803.
Xiao, Z.-G., Liu, H., Fu, J.-P., Hu, W., Wang, Y.-P. and Guo, Q.-L. (2010). Cloning of common carp SOCS-3 gene and its expression during embryogenesis, GH-transgene and viral infection. *Fish Shellfish Immunol.* **28**, 362-371.

Table S1. Mean (± s.e.m.) wet weight percentage of body water, ash, fat and protein in fasted (FU) and fed (FF) Arctic charr sampled in March, May (only FU fish) and June

	March		May		June	
	FU	FF	FU	FF	FU	FF
Water	76.1±0.5	76.6±0.5	77.4±0.6	–	80.7±0.5	71.4±1.4
Ash	1.9±0.2	1.7±0.1	1.7±0.1	–	1.9±0.3	1.6±0.3
Fat	4.8±0.5	4.6±0.5	3.8±0.6	–	1.2±0.4	10.4±1.5
Protein*	17.2±0.2	17.1±0.3	17.2±0.2	–	16.1±0.28	16.4±0.5

*Protein percentage calculated by difference.

Table S2. Mean (± s.e.m.) body mass (M_b) and condition factor (CF) of FU fish sampled in May and June, and their respective M_b and CF in March, May and June, and the M_b and CF in March and June of the FF fish sampled in June

	March	May	June
FU fish			
Sampled May (*N*=10)			
M_b	154.0±5.6	151.7±6.5	
CF	0.88±0.01	0.86±0.02	
Sampled June (*N*=10)			
M_b	155.4±9.3	149.0±9.0	138.1±7.5
CF	0.88±0.01[a]	0.83±0.01[b]	0.75±0.01[c]
FF fish			
Sampled June (*N*=7)			
M_b	164.8±15.3[a]		338.7±52.3[b]
CF	0.95±0.03[a]		1.20±0.06[b]

Different letters denote significant differences between sampling dates.