THE ARCTIC CHAR *SALVELINUS ALPINUS* (L.) SPECIES COMPLEX IN IRELAND: A SECRETIVE AND THREATENED ICE AGE RELICT

Fran Igoe and Johan Hammar

ABSTRACT

Members of the Arctic char *Salvelinus alpinus* (L.) species complex were most likely the first freshwater fish to colonise Ireland after the last Ice Age. Once widespread and anadromous, they now form isolated populations, confined to inland freshwater lakes with suitable habitat (well-oxygenated clean water, gravel shores and adequate depth when in the presence of other fish species). Adapted to Arctic conditions, they are extremely sensitive to environmental changes within their range further south, in which Ireland lies. The greatest threats to their present survival in Ireland are interspecific interactions from introduced fish species, eutrophication, acidification and climate change. The rate of extinction of entire populations has increased over the last few decades, and immediate steps must be put in place to preserve our remaining discrete populations. As marginal populations at the southern edge of the species range in Atlantic Europe, Arctic char in Ireland potentially hold some of the oldest genetic material in western Europe for the species complex. Such populations may be an important source of genetic material for the long-term survival of the species. Isolated in their respective lakes/lake catchments since the last Ice Age, they are of both genetic and evolutionary interest to scientists.

This paper draws attention to the limited ecological data available on Arctic char in Ireland and attempts to place Irish Arctic char populations in context with the rest of the species' range. Where possible, recent information is given on the various aspects of the biology, distribution and current status of the species.

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INTRODUCTION

Arctic char have a circumpolar distribution and are the most northerly-distributed freshwater fish in the world. Treated as a species complex, they belong to the genus *Salvelinus*, which evolved some five to ten million years ago (Power 2002). Other well-known taxa belonging to this genus are the Dolly Varden (*S. malma*), brook trout (*S. fontinalis*), lake trout (*S. namaycush*), bull trout (*S. confluentus*) and the white-spotted char (*S. leucomaenis*).

Adapted to the climatic extremes of the Arctic, the Arctic char are the only fish 'taxon' found naturally at high latitudes in the Arctic. However, they persist further south in deep, cold lakes or at high altitudes in environments that retain quasi-Arctic conditions. Relicts of a time when the polar ice sheets extended much further south, these char are referred to as marginal populations. Ireland is situated along the southern marginal zone. In this respect, outside of the Alpine populations, Irish lakes potentially hold some of the oldest genetic material in western Europe for the species complex.

In the Arctic, char have evolved a range of strategies to survive and multiply. As landlocked char are often the only fish species in an impoverished environment, it is not uncommon for them to turn to cannibalism (Hammar 1998a; 2000). Further south (but still in the Arctic) many populations migrate to sea and achieve sizes up to 15kg (Johnson 1980). The bimodal size and age distribution associated with many Arctic populations is a reflection of thermodynamic processes (Johnson 1981; 1983; 1994; 2002) and their life-history strategy patterns (Hammar 1989; 1998a; 2000). Similar situations must have prevailed in Ireland during and shortly after the last Ice Age. However, as the sea warmed and the annual cost of going to sea in terms of predation and competition for coastal food increased, Irish Arctic char lost their anadromous behaviour and became lake residents. They now live, feed and reproduce within the confines of lakes. Irish Arctic char are not physically landlocked, however, as many Irish char lakes support diadromous populations of other salmonids and eel (Fig. 1). In addition char have been recorded moving between lakes

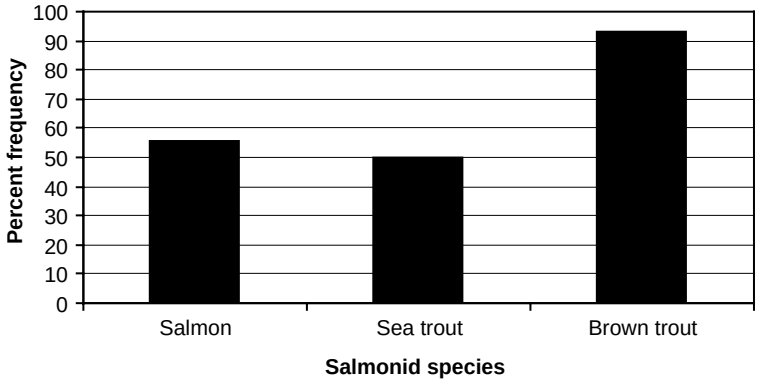

Fig. 1 — Percentage frequency of Arctic char lakes with other salmonid species. Note over 50% of Irish char lakes still hold anadromous salmonids. The status of eel is unknown in Irish char lakes; however, the extent of eel attacks on char in survey nets, suggests that they are widespread.

(e.g. between Lough Muck and Lough Fee, Co. Mayo (D. Quigley, pers. comm.)), and occasionally anglers have caught char in some Irish rivers, e.g. River Currane (Went 1944) and Gowla River (Went 1955).

The low numbers of encounters between Irish char and humans today has led to the belief that they occur in very low numbers in loughs where they survive. This is not necessarily the case in all parts of Ireland: where viable populations exist, they may in some lakes outnumber sympatric brown trout (Igoe *et al*. 2001b). Little has been published on Irish Arctic char populations, and general information on their biology is lacking (Cross *et al*. 1998; Tierney *et al*. 2000). This contrasts with other members of the salmonid family that also occur in Ireland (brown trout, *Salmo trutta,* and Atlantic salmon, *Salmo salar*). These species have been studied more thoroughly, due to their importance as commercial and angling resources. In contrast, native Arctic char are not exploited commercially or recreationally, and they are generally perceived to be of no commercial value in Ireland. A small traditional local recreational fishery does exist, however, in Lough Eske (Igoe 2002). The general appeal of Arctic char may increase, as has occurred in other countries with declining char populations. With the growth of specialist angling, the potential value of Irish char as an angling species may become more widely appreciated. Additionally, the biodiversity and conservation value of Arctic char is being realised, and there is a growing acceptance that Arctic char are part of a very special and relict fauna inherited from the last Ice Age and are consequently indicative of pristine environmental conditions.

METHODS

Some of the data presented were collected during recent surveys undertaken by the Irish Char Conservation Group. Experimental netting surveys were carried out using the standard benthic Nordic type monofilament nylon gillnets (made by Lundgren in Sweden), which are composed of different mesh sizes following a geometric series with a ratio between mesh-sizes of about 1.25. The gill nets are 30m long and 1.5m deep and are composed of 12 different mesh panels, each about 2.5m, with 5–55mm between knots. The netting is carried out according to protocols described by Appleberg (2000). Additional material was collected through questionnaires and from anglers. Laboratory analysis techniques used are described in Hammar (1998a).

TAXONOMY

Internationally there has been much debate over the taxonomy of Arctic char. Early fish taxonomists favoured splitting the species into many species or subspecies, based on a range of morphological, meristic and other traits (e.g. Artedi 1738; Linnaeus 1758; Nilsson 1832; Regan 1911; Kendall 1914). Later a single species concept was favoured. In more recent years, a general acceptance has emerged that the Arctic char is more accurately described as a species complex. This is in recognition of the variability in morphometric, meristic, genetic and life-history patterns displayed by Arctic char throughout its range (e.g. Behnke 1980; 1984; Savvaitova 1980; 1995; Brunner *et al*. 2001).

In Ireland the taxonomy of Arctic char was also a source of confusion. The taxonomist Albert C.L.G. Günther (1862; 1863) recognised two

species of char (*S. colii* and *S. grayi*) from specimens obtained from Irish lakes. Later the British taxonomist C. Tate Regan (1908; 1911) identified six species of Irish char (Table 1). Regan felt that the traits were sufficiently different to justify species designation. He made the argument that if char were to die out in British and Irish lakes, and only four of the more distinctive forms remained, all zoologists would agree that they would represent four well-marked species. Subspecies categorisations were common until the latter half of the twentieth century (e.g. Went 1945; 1971a; Healy 1956). By the late 1970s the single species concept was generally accepted (e.g. Went 1978).

The above taxonomic descriptions of Irish char relied on interpretations of meristic and morphometric measurements. New developments in the field of fish genetics offered a less subjective approach to systematics and taxonomy that was independent of environmental factors. Ferguson (1981) investigated the systematics of Irish char by examining allozyme and protein patterns of specimens taken from seven Irish lakes (including four of Regan's char species). By isoelectric focusing he was able to determine that these char were similar genetically and derived from a common ancestor. He concluded that the previous subspecific groupings probably reflect groupings based on environmental convergence of morphological and other features. Ferguson stressed, however, that Irish char represent excellent models for the study of genetic changes in isolation and

Table 1—Main diagnostic and meristic features, common names, territories and status of Regan's six Irish char types. Modified Regan (1911).

Name	*Main characteristics*	*Common name*	*Lake identified in*	*Status*
S. colii	Depth of body 4 to 5 times of body length, least depth of caudal peduncle about two-fifths the length of head, pectoral fin extending from one half to nearly three quarters of the distance from its base to the pelvics; 138 to 168 in a longitudinal series; 62 to 63 vertebrae.	Coles char	Most common form, first described from L. Eske	~30% populations extinct
S. grayi	Depth of body 3.5 to 4 times of body length, least depth of caudal peduncle one half or nearly one half the length of head, pectoral fin extending two thirds to nine tenths of the distance from its base to the pelvics; 128 to 162 in a longitudinal series; 58 to 60 vertebrae.	Gray's char or 'freshwater herring'	L. Melvin only	Extant
S. trevelyani	Males with snout produced, acutely conical, and the teeth rather strong	Trevelyan's char	L. Fin (Donegal) only	Extant
S. fimbriatus	18 to 19 gill-rakers on the lower part of the anterior branchial arch	Coomasaharn char	L. Coomasaharn only	Extant
S. scharffi	More than 180 scales in a longitudinal series; maxillary extending to or a little beyond the posterior edge of pupil in a male of 11 inches; snout conical, rather short.	Scharff's char	L. Owel, L. Ennell only	Extinct
S. obtusus	Snout obtuse, with the upper profile decurved; lower jaw rounded anteriorly, shorter than and included within the upper; interorbital region flat; anal fin with 8 to 11 branched rays.	Blunt snouted Irish char	Killarney lakes, L, Accose, L. Tay, L. Dan only	50% populations extinct

emphasised that all possible measures should be taken to conserve as many as possible of these populations in their pristine state. The techniques used by Ferguson were insensitive indicators of genetic differentiation of populations that have been isolated for less than 50,000 years (i.e. before the final retreat of the last Ice Age), and the advent of more sophisticated genetic profiling techniques of mitochondrial, mini- and micro-satellite DNA should offer more insight into the more recent evolutionary period of Irish char (Hartley *et al*. 1992).

DIET OF IRISH CHAR

The diet of Arctic char in Ireland is typical of that described for char from similar regions (e.g. Frost 1977; Greer 1991). Table 2 lists studies that generally indicate that pelagic feeding is dominant for Irish char, particularly during summer months (see also Fig. 2).

Bioaccumulation of radioactive caesium Cs-137 in char in summer months also provides corroborative evidence for a dominance in pelagic feeding in warmer months by Irish char (Table 3). Generally, lower levels of Cs-137 were detected in char tissue compared to trout in a study of four Irish lakes. This is consistent with findings in Sweden (Hammar 1998b), where in summer the littoral-benthos feeding trout accumulated higher levels of Cs-137 than pelagic char feeding on zooplankton. The Irish samples were collected between the months of May and September, indicating that Arctic char in the four unproductive lakes studied were principally zooplankton feeders, at least during the summer period. Pelagic food items eaten by Irish char include *Daphnia* spp, *Leptodora kindti*, *Chaoborus* sp. and various chironomid life stages. The semi-benthic cladoceran *Eurycercus lamellatus* is also commonly taken (Tierney *et al*. 2000). Considerably fewer data are available for the diet of Irish char in colder months. Studies in Lough Mask illustrate that benthic feeding dominated during this period (Fig. 3). *Asellus* sp., *Gammarus* sp. and Chironomidae are the dominant benthic species, particularly in the more productive lakes such as Lough Mask, Lough Corrib and Lough Conn (Tierney *et al*. 2000). The two latter char populations are now extinct (Igoe *et al*. 2001). Benthic species also include a range of molluscs (e.g. Sphaeridae, *Planorbus* spp and *Valvata* spp).

Table 2—Studies of loughs that generally indicate that pelagic feeding is dominant for Irish char, particularly during summer.

Lough	*Reference*
Lough Mask	O'Grady *et al*. 1996; Tierney *et al*. 2000; Doherty and McCarthy 2001
Lough Conn	O'Byrne 1988; Tierney *et al*. 2000
Lough Dunlewy Lough Veagh	Hagan 1995
Lough Finn	Twomey 1984
Lough Eske	O'Byrne 1988; Tierney *et al*. 2000; Doherty and McCarthy 2001
Lough Fermoyle Lough Glenawough	O'Byrne 1988
Loughs Nabac Lough Corrib Lough Cloonsneacta	Tierney *et al*. 2000
Muckross Lough	See Fig. 2

SIZE, AGE AND GROWTH OF IRISH CHAR

The majority of Irish char populations grow to lengths of 250–300mm and weights of 150–250g. Typical length frequency distributions for a number of Irish populations sampled by gillnets of multiple mesh size are unimodal (Fig. 4). The size range of Irish char reflects their pelagic feeding biology and the absence of anadromy or piscivory (Fig. 5). Populations with greatest individual size have been associated with the more productive lakes, which offer an abundance of benthic invertebrates. Arctic char in excess of 30cm were commonly encountered in Lough Corrib, Lough Mask and Lough Conn (Igoe *et al*. 2001b). As the latter two populations are now extinct, individuals in the population of Lough Mask would appear to have the greatest growth potential for an Irish char lake today. In March 2003, a 37cm female was captured, which is the largest authenticated record for wild char in Ireland to date (ICCG unpublished). Literature cited by Went (1945) reports char of 16 inches (41cm) from Finloe Lake, Co. Clare, and Thompson (1856) reported that char in Lough Owel, Co. Westmeath, attained weights of 3lb (1.4kg). Indeed, there is even a report of char measuring two feet (60cm) in two lakes in the Cummeragh Mountains (Smith 1774). Did these char in the Cummeragh Mountains have access to abundant and large-sized invertebrates, or is it possible that they had developed a piscivorous lifestyle, similar to landlocked char in southern Sweden, Norway and Finnish and Russian Karelia?

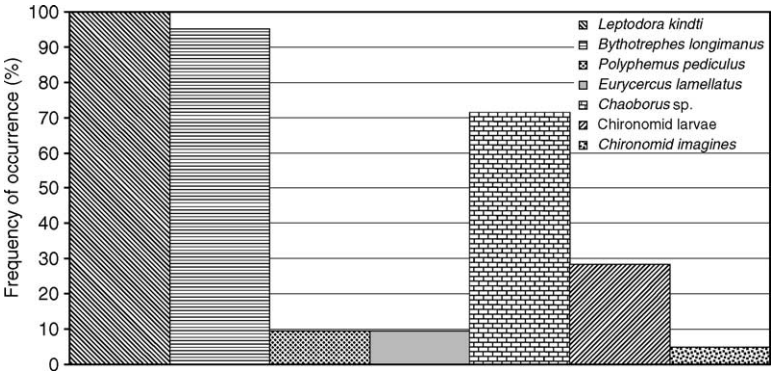

Fig. 2— Percentage frequency of occurrence of food items recorded in Arctic char captured in Lundgren Nordic benthic gill nets set in Muckross lake (3–5 September 2002).

The population has yet to be identified and survey efforts to discover the identity of these lakes have so far proved unsuccessful (Igoe *et al*. 2001a).

Most age studies of Irish char were carried out by examination of growth patterns on their scales (Went 1945; Tierney *et al*. 2000; Doherty and McCarthy 2001). However, in other countries researchers (e.g. Nordeng 1961) realised that uncoupling of somatic growth and scale development results in an underestimation of age, particularly with respect to older fish. We present data that illustrate that scales underestimate the age of older Irish char and should not be used for age determinations (Table 4). Twomey (1984) also found that the use of scales from char from Lough Finn (Co. Donegal) underestimated their age. Figs 6a and 6b show the age distribution of Arctic char taken in benthic gillnets set in Muckross and Coomasaharn Loughs that were aged using otoliths. These figures illustrate that Irish char are relatively short-lived in comparison to populations in Arctic systems, where individual ages up to 30 years have been reported (Johnson 1980; Hammar 1998a). The maximum age recorded for Irish char is nine years, as found in Lough Eske (O'Byrne 1988), and Muckross Lake (Fig. 7a). Growth of Irish Arctic char is relatively fast for the first few years and is comparable to brown trout. However, there is a rapid slow down, usually after the third year, with little growth evident thereafter (Figs 7a and 7b).

SPAWNING AND EARLY LIFE HISTORY OF IRISH CHAR

Little is known about the spawning behaviour of Arctic char in Ireland, and few spawning sites are known. All of these sites occur along lakeshore lines. Investigation into the existence of stream spawning populations in Ireland is needed as anecdotal accounts supporting the existence of river spawning occur (P. Mcgillicuddy, pers. comm.). Interestingly, Went (1945) cites an

Table 3— Concentration of radioactive caesium in sediment and fish from four Irish char lakes (in County Donegal) in May and September, illustrating the lower accumulations in char compared to trout and pisciverous pike.

Lake	*Year*	*Cs–137 (Bq kg^{-1})*				*Cs–134 (Bq kg^{-1})*			
		Sediment	*Pike*	*Trout*	*Char*	*Sediment*	*Pike*	*Trout*	*Char*
Lough Finn	1989	143–899		84; 108	96	31.5–142.0		17.5;23.4	24.2
	1991	42–408		94	24	<1.6–32		7.9	<1.4
	1992	76		18–88	17–20	4.2		<1.2–5.2	<1.8
Lough Eske	1990	127;139		39;55	29	11.3;11.8		4.5;5.5	2.8
Lough Derg	1990	35–244	278	46–92	35; 39	1.8–13.1	33.2	5.0–9.9	4.2; 5.6
Lough Gartan	1990	68–436		100; 110	86	8.8–43.8		11.5;13.5	9.8
	1991	151–360		40–91	57	7.9–18		3.3–7.8	4.8

Concentrations in wet weight in fish and dry weight in sediments.
Where one data point is shown, $n = 1$; where data is separated by a semicolon, $n = 2$; for all other samples $n \geq 3$.
Data reproduced from O'Sullivan *et al*. (1992).

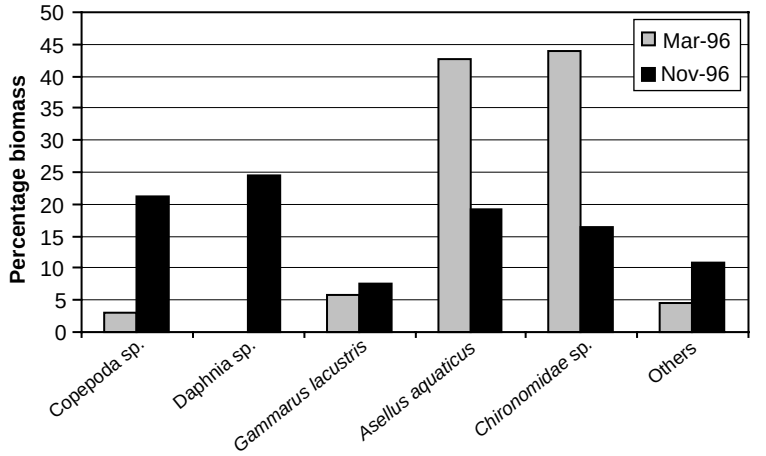

Fig. 3 — Graphical illustation of dominant species recorded in char stomachs from Lough Mask. Benthic prey items were dominant in char stomachs ($n = 60$) in March 1996 compared pelagic food items November 1997 ($n = 38$). Modified from Doherty and McCarthy (2001).

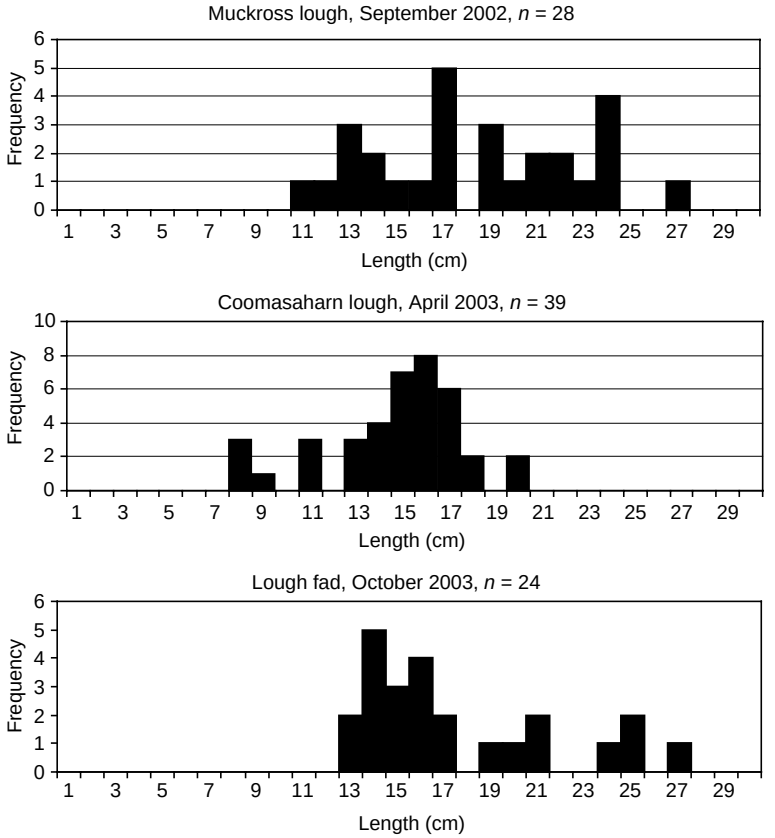

Fig. 4 — Length frequency distribution of Arctic char from three Irish lakes sampled by the Irish Char Conservation Group with Lundgren's experimental benthic gillnets.

account of a river spawning char population given in the Cromwellian Civil Survey (1656) for the Baroney of Muskerry of Lough Gugane B (identified by Went 1945 as Lough Allua): this population of char is now believed to be extinct. The account states that the char were 'to be found in November not by angling but by a Nett when ye go up the small River or Brooks to spawn the aforsd'. Similar exploitation of char was noted in St Mary's Lake by Maitland (1992) in Scotland and in the Rangely Lakes in Maine, USA, by Kendall (1914). More recent scientific descriptions of char spawning in running water have been recorded for some lake resident char populations,

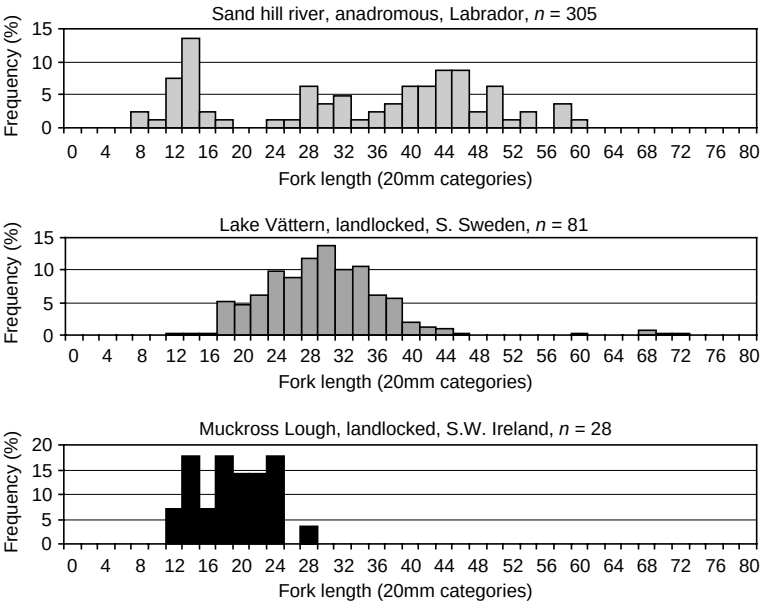

Fig. 5—Length frequency distribution of Arctic char from an Irish lake (Muckross Lough) sampled by the Irish Char Conservation Group with Lundgren's experimental benthic gillnets, compared to char sampled in Lake Vättern, southern Sweden (a heavily exploited landlocked piscivorous population), and Sand Hill River, Labrador (an anadromous population).

e.g. in Scotland (Maitland *et al*. 1984), England (McCubbing *et al*. 1998) and Sweden (Hammar 1984).

Igoe *et al*. (2001b) give details on locations of likely spawning sites for three Irish limestone lakes based on the experience of local fisheries personnel. All sites were located in relatively shallow water over gravel beds. More specific data are available for Lough Eske in County Donegal. The spawning period can start from October to late November and may last up to three weeks. Rod catch data from this lake suggest that males come onto the spawning grounds first and remain there for a longer period than females (Igoe 2002). This pattern is commonly reported elsewhere (Johnson 1980). We examined the spawning beds in Lough Eske by snorkelling in 2002 and 2003. Spawning takes place in shallow water (0.3–1.2m deep) less than 10m out from the shoreline along two point bars. The lake side of the gravel beds shelve steeply into the lake and are well washed due to the prevailing winds. The dispersion of the eggs over the bottom substrate suggests that eggs are broadcast over the site rather than deposited in excavated redds. Eggs were only found over gravel areas clean of detritus or sediment, along a gravel bar running

Table 4—Comparison of age analysis using two structures.

Lake	*Geology*	*n*	Structure	*Mean age (years)*	*Min. age (years)*	*Max. age (years)*
Lough Eske	Shales/sandstones/ schists	23	Scale	3.5	3	3
			Otolith	4.8	3	7
Lough Kindrum		25	Scale	2.9	2	4
			Otolith	5.0	3	7
Lough Conn	Ordovician limestone	24	Scale	2.5	2	4
			Otolith	4.3	3	7

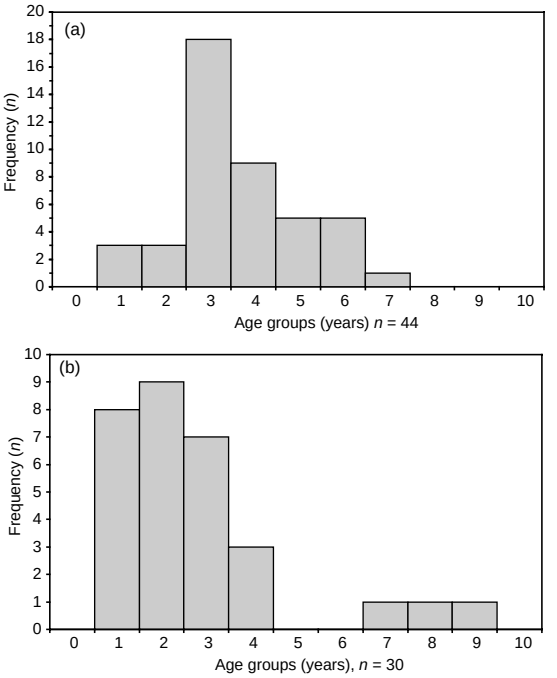

Fig. 6 — Age class distribution for Arctic char sampled from a) Lough Coomasaharn, 23–24 April 2003; b) Muckross Lough, 3–5 September 2002.

parallel with the shore. Fig. 8 shows the gravel composition of the Lough Eske spawning ground, which is similar to that reported elsewhere (e.g. Rubin and Buttiker 1992; Rubin 1993; Frost 1965). The particle profiles of these spawning beds are not dissimilar to those preferred by Irish sea trout and salmon (Fluskey 1989). No information of hatching dates and incubation periods are available for Irish char populations in the wild.

Age and size at first spawning vary widely for Arctic char (Johnson 1980). Depending on intra- and inter-specific interactions, piscivorous populations in the far north as well as in the far south of Scandinavia tend to achieve maturity at a greater age, whereas more central and non-piscivorous populations generally achieve maturity at a younger age. The rapid early growth of most Irish char enables the fish to reach the critical stage required for gonadal production usually in their third year. A similar phenomenon is noted in Irish brown trout populations (Kennedy and Fitzmaurice 1971). In Lough Conn spawning char ranged in age from 3 to 7 years and in Lough Eske from 3 to 9 years (Fig. 9). In Muckross Lough, Killarney National Park, char with mature gonads ranged from 3 to 9 years in age (ICCG/ISACF survey September 2002). Initial spawning size reflects the growth rates achieved in Irish lakes, again probably reflecting prevailing ecological conditions. The smallest mature char recorded in Coomasaharn Lough in 2003 were a 12.5cm female and a 12.7cm male. In Lough Eske the smallest spawner was a 17.1cm male (in 2000), compared to a 19.0cm male in the more productive Lough Conn (in 1989). In Ireland, although yet to be demonstrated scientifically, it is likely that the majority of char spawn annually as they do in other lakes, e.g. in Lake Windermere (Frost 1965). Autumn spawning appears to be the norm for most Irish char populations (O'Grady *et al*. 1996; Tierney *et al*. 2000). However there is a strong possibility that spring spawning occurs in some Irish loughs as a recent snorkelling survey by the ICCG of Lough Talt, Co. Sligo, on 18 February 2004 found that char had recently spawned, indicating that the spawning period in some Irish loughs is not necessarily confined to the November/December period, as previously thought.

FECUNDITY OF IRISH CHAR

Fecundity of Irish char is similar to that reported for other non-migratory populations (Johnson 1980). In Muckross Lough, the number of eggs in female char collected in September 2002 increased with increasing fish length, with a maximum egg number of 826 eggs recorded in a 26.4cm female (Fig. 10).

PARASITES IN IRISH CHAR

Published work on parasites in Irish char is only available for Lough Corrib (Conneely and McCarthy 1984), Lough Eske and Lough Mask (Doherty and McCarthy 2001). Tierney *et al*. (2000) list additional unpublished information on parasites. The few macroparasites of Irish char recorded so far (Table 5) are the ones commonly recorded in other char populations with similar feeding biology in northern Europe. The parasite community of an Arctic char reflects a lifetime feeding on various intermediate hosts. Hosts such as cyclopoid copepods, amphipods, molluscs and insects are all significant prey organisms for Irish char and therefore can be used to deduce more long-term feeding patterns of Irish char. In addition, some of these parasite species specifically use Arctic char as final host and should thus also be treated as glacial relicts.

The limited data to date suggest that the parasite communities and their prevalence in Irish char populations vary across the island, reflecting varying availability of the intermediate hosts, but perhaps also varying degrees of adaptive pathological defence systems towards parasite infection in Arctic char. Recent examination of the Arctic char population in Coomasaharn Lough in the southwest of County Kerry, perhaps

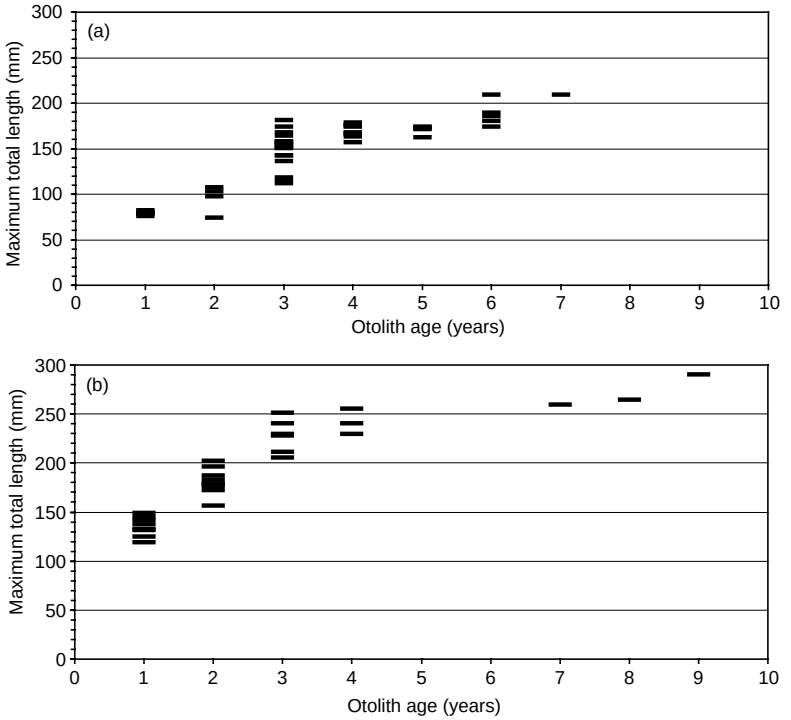

Fig. 7— Growth data for Arctic char sampled from a) Lough Coomasaharn, 23–24 April 2003; b) Muckross Lough, 3–5 September 2002.

unglaciated since *c*. 20,000 BP, showed that although the char had been feeding heavily on *Cyclops* sp. in late April, the prevalence and intensities of *Diphyllobothrium* sp. cysts were extremely low. Many of the plerocercoids were encrusted and dead, as is commonly seen in other zooplankton specialists such as certain taxa of *Coregonus*. This indicates that either the infection of the copepods as intermediate host is low, possibly due to low activity of diving birds (final host) or, alternatively, that the char population in Coomasaharn Lough may have developed a physiological resistance towards the pathogenic parasite. This particular char population was once identified as a unique char species, *Salvelinus fimbriatus*, on account of its high number of gillrakers. Both the prominent lower jaw and high gillraker number are two other characteristics of zooplankton specialists. In contrast, the coexisting brown trout population in Coomasaharn Lough demonstrated higher intensities of *Diphyllobothrium* sp., probably due to predation by trout on small char commencing when the former are at a young age.

Evidence for huge numbers of cestodan parasites (using *Cyclops* sp. as intermediate hosts) in Irish char is absent, providing further evidence of the absence of cannibalistic behaviour as illustrated by Hammar (1998a; 2000).

FISH COMMUNITIES IN IRISH CHAR LAKES

Indigenous fish species

Brown trout and the eel *Anguilla anguilla* are the most common native species found in Irish Arctic char lakes. Other species that commonly occur are Atlantic salmon and three-spined stickleback, *Gasterosteus aculeatus*. Arctic char are reported to have occurred in two lakes (Lough Erne and Lough Neagh) that contain pollan, *Coregonus autumnalis*. Both of these char populations are now extinct (Went 1945). In excess of 50% of Irish char lakes contain migratory salmonids. In lakes free from fish introductions, brown trout already commonly displace char from the more desirable littoral and benthic areas, and char become confined to the pelagic zone, especially when food is limited (Nilsson 1963; 1967; Hammar 1998b). Although little information is available on the trophic and the seasonal relationships between trout and char in Ireland, fishery surveys suggest that trout are usually more numerous in the littoral areas and char in the deeper water (NRFB 1994; Hagan 1995; O'Grady *et al*. 1996). Interaction between trout and char is discussed in more detail under diet. During a fish stock survey of Lough Mask in February 1996, char were found at the bottom in all depth zones (Igoe *et al*. 2001b). Fig. 11 illustrates that the greatest relative proportion of char in the catch was in the

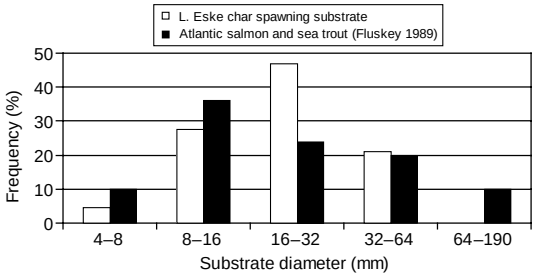

Fig. 8 — Size characteristics of spawning gravel from Lough Eske (measurements based on *y*-axis) by pebble count analysis (Wolman 1954). This is presented with similar data for sea trout and Atlantic salmon for Irish Rivers (Fluskey 1989).

sub-littoral area. Here the char had been feeding mostly on benthos (O'Grady *et al*. 1996). In early spring the benthos is very productive in this lake, and there is an abundance of chironomid larvae and crustaceans such as *Gammarus lacustris* and *Asellus aquaticus*. The trout and char were randomly mixed in many of the survey nets (F. Igoe, pers. obs.). Evidently, at least in the case of productive lakes such as Lough Mask, when food availability is high, niche boundaries between trout and char are probably more apt to break down. This situation is described from Swedish lakes (e.g. Nilsson 1965; 1967; Hammar 1998b).

There appears to be a strong association between piscivorous brown trout (or ferox trout) and Arctic char, which is its major prey. Both Campbell (1979) and Greer (1995) describe this relationship for Scottish lochs, and in Scandinavian lakes brown trout is treated as a principal predator controlling the size- and age-structure of Arctic char populations (e.g. Filipsson and Svärdson 1976; Aass 1984). In Ireland piscivorous trout are noted from numerous char lakes: e.g. Loughs Melvin (Ferguson 1995), Corrib, Mask, Nafooey (O'Grady *et al*. 1996), Talt (O'Neill, pers. comm.), Dan (Eastern Regional Fisheries Board 1984), and Veagh (Bowman 1991), Anascaul, Iskanamacteary, Coomasaharn and Glenawough (Igoe *et al*. 2001b; Kalcuka and Igoe 2004). Genetic analyses are required to determine if the latter populations are conspecific with the true ferox of Lough Melvin, as described by Ferguson and Taggart (1991). Ferguson (this volume) gives more detail on the ecology, taxonomic, and genetic status of ferox trout in Ireland.

The long-term influence of eel is unknown, although the high incidence of predation by eel on char in experimental gillnets suggest that they may also be a factor influencing char niche width (Hammar 1987).

Marginal Arctic char populations are generally sensitive to the presence of other fish species and have a tendency to be less dominant, where they coexist in Ireland. The occurrence of a lake in Ireland where Arctic char occur naturally in the absence of other salmonids and other fish species therefore would be of particular scientific interest. The ICCG carried out a recent survey (October 2003) of Lough Fad in County Donegal. The absence of any other fish species but char in the nets, and no evidence of eel activity strongly supports the local belief (O'Reilly 1998; John O'Kane, pers. comm.) that the lake only holds char (Igoe and Greer 2004). If confirmed, the recent findings in Lough Fad will be of particular interest from an ecological and evolutionary perspective, as it is unusual for char to be the only salmonid present in lakes along the southern margins of their distribution. Lough Gortglas and Lough Cloonsneacta in County Clare were reported to have been char-only lakes at one time also, but regrettably these populations are now appear to be extinct (Igoe *et al*. 2003).

Non-indigenous fish species

The additional stresses of competition and predation by non-indigenous fish species, when added to those already in place on account of the presence of native species, lead to a further reduction in the char niche, sometimes to a point leading to extinction of the char population (Hammar 1998a). In 2001 the ICCG circulated a questionnaire aimed at determining the ecological status and fish composition of loughs in which Arctic char are found to the seven Regional Fisheries Boards with national responsibility for inland fisheries management in Ireland. Each Regional Board was presented with a list of char lakes in their region and asked to provide information on the fish fauna for each lake. Many of the lakes had never been scientifically surveyed prior to this exercise, and the respondents had to rely mostly on angling information. Therefore lampreys (*Petromyzon marinus* and *Lampetra* spp) and small fish species such as sticklebacks (*Gasterosteus aculeatus* and *Pungitus pungitus*) that were unlikely to be encountered by anglers were omitted from the analysis. Six out of seven boards participated in the survey, and members of ICCG, being familiar with the lakes in the seventh region, filled in the outstanding form. The results of this questionnaire have been updated to include lakes where new discoveries of char populations have been made.

Data from lakes that had surviving char populations were compared with data from those where char had become extinct (Fig. 12). Lakes where the status of the char population was uncertain were omitted from the analysis. Non-indigenous 'angling species' recorded in the study were rudd (*Scardinius erythrophthalmus*), roach

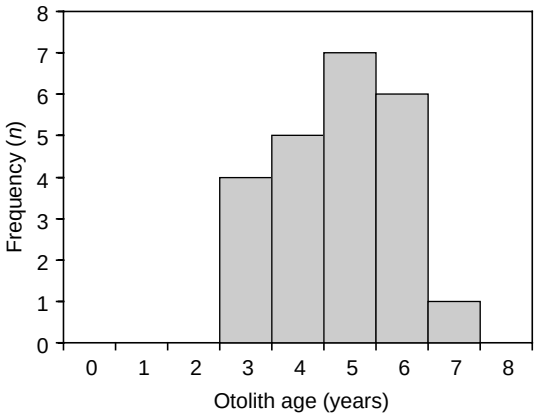

Fig. 9 — Age profile of an Irish char spawning population. Samples captured by angling in November 2000 on the shore of Lough Eske, Co. Donegal.

(*Rutilus rutilus*), pike (*Esox lucius*), perch (*Perca fluviatilus*), bream (*Abramus brama*) and tench (*Tinca tinca*), some of which have been associated with extinctions of char in other countries. The results of the questionnaire showed that a greater proportion of lakes that had lost their Arctic char populations contained one or more of these non-indigenous species compared to those that had surviving char populations (Chi square = 9.6, 1 df, $P < 0.05$). The non-indigenous species were present in 62% of lakes with former char populations ($n = 21$) compared to only 15% of lakes still believed to hold char ($n = 41$). In addition the maximum number of these non-indigenous fish species occurring in lakes with surviving char populations was three, whereas in lakes where char had disappeared the maximum number was six. This suggests that in lakes where char survive in the presence of a non-indigenous fish species, the risk of extinction increases with every subsequent introduction. These data clearly illustrate that introductions of non-indigenous fish species is undesirable in Irish char lakes.

Increasing levels of organic enrichment alter the chemical and ecological conditions of a lake in favour of cyprinids and other non-indigenous species. In addition, planktivorous fish such as roach have the capacity to graze zooplankton biomass to such an extent that the lake's ability to cycle nutrients is reduced, further exacerbating the eutrophication process. Non-indigenous predatory fish species such as pike can be highly detrimental to resident as well as migratory salmonids. Shallow lakes with limited refuge from predators would be most affected (Langeland 1995). A record exists for char in Castlebar Lough in County Mayo (Went 1945). Pike were introduced to the catchment sometime later (Maxwell 1843), and char are now no longer present in the lake. This lake is only 4m deep, and although water quality has declined in recent times, it is very likely that pike were probably the primary cause of their extinction.

Larger lakes, which are usually deeper and have more complex bathymetric profiles, offer more refugia for char from predators, and a number of larger Irish lakes hold populations of both pike and char. In these lakes predation on char probably occurs all year round, but principally occurs in the autumn and early winter months when char enter shallow water to spawn. Char have been reported from the stomach contents of pike in Lough Corrib, Lough Mask, Lough Nafooey and Lough Conn (Twomey 1960; Went 1971a; Magrane 1998; Igoe *et al*. 2001b). From the 1960s to 1980s an annual pike culling exercise was organised by the local fishery authority to intercept pike gathering in shallow water to feed on spawning char in Lough Conn. This autumnal migration of pike ceased in the 1990s, when the char became extinct (Igoe *et al*. 2001b).

Geographic distribution and current status of Irish char populations and current threats

Arctic char were once widespread in Ireland (Went 1945). Igoe *et al*. (2003) carried out a recent review of their distribution and identified 70 Irish lakes with records of native char populations (Fig. 13). Subsequently in 2003 further surveys by ICCG research teams have identified four new populations and anecdotal records have been put forward for at least one other population (M. Hennessy, pers. comm.), which gives a grand total of 75 separate lake populations. Table 6 gives summary data of the physical characteristics of lakes from which char have been identified. The surface areas of lakes from which char have been recorded range from very large (e.g. Lough Neagh, at 38,300ha) to small (e.g. Cornagall Lough, at 0.9ha). Altitude ranges from 250m (Lough Tay) to just 4m (Lough Currane). Regrettably these four populations are now probably extinct. Bathymetric data on Irish char lakes is limited, although maximum lake depths are available for some lakes ($n = 48$). These depths range from only 4m (Castlebar Lough) to 70m (Muckross Lough).

Since the 1830s, records indicate that the range of Arctic char in Ireland has slowly contracted (Went 1945). Extinctions of populations have occurred for a variety of reasons: Igoe *et al*. (2001) give further information on the causes of this decline. In the last few decades the decline has increased rapidly, and a few high profile extinctions (e.g. extinctions in Lough Conn and Lough Corrib) have caught the attention of the national media.

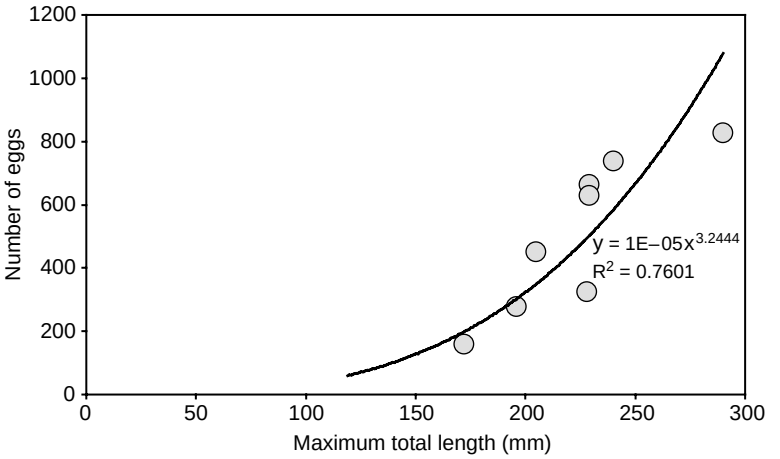

Fig. 10— Fecundity of female Arctic char taken in gill nets in Muckross Lake, Killarney, 3–5 September 2002.

Igoe *et al*. (2003) estimated that some 34% of Irish populations have become extinct, based on best available information. These authors advocate a complete survey of Irish char lakes to ascertain their true status. In the absence of a comprehensive survey, however, they felt that it was important to attempt to classify the status of the populations and get some perspective on the rate of extinction nationally. With the discovery of new lakes and improvements in our knowledge of the true status of char in lakes formerly lacking detailed survey data, this estimate is likely to change. Recent surveys by the ICCG in 2003 have identified four new char populations and showed that

Table 5— List of key parasite taxa recorded in some Irish char populations.

Genus/species	*Loughs*				
	Corrib[1]	*Eske*[2]	*Mask*[3]	*Muckross*	*Coomasaharn*
Discocotyle sagittata					
Crepidostomum farionis	+		+		
Sphaerostoma bramae			+		
Phyllodistomum conostomum	+			+	+
Phyllodistomum umblae		+	+		
Diplostomum sp.	+				
Diplostomum gasterostei		+	+		
Diplostomum spathaceum		+	+		
Tetracotyle sp.		+	+		
Diphyllobothrium spp	+			+	+
Diphyllobothrium dendriticum		+	+		
Diphyllobothrium ditremum		+	+		
Eubothrium salvelini	+	+	+	+	+
Proteocephalus sp.					+
Cystidicola farionis	+		+		
Unidentified sp.					+
Raphidascaris acus		+	+		
Acanthocephalus lucii	+		+		
Acanthocephalus clavula	+		+		
Pomphorynchus laevis	+		+		

[1] Conneely and McCarthy 1984.
[2] Doherty and McCarthy 2001.
[3] Doherty and McCarthy 2001.

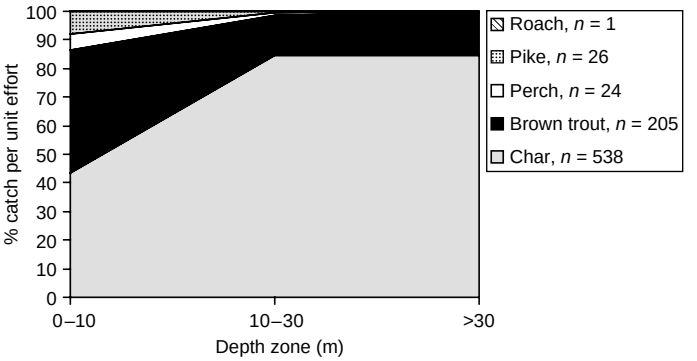

Fig. 11 — Vertical distributions of fish captured in benthic gill nets set in Lough Mask over a three week period (February/March) assigned to three depth zones. Modified from Igoe *et al*. (2001) and O'Grady (1996).

the populations of Arctic char in Lough Iskanamacteary, Co. Kerry, and Lough Keel, Co. Donegal, are not in fact extinct. However, these surveys also failed to locate populations in Lough Currane and Lough Anascaul, Co. Kerry, and Lough Easky, Co. Sligo, where char were still thought to be present.

Not surprisingly, the highest rate of extinction of char occurs in areas of greatest human influence. For example, all populations east of the River Shannon, in the Shannon catchment and in County Clare are now extinct. Other populations such as those in Lough Mask, Co. Mayo, and Lough Talt, Co. Sligo, also may be under pressure, have been the subject of concern. The recently discovered Arctic char populations occur in previously unsurveyed lakes with minimal anthropogenic disturbance.

Igoe *et al*. (2003) review the threats to Arctic char in Ireland but concede that more targeted research on issues affecting Arctic char needs to be carried out in this country. The main areas of concern are listed in Table 7. Eutrophication, introductions of non-indigenous fish species and lake acidification are probably the most widespread of these threats. The former two are of particular concern as they often act together, shifting lake ecology in a direction deleterious to char. Low altitude lakes in developed areas are most at risk from pollution and fish introductions, while higher altitude lakes in areas with an underlying rock matrix of poor pH-buffering capacity (e.g. granite) and naturally acidic soils types (e.g. peat) are most susceptible to acidification problems (Igoe and Kelly-Quinn 2002). Water abstraction for industrial and domestic usage may become a more serious problem in some lakes, by altering food webs and exposing spawning gravels. Exposure of extensive littoral areas to desiccation has been noted for Lough Kindrum, Lough Cloonsneacta and Lough Fad (Igoe *et al*. 2003; F. Igoe, pers. comm.). Mitigation measures are available to help alleviate some of these effects (e.g. Kircheis 1980) if alternative water supplies cannot be sourced.

The potential impact from fish farming is a major issue in Scotland (R. Greer, pers. comm.). In Ireland, although farming of char is limited, escapes have been noted from at least one farm (Igoe *et al*. 2003).

Arctic char are adapted to cold water conditions, and increases in summer temperatures due to climate change have been identified as a possible threat to the long-term survival of Arctic char in Ireland (Igoe *et al*. 2003). In Hammar's (1998a) study of Arctic char in the high Arctic, findings indicated that temperature affects parental traits of importance (e.g. the sexual maturity process, frequency of spawners and number and quality of eggs) for reproductive success, as well as selection for a variant allele influencing cold resistance.

Temperature is therefore obviously a factor to be considered in the context of the long-term survival of Arctic char in Ireland, but we argue that short-term climate change concerns associated with global warming may be overstated in the absence of other stressors (e.g. eutrophications and non-indigenous fish introductions). There is evidence to suggest that Ireland and western Europe experienced climatic changes consistent with Roman and medieval warm periods and Dark Ages and Little Ice Age cold periods (e.g. McDermott *et al*. 2001) and that it is likely that Ireland experienced summer temperatures within the range predicted for the next *c*. 50 years (Fraser Mitchell, pers. comm.). Although we are uncertain about conditions during the Little Ice Age (*c*. 1750s), it is likely that the majority of Irish char populations were lake resident, and therefore populations lost during warm periods were permanently lost without subsequent recolonisation from other populations. We argue, therefore, that predicted increased temperatures in the immediate future ($< 1^{\circ}$C mean summer) do not pose a direct threat to Arctic char survival in pristine Irish char

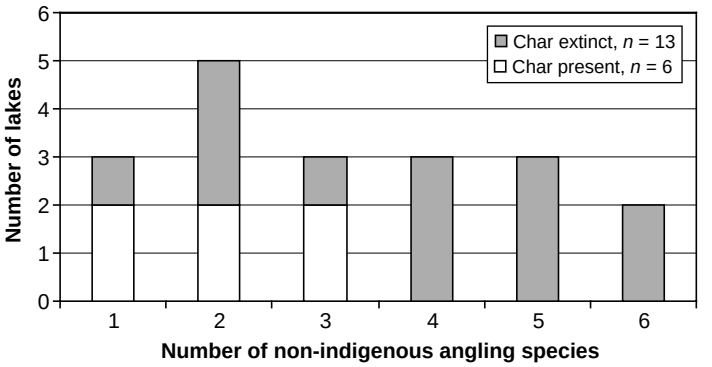

Fig. 12 — Illustration showing the association between increasing numbers non-indigenous angling fish species and extinction of char from Irish lakes.

lakes. Conversely increasing water temperatures due to climate change will certainly pose a threat to populations in lakes already experiencing anthropogenic pressures due to increased phosphorous loading or the presence of non-indigenous thermophilic fish species such as roach. Under these conditions the lakes' ecology will evolve in a direction not favourable to Arctic char survival. However, in a general context, the status of more remote populations in oligotrophic lakes may be secure, so long as water quality and the current fish assemblage can be maintained.

Current legislation relevant to protection of Arctic char in Ireland

Fitzsimons and Igoe (this volume) discuss the role of fisheries and other legislation in the protection and conservation of Ireland's freshwater fish fauna. They also emphasise that the existence of legislation in the absence of adequate resources to ensure its implementation will result in failure. Many would argue that the decline in water quality in Ireland over the last few decades is a case in point. Legislation with direct relevance is briefly discussed below. Fitzsimons and Igoe (this volume) give more detail, particularly with regard to maintenance of good water quality and planning issues.

Fish introductions

The introductions of non-indigenous fish species, such as roach, have had a negative impact on the native fish fauna and recreational game angling in Ireland (Fitzmaurice 1981). The use of live bait by anglers was identified as the primary vehicle responsible for the transfer of newly established non-indigenous species across catchments in Ireland. In 1977 a by-law was enacted which forbade live baiting. However enforcement of this issue is difficult, and the range of non-indigenous species such as roach, rudd and dace is still expanding. For example, roach were recently documented in Lough Mask (O'Grady *et al*. 1996) and more recently, roach × rudd hybrids were recorded for the first time in Lough Melvin in 2001 (M.F. O'Grady, pers. comm.). This lake has been described by Ferguson (1995) as having a unique fish community due to its distinct salmonid community, and the introduction of yet another cyprinid (roach) is thus a worrying development. As we discuss earlier, there is a strong association between these introductions and the disappearance of char in a number of our lakes, the most recent disappearance being the char of Lough Corrib, which coincided with the introduction of roach, although other factors may also be involved in the extinction of char from this lake (Igoe *et al*. 2001b).

1987 Fisheries Ammendment Act

Until the 1980s the only salmonids covered by the fisheries acts were salmon, sea trout and brown trout. In the Fisheries (amendment) (No.2) Act, 1987, the definition of trout was expanded to include Arctic char and rainbow trout (*Oncorhynchus mykiss*). Therefore any reference in the Irish fisheries acts referring to trout now also applies to Arctic char. This provides for the protection of char spawning grounds and the taking of juvenile char and designates a closed season. The relevance of the 1987 act is questionable as exploitation is not a threat to Arctic char survival in Ireland, although the act has some relevance with respect to road development adjacent to char lakes and water abstraction.

Water quality

Water quality deterioration has been identified as one of the main threats to Arctic char in Ireland (Igoe *et al*. 2003). Implementation of the phosphate regulations has been difficult and the results are not very encouraging: for example, in Lough Conn, improvements in urban sewage discharge are being offset by increased agricultural and septic tank runoff (M. McGarrigle, pers. comm.). Ratification of the European Water Framework Directive is

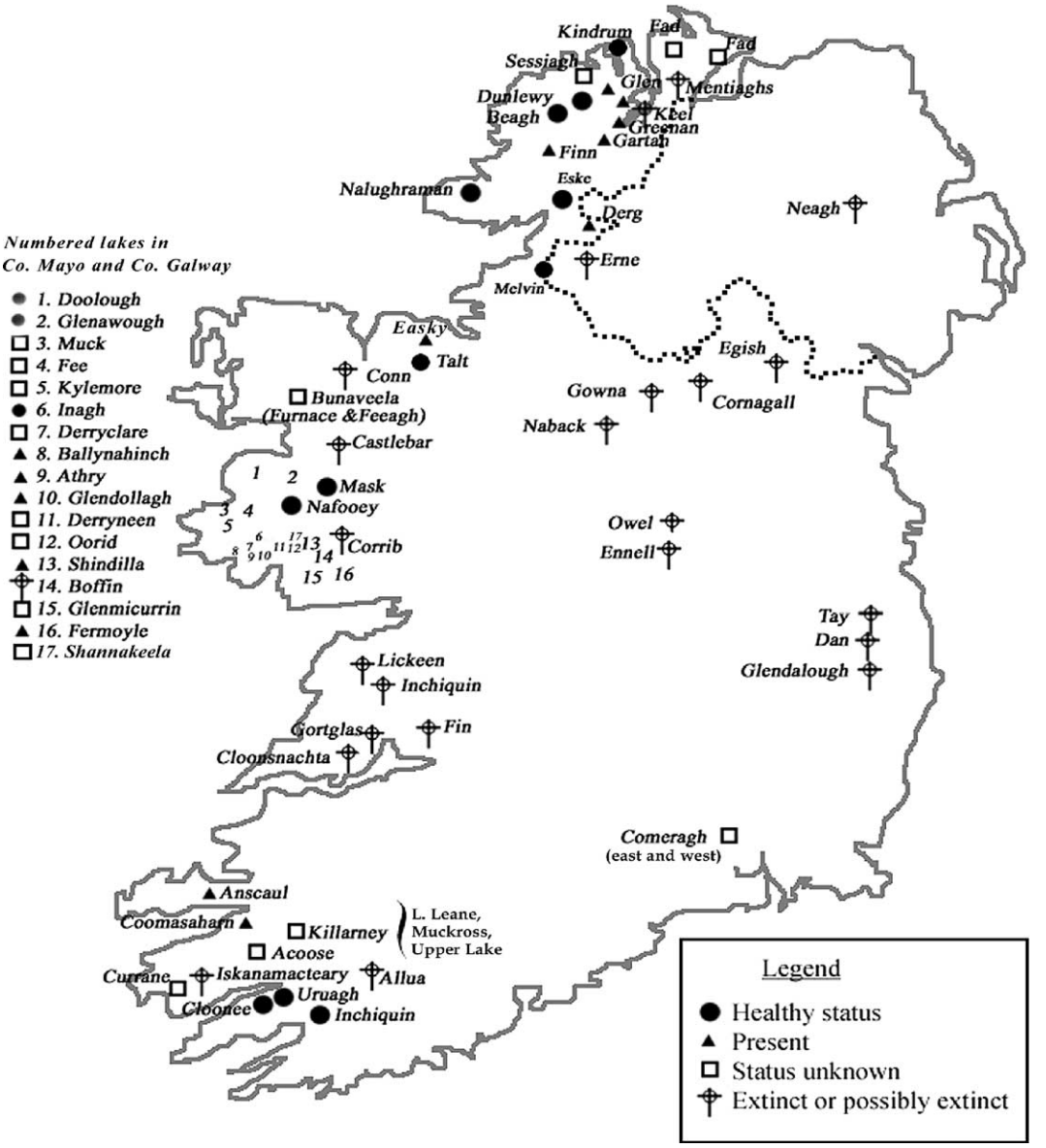

Fig. 13—Distribution and status of Arctic char populations in Ireland. Source Igoe *et al*. 2003. Four new Irish records discovered by the ICCG are not marked (Cloon Lough, Derriana Lough, Cloonloughlin and Lough Caragh in County Kerry).

viewed by many as the panacea to our water quality problems. Member states must define good ecological status and reference conditions for surface and ground water. However, unless sufficiently high standards are set and rigorously implemented, water quality will still continue to be a serious issue for Arctic char in many of our lakes.

Special areas of conservation and the Wildlife Act

Arctic char are not listed as a priority or Annex II species under the EU Habitat's Directive and are therefore not offered direct protection. However a number of lakes with Arctic char also contain either Annex I habitats or Annex II species. Special Area of Conservation designation in these cases should impart some protection to the resident char (C. O'Keeffe, pers. comm.). Arctic char and our other rare fish will remain outside of the amendment to the 1975 Wildlife Act (P. Buckley, pers. comm.).

CONSERVATION RECOMMENDATIONS

Nyman (1984) provides a useful list of management recommendations for char lakes in Sweden. We believe that it is appropriate to draw up a similar list specific to the conservation needs of Irish populations. Fishery managers and others tasked with the future conservation of Arctic char in Ireland may find the list helpful as guideline criteria.

Our guidelines are as follows:

- Control and limit phosphorous inputs from all sectors.
- Prevent the introduction of non-native fish or other organisms to lakes with Arctic char.
- Carry out a risk analysis prior to stocking out brown or rainbow trout into waters that contain char. Stocking of large fish should be avoided to prevent likely predation on native char.
- Limit activities that may increase acidification problems in poorly buffered Arctic char lakes (e.g. conifer plantations).
- Investigate impacts of water abstraction projects in Arctic char lakes and place remediation works where necessary.
- Improve awareness of Arctic char as an important element of native biodiversity among the general public and among policy makers in particular.
- Protect Arctic char spawning areas from silt and gravel abstraction or removal. Where lake impoundment is considered necessary in the public interest, ensure that remediation works to protect the char population are carried out.
- Ensure farmed char do not have access to waters containing native char.
- Regularly monitor the status of Arctic char populations and ecological conditions of their lakes.
- Promote research into the biology and ecology of Arctic char in Ireland and encourage exchange of information with the international scientific and fishery management community.

Table 6— Summary statistics of physical characteristics for Irish lakes, from which Arctic char have been recorded.

	Altitude (m)*	*Area (ha)*	*Max. depth (m)*
Mean	71.0	1138.3	30.6
Median	43.0	94.0	29.2
SD	61.5	4945.0	14.4
Min.	4.0	0.9	4.0
Max.	250	38300	70
n	75	75	48

*metres above sea level.
n = number of measurements available.

Table 7— Arrangement of main threats and their potential effects on Irish char populations in order of significance.

Threat	*Direct*	*Indirect*
Eutrophication	Deoxygenation, siltation of spawning gravels.	Favouring other fish species or altering invertebrate fauna
Fish introduction	Predation on or competition for food.	Altered lake ecology, e.g. excessive grazing on zooplankton leading to increased phytophankton levels. Possibility of disease.
Acidification	Toxic effect of low ph on char, and reduced reproductive success.	Alters ecological processes in the lake.
Climatic change	Increased water temperatures will affect char particularly in warmer months.	Indirect effects include favouring of other fish species such as cyprinids—increasing competition.
Heavy engineering	Depends on activity—may result in disturbance (e.g. siltation) of spawning areas reducing reproductive success	
Water abstraction	May reduce spawning areas available to char. Could also result in reducing refuge area (deeper cool water) for char in warm weather. Indirect—increase competition with other fish species.	Loss of littoral invertebrates causing compressed diet niche
Fish farming	Possible transfer of disease, enrichment of lake. Escapees of non-native fish will probably mate with natives possible altering the genetic integrity.	Introgression

FUTURE CONSIDERATIONS

Clearly, the conservation of our remaining char populations is important. Ireland's char populations have been more or less genetically isolated in their respective lakes since the last glacial period (13,000 to 18,000 years ago), and these lakes, therefore, contain some of the oldest genetic material for char in western Europe. Alexander and Adams (2000) examined the phenotypic variation of Arctic char from Irish and Scottish lakes and concluded that they vary to a high degree in coloration, pattern, and morphological characteristics. They hypothesised that variances in the morphological structures (such as size and shape of head) may be a function of diet; eye size, a function of depth of living; body size, a function of food availability and adaptation to foraging and predator avoidance. Colour and pattern may possibly be functional, diet-related or the result of the long period of isolation and consequential genetic drift. Ferguson (1981) highlighted Irish char as excellent models for the study of genetic changes in isolation. We therefore argue from genetic, ecological and evolutionary perspectives, that Irish char populations are of national and international scientific and heritage interest.

In addition to their high scientific interest, Arctic char, due to their sensitivity to environmental change in temperate regions, are also ideal models to monitor climate change. Due to their sensitivity to water pollution (both organic and chemical) they offer added value as excellent indicators of long-term water quality, and their presence is essentially a form of quality assurance.

Conservation of Arctic char will, however, require improved data sets to help in the development of a greater understanding of the mechanisms controlling char survival in Ireland. This information will be necessary to promote 'realistic' conservation measures necessary to protect Irish Arctic char and their habitats. Increased public awareness is an important aspect of this process to heighten awareness among policy and decision makers. The Irish Char Conservation Group, which was set up with this aim in the year 2000, has been successful in creating a public profile for the species. The group is now also in the active process of collecting new biological information. However, state agencies need to acknowledge that Arctic char and other members of our indigenous fish community are species requiring serious conservation attention. The traditional approach of many state agencies is to only recognise the commercial value of a fish species and to ignore species such as char, which are often perceived to be of no commercial value. This narrow focus must be replaced by a more modern approach, which recognises the intrinsic value of these species in a biodiversity context. In particular local authorities in Ireland need to take a more proactive approach with regard to the protection and maintenance of fish communities in public water supply areas, by adopting environmentally sustainable approaches that can allow for public use and protection of the these sensitive species. The presence of Arctic char in drinking water supplies ought to be viewed as beneficial as Arctic char require good water quality and therefore can act as a water quality assurance.

Igoe *et al*. (2003) emphasised the need to carry out a nationwide study of Irish char populations. Recent discoveries of new char populations, including what appears to be a char-only lake (Lough Fad), clearly illustrate that the task of identifying the true distribution and ecological diversity of Irish char lakes is only beginning. Examination of genetic material, cultural factors and likelihood of long-term survival probabilities must form an integral part of future conservation efforts. However, it may be necessary to prioritise populations with a view to conservation in the first instance. In the interim it is evident that serious steps must be made to ensure the survival of the char in a number of important Irish char lakes, e.g. those in Lough Mask (the last of the great western Irish lakes to hold char (Igoe *et al*. 2001)), Lough Coomasaharn (Co. Kerry), Lough Finn (Co. Donegal), Lough Melvin (Co. Leitrim and Co. Fermanagh), Muckross Lough (Co. Kerry) and Lough Eske (Co. Donegal), which still retain the prototypes of Regan's char 'species'.

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