

Correlations between thyroidal and reproductive endocrine status in wild Atlantic cod

L. A. Comeau and S.E. Campana

Fisheries and Oceans Canada
Bedford Institute of Oceanography
1 Challenger Drive
P.O. Box 1006
Dartmouth, Nova Scotia, B2Y 4A2

2006

**Canadian Technical Report of
Fisheries and Aquatic Sciences 2682**



Pêches et Océans
Canada

Fisheries and Oceans
Canada

Canada

Canadian Technical Report of
Fisheries and Aquatic Sciences 2682

2006

**Correlations between thyroidal and reproductive endocrine status
in wild Atlantic cod**

by

L. A. Comeau¹ and S.E. Campana

Fisheries and Oceans Canada
Bedford Institute of Oceanography
1 Challenger Drive
P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2

¹Present address: Fisheries and Oceans Canada, Gulf Region, P.O. Box 5030, Moncton, New Brunswick, E1C 9B6 E-mail: comeaul@dfo-mpo.gc.ca

© Her Majesty the Queen in Right of Canada, 2006
Cat. No. Fs 97-6/2682E ISSN 0706-6457

This publication should be cited as follows:

Comeau, L.A. and S.E. Campana. 2006. Correlations between thyroidal and reproductive endocrine status in wild Atlantic cod. Can. Tech. Rep. Fish. Aquat. Sci. 2682.

TABLES OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES.....	v
ABSTRACT	vi
RÉSUMÉ.....	vi
INTRODUCTION.....	1
MATERIALS AND METHODS	1
SAMPLE ATTRIBUTES.....	1
HORMONE MEASUREMENTS	2
STATISTICS.....	2
RESULTS.....	3
DISCUSSION	4
EFFECTS OF THYROID HORMONES ON REPRODUCTIVE FUNCTION	4
EFFECTS OF GONADAL HORMONES ON THYROIDAL FUNCTION	4
BIOLOGICAL IMPLICATIONS	5
CONCLUSION	5
ACKNOWLEDGEMENTS	5
REFERENCES.....	6

LIST OF TABLES

Table 1.	Results of stepwise multiple regression analyses with the free T ₃ index as the dependent variable. The <i>t</i> statistics provides an indication of the relative importance of each parameter; the <i>P</i> and Probability values indicate the significance of individual parameter and of the overall regression, respectively.	9
----------	---	---

LIST OF FIGURES

- Figure 1. Seasonal changes of total T_4 , total T_3 and I_G . ●, monthly means of either total T_4 [(a), (b)] or total T_3 [(b), (c)]; Δ, monthly means of I_G . Trend lines show three-point centred moving averages for hormones (—) and I_G (---) series. Missing months were replaced with computed values (linear interpolation of two neighbouring values) before running the three-point centred average function. 10
- Figure 2. Interrelationships between total thyroid hormones (either total T_4 or total T_3), I_G , and gonadal hormones. Data points represent means from 25 percentile groups categorized based on variable x . Data collected throughout the year were included in the analysis. ●, total T_4 ; ○, total T_3 ; □, E_2 ; ■, testosterone. Error bars show S.E. 11
- Figure 3. Seasonal averages of the free T_3 index (a) and free T_3 levels (b) in males (filled bars) and females (open bars). Error bars show S.E. 12
- Figure 4. Relationships between the \log_{10} free T_3 index and E_2 (□, $r^2 = 0.51$, $P < 0.001$) in females, and also between the \log_{10} free T_3 index and testosterone (■, $r^2 = 0.60$, $P < 0.001$) in females. Data points represent individual fish sampled between November and January (1996 and 1997). 13
- Figure 5. Relationships between the \log_{10} free T_3 index and total T_3 levels in females (Δ, $r^2 = 0.45$, $P < 0.001$), and also between the free T_3 index and \log_{10} total T_3 levels in males (▲, $r^2 = 0.58$, $P < 0.001$). Data points represent individual fish sampled between January and March (1996 and 1997). 14

ABSTRACT

We monitored thyroidal and reproductive hormones in blood serum from wild Atlantic cod (*Gadus morhua* L.) over a two-year period. Here we examine potential interactions between the two hormone groups. We found few indications of interactions in males. However, rising levels of L-thyroxine (T_4) and 3,5,3'-triiodo-L-thyronine (T_3) in females concurred with early ovarian development. T_3 levels declined after the ovaries reached a certain size (gonadosomatic index $c.$ 3.0) and after estradiol-17 β (E_2) rose above 1.0 ng ml⁻¹. We suggest the thyroidal and reproductive systems in cod interact during certain phases of the ovarian cycle.

RÉSUMÉ

Nous avons effectué un suivi des hormones thyroïdiennes et gonadiques dans le sérum de la morue (*Gadus morhua* L.) pendant une période de deux ans. Dans ce document, nous examinons les interactions potentielles entre les deux groupes d'hormones. Nous avons trouvé peu d'indication d'une interaction potentielle chez les individus males. Toutefois, chez les individus femelles, une augmentation des niveaux de L-thyroxine (T_4) et tri-iodo-L-thyronine (T_3) coïncida avec le début du développement ovarien. Les niveaux de T_3 diminuèrent suite à une certaine croissance des ovaires (indice gonadosomatique d'environ 3,0) et lorsque les niveaux d'estradiol augmentèrent à des niveaux au-delà de 1,0 ng ml⁻¹. Nous suggérons que les systèmes thyroïdiens et reproducteurs chez la morue interagissent pendant certaines phases de cycle ovarien.

INTRODUCTION

There is mounting evidence that complex interactions between the thyroidal and reproductive endocrine systems provide some control over competing somatic and gonadal growth processes in salmonid and freshwater teleosts (see Dickhoff *et al.*, 1989; Cyr & Eales, 1996). However, little is known about the two endocrine systems in marine fish. Woodhead (1959, 1975) argued that major seasonal changes in thyroidal activity in the Barents Sea cod *Gadus morhua* L. were more closely related to migratory behaviour than to reproductive function. Since then the course of thyroid hormones (TH) over at least one complete reproductive cycle has been documented for plaice *Pleuronectes platessa* L. (Osborn & Simpson, 1978), winter flounder *Pseudopleuronectes americanus* Walbaum (Eales & Fletcher, 1982), and more recently cod (Comeau *et al.*, 2000). No significant correlations between thyroidal and reproductive status were found (plaice, flounder) or reported (cod).

Possible reasons for the difficulty in detecting links between the two endocrine systems include the criteria used for the assessment of endocrine status. The thyroid histological indices used in the study of Barents Sea cod (Woodhead 1959, 1975) are now considered unreliable for detecting short-term changes in the circulating levels of thyroid hormones (Eales & Brown, 1993; Cyr & Eales, 1996). Similarly, because only total (protein bound and unbound) TH levels were measured in pleuronectiformes (Osborn & Simpson, 1978; Eales & Fletcher, 1982), certain interactions between the reproductive and peripheral thyroid systems may have gone undetected (Cyr & Eales 1989, 1992). Moreover, TH levels in pleuronectiformes were compared with gonadal condition indices, which may not have been reflective of gonadal hormone levels (e.g., see Pankhurst & Conroy, 1987; Pankhurst & Kime, 1991; Methven *et al.*, 1992; Kjesbu *et al.*, 1996).

Our main objective was to correlate the thyroidal and reproductive systems in wild cod. We closely monitored the natural course of endocrine hormones, including E₂ and free 3,5,3'-triiodo-L-thyronine (T₃), over two complete reproductive cycles. Our results led to the conclusion that interactions between the two endocrine systems in this marine teleost are plausible, particularly in females. We discuss the biological implications arising from these results.

MATERIALS AND METHODS

SAMPLE ATTRIBUTES

Sexually matured Atlantic cod were sampled from the southern Gulf of St. Lawrence population between July 1995 and November 1997. The number of fish collected each month ranged from 13 to 224 (average = 91) and the two sexes were generally well represented. The mean fork length of cod in samples varied from 47 to 57 cm (average = 52 cm, SE = 0.5 cm). Most samples were captured using mobile gear vessels that carried out 60 min sets. In October and November 1996, however, 43% of the samples were collected using baited-longlines. The soaking time of longlines ranged from 4 to 24 h. No effects of gear-type on the concentrations of hormones were found (Mann-Whitney test, $P < 0.22$) when comparing samples collected with mobile and longline gear in the same area on the same day.

Blood samples were retrieved within about 20 minutes after the fish were boated. The aorta was cut and blood was allowed to flow directly into 7-ml Vacutainer vials. The vials were capped and refrigerated for 12 to 24 h. The serum fraction was then transferred into 2.5-ml cryovial tubes and stored at -72°C until analysed. Cod were kept on ice and dissected within 48 h or frozen at -20°C and dissected after having been partially thawed. We determined the gonadosomatic index (I_G) as $100 \times$ the wet weight of the gonads divided by the wet weight of the carcass (total body weight minus combined weight of liver, gonads, and stomach) (Schwalme & Chouinard, 1999).

HORMONE MEASUREMENTS

We measured total L-thyroxine (T_4) and total T_3 on 1,665 serum samples using a combined radioimmunoassay (RIA) technique (Omeljaniuk *et al.*, 1984) and the reagents employed by Cyr *et al.* (1998). Details of the procedures are also given in Comeau *et al.* (2000). Of the 1,665 samples, 856 contained a sufficient amount of serum to determine the fraction of T_3 that was freed from carrier proteins. A free T_3 index, representing the percentage of serum T_3 in the free form, was measured on G-25 Quik-Sep columns (Isolab Inc., Akron, OH) according to the procedure of Eales & Shostak (1985) adapted for cod serum (Comeau *et al.*, 2002). The free T_3 index was converted into concentration values using total T_3 results from the combined T_4 - T_3 RIA and the following formula:

$$\text{free } T_3 [\text{ng ml}^{-1}] = \text{total } T_3 [\text{ng ml}^{-1}] \times \text{free } T_3 \text{ index } [\%] \times 10^{-2}$$

Gonadal hormones were measured using commercial Coat-A-Count[®] RIA kits (Diagnostic Products Corporation, Los Angeles, CA). A total of 1,115 samples (429 males, 686 females) were processed for the measurement of E_2 levels. A similar number of samples (569 males, 530 females) were analysed for testosterone levels.

Radioactivity was measured on duplicate samples using a Beckman Gamma 5500 Counting System. Except for free T_3 (not applicable), the dilution of serum samples yielded hormone levels close to the predicted values, and the dilution curves of samples were parallel to the dilution curves of standards. Intra- and interassay coefficients of variation were less than 10%.

STATISTICS

Monthly means of TH and the I_G were plotted against time. To examine the thyroidal profiles as a function of reproductive status, we ranked the reproductive variable (I_G , E_2 , or testosterone) based on percentile groups; 25 groups were created, with each group containing approximately 36 cases (individuals). Arithmetic means of reproductive and thyroidal measurements were computed for individual groups; the means were plotted against each other and visually inspected for trends.

Simple and multiple linear regression analyses were used to investigate the relationships between the free T_3 index and three explanatory variables (E_2 , testosterone, total T_3). The analyses were based on individual fish and were restricted to narrow phases of the reproductive cycle, each extending over a three-month period. For females, the free T_3 index was \log_{10} transformed to ensure linearity; for males, the total T_3 variable was \log_{10} transformed. In multiple regression analysis, we tested the following models for females and males, respectively:

$$\log_{10} \text{ free } T_3 \text{ index} = \beta_0 + \beta_1 \cdot E_2 + \beta_2 \cdot \text{testosterone} + \beta_3 \cdot \text{total } T_3$$

$$\text{free } T_3 \text{ index} = \beta_0 + \beta_1 \cdot E_2 + \beta_2 \cdot \text{testosterone} + \beta_3 \cdot \log_{10} \text{ total } T_3$$

where β_0 represents the intercept and $\beta_{1 \rightarrow 3}$ are the slopes. The entry and removal of independent variables from the models was based on a stepwise selection approach; the *P*-to-enter and *P*-to-remove values were set at 0.05 and 0.10, respectively. Residual plots and the Durbin-Watson test indicated that the error terms met the assumptions of linear regression analysis.

RESULTS

TH levels generally increased during gonadal recrudescence in autumn (Figure 1). The magnitude of the T_4 upsurge, however, was much higher—by 85% on average—in females than in males ($P < 0.01$, t-test for paired comparisons applied to November – March monthly means). Also, the timing of the upsurge was better synchronized with early ovarian growth (I_G c. 1.0 → 3.0, Figure 2a) than with early testes growth.

TH levels started declining abruptly during late ovarian development (I_G c. 3.0, Figure 2a). In males, T_3 levels declined (slightly) when the testes reached a certain size (I_G c. 2.0, Figure 2b). Testosterone and E_2 levels were elevated during late gonadal development (Figure 2c, d). However, total T_4 levels presented no trend in relation to rising gonadal hormone levels (Figure 2e, f). Only total T_3 levels in females clearly started falling as E_2 levels rose above 1.0 ng ml⁻¹ (Figure 2e).

The free T_3 index presented two major seasonal shifts (Figure 3a): it declined significantly in females in winter (autumn v. winter, $P < 0.01$, Mann-Whitney test), and increased in both sexes in spring (winter v. spring, $P < 0.001$, Mann-Whitney test). These seasonal changes are noteworthy because they rendered the absolute free T_3 levels less variable across seasons (Figure 3b). For instance, modelling work indicates that mean free T_3 levels in females would have risen to 1.8 ng ml⁻¹ (SE = 0.2) in winter had the free T_3 index been fixed to the autumnal values; in reality, mean free T_3 levels in females peaked at 1.3 ng ml⁻¹ (SE = 0.2) in winter. By shifting its course again in spring, the free T_3 index upheld free T_3 levels close to 0.6 ng ml⁻¹ (SE = 0.1) in both sexes. Without this second shift in the free T_3 index, modelling work shows that free T_3 levels would have declined to values near 0.36 ng ml⁻¹ (SE = 0.04) in spring.

We found negative correlations between gonadal hormones and the free T_3 index in females in winter (Figure 4). E_2 and testosterone respectively explained 51% ($P < 0.001$) and 60% ($P < 0.001$) of the variability associated with the free T_3 index between the months of November and January. Testosterone was retained as the strongest predictor in a multiple regression model that explained 68% ($P < 0.001$) of the variability in free T_3 (Table 1). In spring, however, total T_3 became the best predictor of changes in free T_3 (Figure 5; Table 1). According to the models, the tendency to free T_3 from plasma proteins in spring was due in large part to low T_3 substrate availability. Also, the relationships were significant only for cases with total T_3 levels below 35 ng ml⁻¹, indicating a possible threshold for triggering the release of T_3 from binding proteins.

DISCUSSION

EFFECTS OF THYROID HORMONES ON REPRODUCTIVE FUNCTION

Woodhead (1959, 1975) suggested that enhanced thyroidal activity in cod is functionally related to migratory behaviour. In the present study, we report that TH may also aid in the initiation of new reproductive cycles. We found appreciable total T₃ levels during testicular recrudescence, consistent with enhanced T₃ substrate in the testes of chum salmon *Oncorhynchus keta* Walbaum (Tagawa *et al.*, 1994), and also with the presence of nuclear T₃ receptors in the testes of freshwater perch *Anabas testudineus* Bloch (Jana & Bhattacharya, 1993). In cod, the thyroidal upsurge in relation to ovarian recrudescence was particularly remarkable and clearly involved both T₃ and T₄. The exact significance of such endocrine activity is not known, although previous work suggest that TH enhance vitellogenin uptake from plasma into the eggs (Shibata *et al.*, 1993) and act in synergy with gonadotrophins to stimulate early ovarian follicle growth (Cyr & Eales, 1988, 1996). The thyroidal upsurge in female cod may thus have been related to early oocyte maturation.

EFFECTS OF GONADAL HORMONES ON THYROIDAL FUNCTION

Previous work on salmonids suggested that rising E₂ levels during the later stages of ovarian development exert a negative effect on the thyroid gland, thereby reducing TH levels in circulation (Leatherland, 1985; Yamada *et al.*, 1993). Falling TH levels are likely required for the final maturation of the ovaries. In cod, we found a close association between late ovarian growth ($I_G > 3.0$) and falling total T₄ levels, although there was no evidence that this decline in T₄ was driven specifically by E₂. On the other hand, our data are in agreement with the premise that E₂ suppresses the peripheral thyroid status, namely T₃ production rates (Leatherland, 1985; Cyr *et al.*, 1988; Flett & Leatherland, 1989; Yamada *et al.*, 1993) and the free T₃ index (Cyr & Eales, 1989).

Testosterone might have also contributed to the lowering of the free T₃ index. Both steroids were present in appreciable concentrations in females, and their combined effect provides a reasonable explanation for the free T₃ index declining significantly in females in winter.

Falling (< 35 ng ml⁻¹) total T₃ levels, however, seemed largely responsible for the elevation of the free T₃ index in spring. This finding is consistent with the observation that arctic charr *Salvelinus alpinus* L. with low total T₃ levels contained relatively few T₃ binding proteins (Eales & Shostak, 1985). In cod, as in many other teleosts, the liver manufactures the bulk of the circulating T₃ (Eales & Brown, 1993; Cyr *et al.*, 1998). Poor feeding conditions on winter grounds (Schwalme & Chouinard, 1999) likely depressed hepatic T₃ production rates in southern Gulf cod (Comeau *et al.*, 2000), perhaps triggering in turn a reduction in the number of T₃ binding proteins. We conclude that gonadal hormones are probably not the only factors influencing the free T₃ index in wild cod, especially at times when T₃ production rates fall below a certain threshold.

BIOLOGICAL IMPLICATIONS

In cod, it is likely that the release of T_4 by the thyroid is activated at the autumn equinox (Comeau *et al.*, 2001). Therefore, endocrine stimulation of ovarian recrudescence may be synchronized in several cod populations throughout the northern hemisphere. To date, evidence of ovarian cycles being initiated near the autumnal equinox is available for southern Gulf of St. Lawrence cod (Schwalme & Chouinard, 1999), northern Gulf of St. Lawrence cod (Lambert & Dutil, 1997), Arctic cod (Hop *et al.*, 1995), Barents Sea cod (Woodhead & Woodhead, 1965; Ponomarenko, 1996), and Pacific cod (Smith *et al.*, 1990).

Once ovarian growth is under way, continued interactions between the two endocrine systems may allow some control over competing somatic and gonadal growth processes. More precisely, it is known that the free T_3 fraction is metabolically potent since it can readily move into target cells and interact with nuclear receptor sites (Eales & Brown, 1993). It is also known that T_3 is more effective than T_4 in promoting fish growth (Higgs *et al.*, 1979). Accordingly, in the female cod, the curtailment of free T_3 levels in winter likely restricts the metabolism and somatic growth rates, and in doing so may allow the metabolic reserves to be directed towards continued oocyte development (Cyr & Eales, 1996). During the spring period, there are probably some adaptive advantages in upholding free T_3 levels above a certain threshold. This second peripheral endocrine adjustment, which was unexpected and poorly correlated with reproductive status, may be necessary for sustaining cell metabolism during a lengthy (500 km – Hanson, 1996) spawning migration in spring.

CONCLUSION

We found that interactions between the thyroidal and reproductive systems in cod were plausible for certain phases of the reproductive cycle, particularly in females. It is suggested that TH contributed to the stimulation of ovarian recrudescence, and that rising levels of E_2 and testosterone, both present in females, exerted a negative effect on the peripheral thyroid status. Despite major differences in reproductive strategies, similar interactions were reported for salmonids (Cyr & Eales, 1996). Thus, it appears that the interactions between the two endocrine systems are important regulators of basic physiological processes such as growth and reproduction.

ACKNOWLEDGEMENTS

We sincerely wish to thank G. Chouinard and M. Hanson of the Department of Fisheries and Oceans (Moncton, New Brunswick) for managing the sampling expeditions; the staff at Biorex Inc. (Caraquet, New Brunswick) for their field assistance; the Marine Fish Division at the Bedford Institute of Oceanography (Dartmouth, Nova Scotia) for providing materials and facilities to L.A.C. Paryse Cormier, Brian Irwin and John Smith kindly made available their laboratories for the isotopic work. Daniel Cyr of the '*Institut national de la recherche scientifique-Santé*' (Pointe-Claire, Québec) gave valued advice regarding RIA procedures.

REFERENCES

- Comeau, L. A., Campana, S. E., Chouinard, G. A. & Hanson, J. M. (2001). Timing of Atlantic cod (*Gadus morhua* L.) seasonal migrations in relation to serum levels of gonadal and thyroidal hormones. *Marine Ecology Progress Series* **221**, 245-253.
- Comeau, L. A., Campana, S. E., Hanson, J. M. & Chouinard, G. A. (2000). Seasonal changes of thyroid hormones in field-collected Atlantic cod in relation to condition indices, water temperature, and photoperiod. *Journal of Fish Biology* **57**, 571-588.
- Cyr, D. G. & Eales, J. G. (1988). The influence of thyroidal status on ovarian function in rainbow trout, *Salmo gairdneri*. *Journal of Experimental Zoology* **248**, 81-87.
- Cyr, D. G. & Eales, J. G. (1989). The effects of short-term estradiol-17 β treatment on the binding properties of T₃-binding proteins in plasma of immature rainbow trout, *Salmo gairdneri*. *Journal of Experimental Zoology* **252**, 245-251.
- Cyr, D. G. & Eales, J. G. (1992). Influence of short-term oestradiol-17 β treatment on plasma thyroxine-binding proteins in rainbow trout, *Oncorhynchus mykiss*. *Journal of Experimental Zoology* **262**, 441-446.
- Cyr, D. G. & Eales, J. G. (1996). Interrelationships between thyroidal and reproductive endocrine systems in fish. *Reviews in Fish Biology and Fisheries* **6**, 165-200.
- Cyr, D. G., MacLatchy, D. L. & Eales, J. G. (1988). The influence of short-term 17 beta-estradiol treatment on plasma T₃ levels and in *in vitro* hepatic T₄ 5'-monodeiodinase activity in immature rainbow trout, *Salmo gairdneri*. *General and Comparative Endocrinology* **69**, 431-438.
- Cyr, D. G., Idler, D. R., Audet, C., McLeese, J. M. & Eales, J. G. (1998). Effects of long-term temperature acclimation on thyroid hormones deiodinase function, plasma thyroid hormone levels, growth, and reproductive status of male Atlantic cod, *Gadus morhua*. *General and Comparative Endocrinology* **109**, 24-36.
- Dickhoff, W. W., Yan, L., Plisetskaya, E., Sullivan, C. V., Swanson, P., Hara, A. & Bernard, M. G. (1989). Relationships between metabolic and reproductive hormones in salmonid fish. *Fish Physiology and Biochemistry* **7**, 147-155.
- Eales, J. G. & Brown, S. B. (1993). Measurement and regulation of thyroidal status in teleost fish. *Reviews in Fish Biology and Fisheries* **3**, 299-347.
- Eales, J. G. & Fletcher, G. L. (1982). Circannual cycles of thyroid hormones in plasma of winter flounder (*Pseudopleuronectes americanus* Walbaum). *Canadian Journal of Zoology* **60**, 304-309.
- Eales, J. G. & Shostak, S. (1985). Free T₄ and T₃ in relation to total hormone, free hormone indices and protein in plasma of rainbow trout and arctic charr. *General and Comparative Endocrinology* **58**, 291-302.

- Flett, P. A. & Leatherland, J. F. (1989). Dose-related effects of 17 beta-oestradiol (E₂) on liver weight, plasma E₂, protein calcium and thyroid hormone levels, and measurements of the binding of thyroid hormones to vitellogenin in rainbow trout, *Salmo gairdneri* Richardson. *Journal of Fish Biology* **34**, 515-527.
- Hanson, J. M. (1996). Seasonal distribution of juvenile Atlantic cod in the southern Gulf of St. Lawrence. *Journal of Fish Biology* **49**, 1138-1152.
- Higgs, D. A., Fagerlund, U. H. M., McBride, J. R. & Eales, J. G. (1979). Influence of orally administered L-thyroxine or 3,5,3'-triiodo-L-thyronine on growth, food consumption and food conversion efficiency of underyearling coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Zoology* **57**, 1974-1979.
- Hop, H., Graham, M. & Trudeau, V. L. (1995). Spawning energetics of Arctic cod (*Boreogadus saida*) in relation to seasonal development of the ovary and plasma sex steroid levels. *Canadian Journal of Fisheries and Aquatic Sciences* **52**, 541-550.
- Jana, N. R. & Bhattacharya, S. (1993). Binding of thyroid hormone to freshwater perch Leydig cell nuclei-rich preparation and its functional relevance. *Zoological Science* **10**, 489-496.
- Kjesbu, O. S., Kryvi, H. & Norberg, B. (1996). Oocyte size and structure in relation to blood plasma steroid hormones in individually monitored, spawning Atlantic cod. *Journal of Fish Biology* **49**, 1197-1215.
- Lambert, Y. & Dutil, J.-D. (1997). Condition and energy reserves of Atlantic cod (*Gadus morhua*) during the collapse of the northern Gulf of St. Lawrence stock. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 2388-2400.
- Leatherland, J. F. (1985). Effects of 17 beta-estradiol and methyl testosterone on the activity of the thyroid gland in rainbow trout, *Salmo gairdneri* Richardson. *General and Comparative Endocrinology* **60**, 343-352.
- Methven, D. A., Crim, L. W., Norberg, B., Brown, J. A., Goff, G. P. & Huse, I. (1992). Seasonal reproduction and plasma levels of sex steroids and vitellogenin in Atlantic halibut (*Hippoglossus hippoglossus*). *Canadian Journal of Fisheries and Aquatic Sciences* **49**, 754-759.
- Omeljianuk, R. J., Cook, R. F. & Eales, J. G. (1984). Simultaneous measurement of thyroxine and triiodothyronine in trout plasma using a solid-phase radioimmunoassay. *Canadian Journal of Zoology* **62**, 1451-1453.
- Osborn, R. H. & Simpson, T. H. (1978). Seasonal changes in thyroidal status in the plaice, *Pleuronectes platessa* L. *Journal of Fish Biology* **12**, 519-526.
- Pankhurst, N. W. & Conroy, A. M. (1987). Seasonal changes in reproductive condition and plasma levels of sex steroids in the blue cod, *Parapercis colias* (Bloch and Scheider) (Mugiloididae). *Fish Physiology and Biochemistry* **4**, 15-26.

- Pankhurst, N. W. & Kime, D. E. (1991). Plasma sex steroid concentrations in male blue cod, *Parapercis colias* (Bloch and Scheider) (Pinguipedidae), sampled underwater during the spawning season. *Australian Journal of Marine and Freshwater Research* **42**, 129-137.
- Ponomarenko, V. P. (1996). Distribution of mature cod *Gadus morhua* of the Barents Sea in relation to seasonal variation in the maturity of gonads. *Journal of Ichthyology* **36**, 363-368.
- Schwalme, K. & Chouinard, G. A. (1999). Seasonal dynamics in feeding, organ weights, and reproductive maturation of Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. *ICES Journal of Marine Science* **56**, 303-319.
- Shibata, N., Yoshikuni, M. & Nagahama, Y. (1993). Vitellogenin incorporation into oocytes of rainbow trout, *Oncorhynchus mykiss*, in vitro: effect of hormones on denuded oocytes. *Development Growth & Differentiation* **35**, 115-121.
- Smith, R. L., Paul, A. J. & Paul, J. M. (1990). Seasonal changes in energy and the energy cost of spawning in Gulf of Alaska Pacific cod. *Journal of Fish Biology* **36**, 307-316.
- Tagawa, M., Ogasawara, T., Sakamoto, T., Miura, T., Yamauchi, K. & Hirano, T. (1994). Thyroid hormone concentrations in the gonads of wild chum salmon during maturation. *Fish Physiology and Biochemistry* **13**, 233-240.
- Woodhead, A. D. (1959). Variations in the activity of the thyroid gland of the cod, *Gadus callarias* L., in relation to its migrations in the Barents Sea. I. Seasonal changes. *Journal of the Marine Biological Association of the U. K.* **38**, 407-415.
- Woodhead, A. D. (1975). Endocrine physiology of fish migration. *Oceanography and Marine Biology Annual Reviews* **13**, 287-382.
- Woodhead, A. D. & Woodhead, P. M. J. (1965). Seasonal changes in the physiology of the Barents Sea cod, *Gadus morhua* L., in relation to its environment. I. Endocrine changes particularly affecting migration and maturation. *International Commission for the Northwest Atlantic Fisheries Special Publication* **6**, 691-715.
- Yamada, H., Horiuchi, R., Gen, K. & Yamauchi, K. (1993). Involvement of four hormones in thyroxine deiodination in several tissues of immature yearling masu salmon, *Oncorhynchus masou*. *Zoological Science* **10**, 587-596.

Table 1. Results of stepwise multiple regression analyses with the free T₃ index as the dependent variable. The *t* statistics provides an indication of the relative importance of each parameter; the *P* and Probability values indicate the significance of individual parameter and of the overall regression, respectively.

Period	E ₂		Testosterone		Total T ₃		Final Model	
	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	<i>r</i> ²	Probability
Nov – Jan (♀)	-1.63	0.11 [†]	-8.94	<0.001	-2.82	<0.01	0.68	<0.001
Jan – Mar (♀)	0.37	0.72 [†]	-3.43	<0.01	-4.14	<0.001	0.58	<0.001
(♂)	0.88	0.39 [†]	-0.36	0.73 [†]	-6.71	<0.001	0.58	<0.001

[†] parameter excluded from model

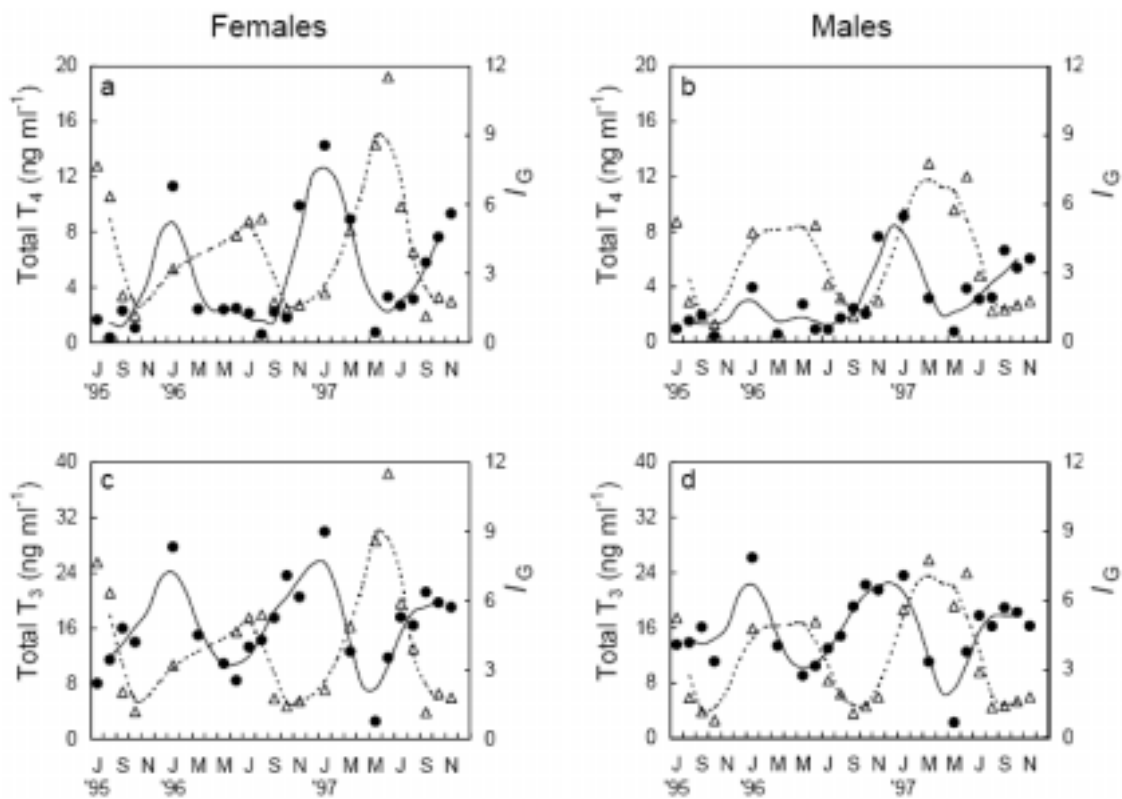


Figure 1. Seasonal changes of total T_4 , total T_3 and I_G . ●, monthly means of either total T_4 [(a), (b)] or total T_3 [(b), (c)]; Δ, monthly means of I_G . Trend lines show three-point centred moving averages for hormones (—) and I_G (---) series. Missing months were replaced with computed values (linear interpolation of two neighbouring values) before running the three-point centred average function.

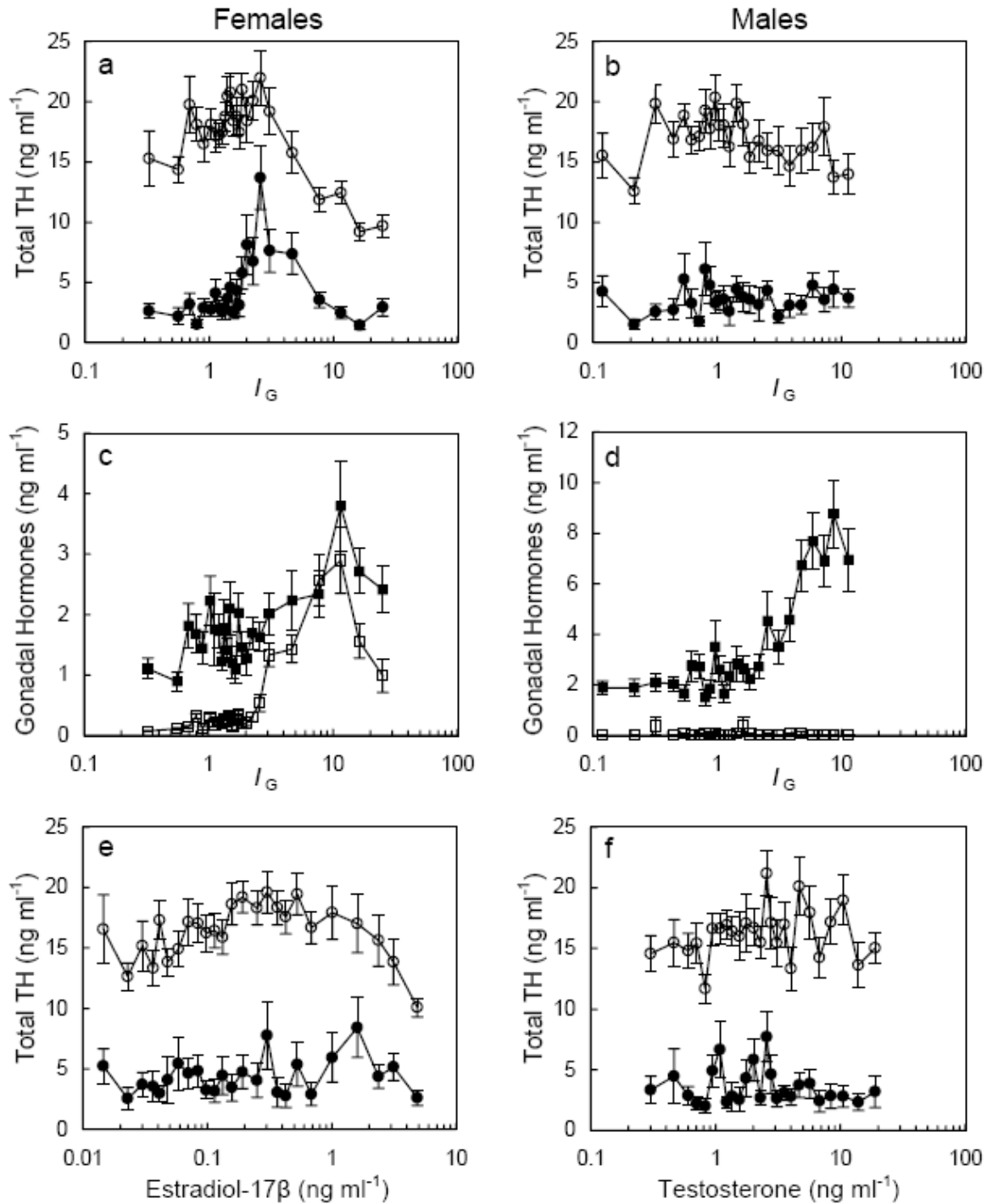


Figure 2. Interrelationships between total thyroid hormones (either total T₄ or total T₃), I_G , and gonadal hormones. Data points represent means from 25 percentile groups categorized based on variable x . Data collected throughout the year were included in the analysis. ●, total T₄; ○, total T₃; □, E₂; ■, testosterone. Error bars show S.E.

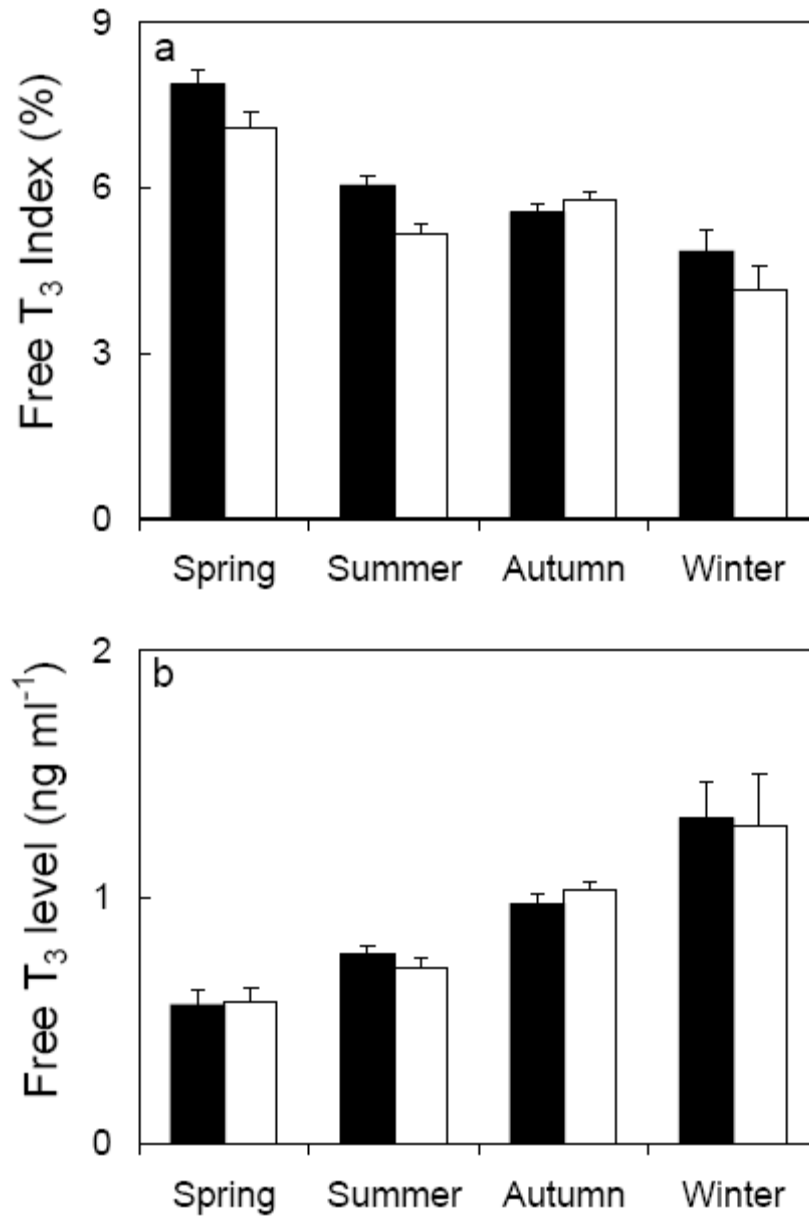


Figure 3. Seasonal averages of the free T₃ index (a) and free T₃ levels (b) in males (filled bars) and females (open bars). Error bars show S.E.

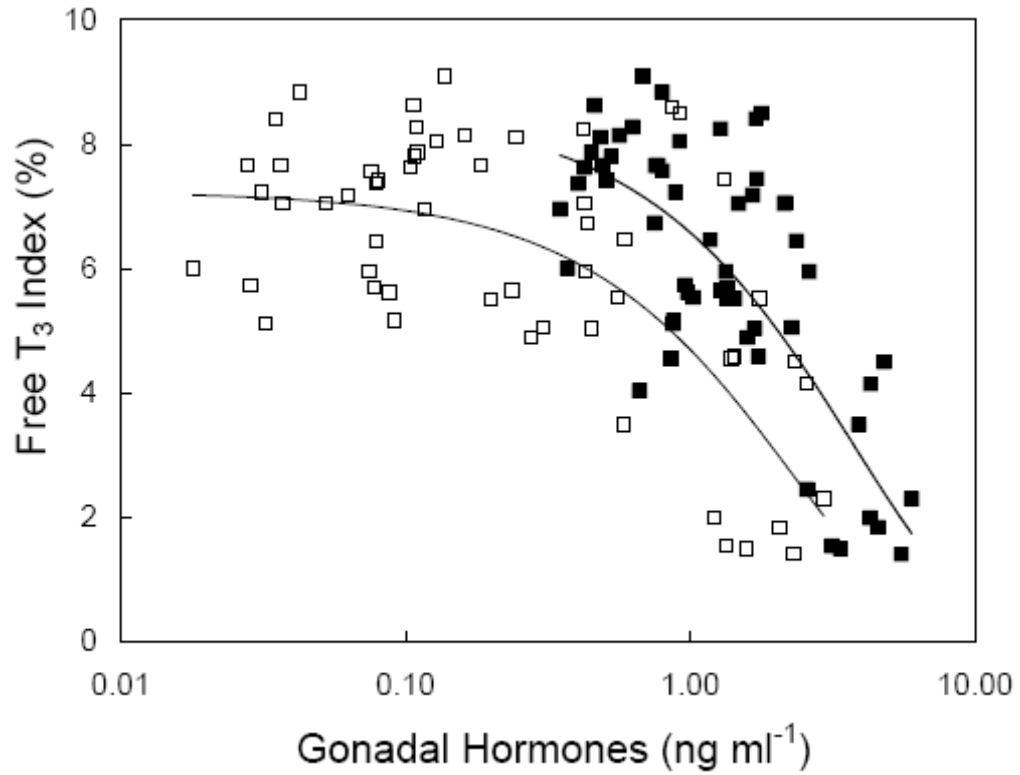


Figure 4. Relationships between the \log_{10} free T_3 index and E_2 (\square , $r^2 = 0.51$, $P < 0.001$) in females, and also between the \log_{10} free T_3 index and testosterone (\blacksquare , $r^2 = 0.60$, $P < 0.001$) in females. Data points represent individual fish sampled between November and January (1996 and 1997).

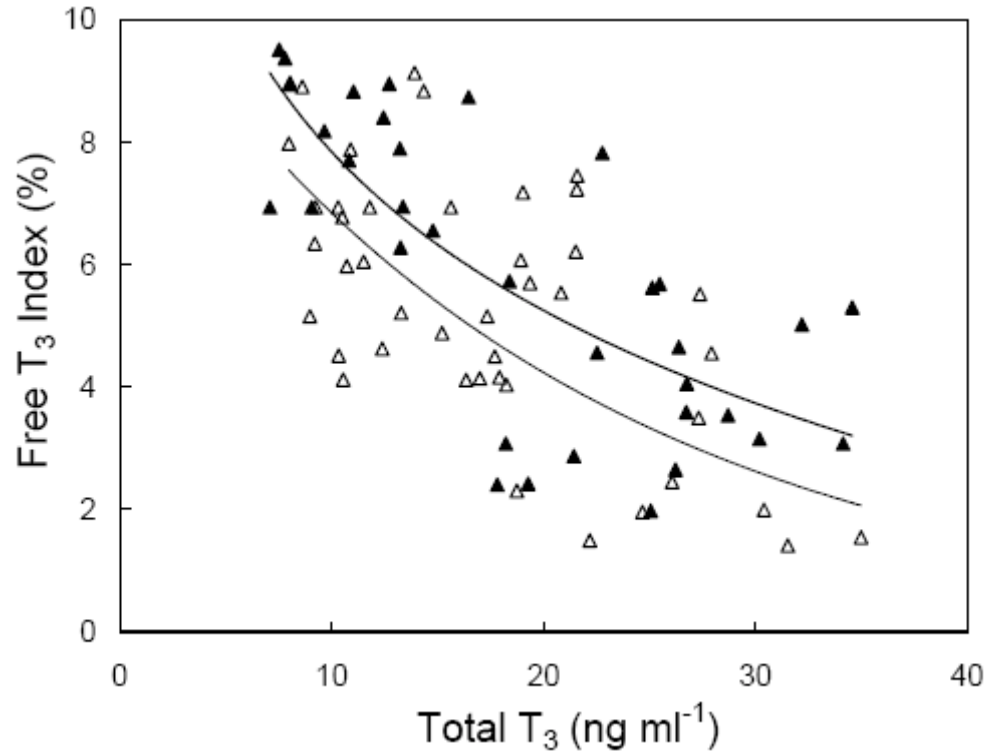


Figure 5. Relationships between the \log_{10} free T₃ index and total T₃ levels in females (Δ , $r^2 = 0.45$, $P < 0.001$), and also between the free T₃ index and \log_{10} total T₃ levels in males (\blacktriangle , $r^2 = 0.58$, $P < 0.001$). Data points represent individual fish sampled between January and March (1996 and 1997).