FISH and FISHERIES

Worldwide status of burbot and conservation measures

Martin A Stapanian[1], Vaughn L Paragamian[2], Charles P Madenjian[3], James R Jackson[4], Jyrki Lappalainen[5], Matthew J Evenson[6] & Matthew D Neufeld[7]

[1]U. S. Geological Survey, Great Lakes Science Center, Lake Erie Biological Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA; [2]Idaho Department of Fish and Game, 2885 W. Kathleen Avenue, Coeur d'Alene, ID 83815, USA; [3]U.S. Geological Survey, Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI 48105, USA; [4]Department of Natural Resources, Cornell Biological Field Station, 900 Shackelton Point Road, Bridgeport, NY 13030, USA; [5]Department of Biological and Environmental Sciences, P.O. Box 65, University of Helsinki, Helsinki FIN-00014, Finland; [6]Alaska Department of Fish and Game, 1300 College Road, Fairbanks, AK 99701-1551, USA; [7]BC Ministry of Environment, #401-333 Victoria Street, Nelson, BC, Canada V1L 4K3

Abstract

Although burbot (*Lota lota* Gadidae) are widespread and abundant throughout much of their natural range, there are many populations that have been extirpated, endangered or are in serious decline. Due in part to the species' lack of popularity as a game and commercial fish, few regions consider burbot in management plans. We review the worldwide population status of burbot and synthesize reasons why some burbot populations are endangered or declining, some burbot populations have recovered and some burbot populations do not recover despite management measures. Burbot have been extirpated in much of Western Europe and the United Kingdom and are threatened or endangered in much of North America and Eurasia. Pollution and habitat change, particularly the effects of dams, appear to be the main causes for declines in riverine burbot populations. Pollution and the adverse effects of invasive species appear to be the main reasons for declines in lacustrine populations. Warmer water temperatures, due either to discharge from dams or climate change, have been noted in declining burbot populations at the southern extent of their range. Currently, fishing pressure does not appear to be limiting burbot populations world-wide. We suggest mitigation measures for burbot population recovery, particularly those impacted by dams and invasive species.

Keywords burbot *Lota lota*, dams, fishery management, invasive species, water quality, worldwide stock status

Correspondence:
Martin A Stapanian, U. S. Geological Survey, Great Lakes Science Center, Lake Erie Biological Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA
Tel.: 419 625 1976
Fax: 419 625 7164
E-mail: mstapanian@usgs.gov

Received 1 Apr 2009
Accepted 4 Aug 2009

Published 2009

DOI: 10.1111/j.1467-2979.2009.00340.x

Introduction

Burbot (*Lota lota*, Gadidae) is the only member of the cod family that lives exclusively in freshwater and it is one of only two freshwater fishes that have a circumpolar distribution, the other being northern pike (*Esox lucius*, Esocidae) (McPhail and Lindsey 1970). Burbot are thought to have evolved from a marine form of gadid that separated 10 million years ago from other forms of Lotinae. The oldest fossil burbot was found in Austria and was dated from the lower Pliocene (Cavender 1986). There is further evidence the genus inhabited freshwater as long as 5 million years ago (Pietschmann 1934; but see Van Houdt *et al.* 2003).

Burbot exhibit a wide, Holarctic distribution (Fig. 1). Phylogenetic studies of burbot confirmed two distinct forms worldwide (Hubbs and Shultz 1941). One form, *L. l. maculosa* (Le Sueur), occurs exclusively in North America, from south of Great Slave Lake, Canada to the southern limit of the species' distribution. The other form, *L. l. lota*, comprises the remainder of the Nearctic range and the entire Eurasian range. Van Houdt *et al.* (2003, 2006) found three mitochondrial DNA clades of *L. l. maculosa* (L.), which arose from allopatric separation in different Wisconsonian glacial refugia. Powell *et al.* (2008) found all three clades in the northwestern USA and southwestern Canada.

Burbot have retained many characteristics of their marine ancestors. For example, the species prefers cool and cold waters, has a high fecundity, and spawns at low temperatures and in large schools with random dispersal of gametes (McPhail and Paragamian 2000). Adult burbot are benthic predators and inhabit large cool rivers of the north temperate region and the hypolimnion of large lakes, preferring temperatures of *c.* 10–14 °C (Cooper and Fuller 1945; Hackney 1973; Hoffman and Fischer 2002). Burbot are thought to be ecologically intermediate in thermal preference between cold-water salmonids (*e.g.*, *Hucho hucho* and *Salmo trutta*, Salmonidae) and more thermophilic cyprinids (Nikčević *et al.* 2000) and can be classified as temperate mesotherms (Hokanson 1977). Burbot commonly spawn at temperatures ranging from 0 °C to <6 °C during winter (Becker 1983). The batch fecundity of burbot, like other cods (McPhail and Paragamian 2000), is enormous, ranging from 6300 eggs (Miller 1970) to more than 3.4 million eggs (Roach and Evenson 1993). Burbot spawn in large 'balls' with a few females at the centre surrounded by many males (Cahn 1936). Eggs and sperm are released as the ball moves through the water. The larvae are pelagic (Clady 1976; Jude *et al.*1979; O'Gorman 1983; Ghan 1990). These cod-like characteristics were likely instrumental in their widespread distribution and persistence over the past 5 million years or more. However, as discussed below, they may have become a liability to many burbot populations because their specialization has made the species vulnerable to natural and anthropogenic habitat disturbances.

Commercial fisheries for burbot in Eurasia occur in Russia, Finland, Sweden, Estonia and Lithuania. With few exceptions (Muth and Smith 1974; McCart 1986; Rudstam *et al.* 1995; Hayes *et al.* 2008; Whitmore *et al.* 2008), commercial harvest of burbot in most of North America is generally restricted to incidental catches during fishing for other species (Branion 1930; Hewson 1955). Burbot are benthic predators and in many systems may function as a top predator (McPhail and Paragamian 2000). There are recreational fisheries for burbot in several European countries, especially countries around the Baltic Sea (Tolonen and Lappalainen

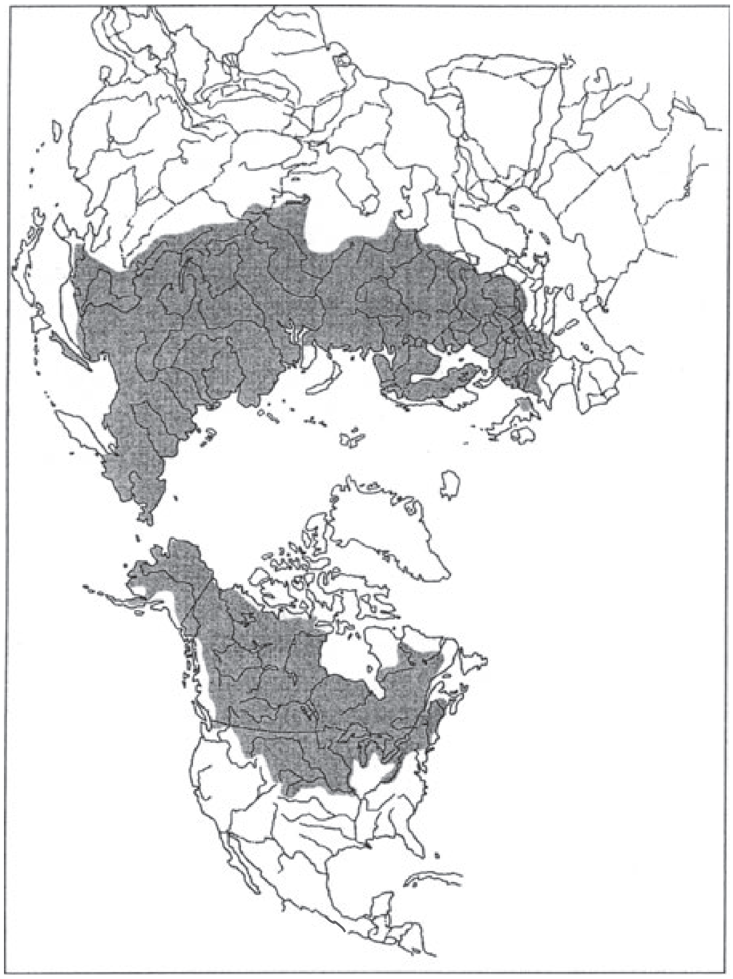

Figure 1 Original range of burbot (modified from Howes 1991 and adapted from McPhail and Paragamian 2000).

1999; Pihu and Turovski 2003; Johnsson *et al.* 2004). In parts of the USA and Canada, burbot have long been targeted by indigenous peoples and recreational anglers as food fish (Paragamian *et al.* 2000; Van Schubert and Newman 2000; Arndt 2001; Prince 2001, 2007; Ahrens and Korman 2002; Kootenai Valley Resource Initiative (KVRI) Burbot Committee 2005; Lheidli T'enneh First Nation 2007). However, in most of North America, burbot have not been as popular with recreational anglers as other predatory species of similar size (Quinn 2000). Although burbot meat is palatable (Branion 1930), low in fat and nutritious (Tack *et al.* 1947; Addis 1990; Stapanian *et al.* 2008 and references therein), burbot is not popular as a food fish in many parts of North America, due mainly to its appearance and slimy exterior texture (Cahn 1936; Hewson 1955; Lawler 1963; Bailey 1972; Muth and Smith 1974), problems with preservation and a lack of prepared products (Stapanian and Kakuda 2008 and references therein). The overall lack of commercial and sport interest in burbot has undoubtedly contributed to its being ignored or regarded as a 'trash' fish by some management agencies (Quinn 2000; but see Paragamian *et al.* 2000).

Burbot population dynamics are not well described and in many waters, they are not incorporated in assessment or management plans (Paragamian 2000b). Although burbot are abundant throughout much of their natural range (Muth and Smith 1974; Bruesewitz and Coble 1993; Evenson and Hansen 1991; Edsall *et al.* 1993), there are many populations that have been extirpated, endangered or are in serious decline (Maitland and Lyle 1990, 1996; Keith and Allardi 1996; Argent *et al.* 2000; Arndt and Hutchinson 2000; Paragamian *et al.* 2008). When burbot populations become threatened, remedial actions may not be implemented until after the population has become stock limited (Paragamian *et al.* 2008).

In this article, we survey the status of burbot populations from all over the world. We explore some of the reasons why burbot populations vary across their distribution and factors responsible for population change. We investigate reasons why some burbot populations are endangered or declining, some have recovered and some do not recover despite management measures. Finally, we synthesize those management practices that have resulted in successful rehabilitation and identify remedial actions for those populations. Our objective is to formulate a more global approach to restore a native predator in much of its range.

Circumpolar status and trends of burbot

Lota lota lota of Nearctic and Eurasia (Table 1)

Western Europe and the British Isles

Burbot are extirpated from the United Kingdom (UK), probably as a result of pressure on habitats (Pinnegar and Engelhard 2008). The species occurred in the Trent, Tame, Dove, Derwent, Nene, Great Ouse, Little Ouse, Cam, Thet, Waveney, Skeme, Esk and Foss rivers (Marlborough 1970; Pinnegar and Engelhard 2008). Burbot remains are found among archaeological excavations throughout the UK (Barrett *et al.* 2004). The last confirmed capture of burbot in the UK was on 14 September 1969 in the lower reaches of the Great Ouse River, and the species is listed in the UK's Biodiversity Action Plan (T. Worthington, University of Southampton, personal communication). Similarly, in Belgium burbot have been considered to be extirpated since 1970 and are subject to introduction programmes (Dillen *et al.* 2008; Vught *et al.* 2008). Burbot have been extirpated in parts of Germany, but specimens have been found in the Danube, Ruhr, Elbe, Oder, and Rhine rivers and in Lake Constance (Harsányi and Aschenbrenner 1992; Fladung *et al.* 2003; Dillen *et al.* 2005; Wolter 2007). Reintroduction programmes of burbot have begun in Germany and the UK (Harsányi and Aschenbrenner 1992; T. Worthington, University of Southampton, personal communication).

Burbot are endangered and protected in the Netherlands and their numbers are probably still declining (De Nie 1997). The species is extremely rare, but specimens have been reported in the

Table 1 Worldwide status of burbot (*Lota lota maculosa* in North America south of Great Slave Lake, Canada to the southern extreme of its range in North America; *L. l. lota* in Eurasia and the remainder of the species' Nearctic range).

Canada	
Alberta	Apparently secure
British Columbia	Apparently secure. Exception: Kootenay population
Labrador	Secure
Manitoba	Apparently secure
New Brunswick	Secure
Northwest Territories	Not ranked
Nunavut	Not ranked
Ontario	Secure
Québec	Secure
Saskatchewan	Apparently secure
Laurentian Great Lakes	Recovered or secure except for L. Ontario
Eurasia	
Austria	Vulnerable
Belgium	Presumed extirpated
Bulgaria	Imperilled
China	Not ranked/unknown
Czech Republic	Vulnerable
Denmark	Not ranked/unknown
Estonia	Declining
Finland	Declining
France	Vulnerable
Germany	Imperilled
Hungary	Vulnerable
Italy	Not ranked/unknown
Latvia	Secure
Lithuania	Secure
Mongolia	Not ranked/unknown
Netherlands	Imperilled
Norway	Not ranked/unknown
Poland	Vulnerable
Russia	Secure
Slovakia	Vulnerable
Slovenia	Vulnerable
Sweden	Declining
Switzerland	Secure
United Kingdom	Presumed extirpated
United States	
Alaska	Secure
Connecticut	Critically imperilled
Idaho	Imperilled
Illinois	Critically imperilled/imperilled
Indiana	Apparently secure
Iowa	Vulnerable
Kansas	Possibly extirpated
Kentucky	Under review
Maine	Apparently secure
Massachusetts	Critically imperilled
Michigan	Apparently secure
Minnesota	Apparently secure
Montana	Not ranked
Nebraska	Possibly extirpated

Table 1 (Continued).

New Hampshire	Secure
New York	Vulnerable
North Dakota	Not ranked
Ohio	Imperilled/vulnerable
Oregon	Not ranked
Pennsylvania	Critically imperilled/imperilled
South Dakota	Secure
Vermont	Vulnerable/apparently secure
Washington	Vulnerable
Wisconsin	Apparently secure
Wyoming	Vulnerable/apparently secure
Laurentian Great Lakes	Recovered or secure except for L. Ontario

Sources: NatureServe (2009) and this paper.

Biesbosch, Volkerak,/Krammer, and the Walloon rivers and lakes Ijsselmeer and Ketelmeer. In France and Austria the species is considered vulnerable, with populations reported in the Seine, Loire, Rhone, Meuse, and Moselle rivers and some high elevation lakes in France (Keith and Marion 2002; Dillen *et al.* 2005, 2008) and rivers and lakes in Austria (Dillen *et al.* 2005; Zick *et al.* 2006). Burbot occur in rivers and lakes in Switzerland and populations are presently considered not threatened (Kirchhofer *et al.* 2007).

Although burbot are native to the River Po and have been introduced elsewhere (*e.g.*, lakes Garda and Iseo) in Italy, the status in that country is not known (Bianco and Ketmaier 2001; Dillen *et al.* 2005; M. Milardi, University of Helsinki, personal communication). Declines in burbot are associated with pollution in some cases. For example, Lake Orta, in northwestern Italy, received effluent rich in copper and ammonium sulphate from a rayon factory during 1927–86. The lake's entire food web, including the burbot population, was destroyed (Bonacina 2001).

Northern Europe, Scandinavia and Baltic Countries

In general, the fish communities in northern Europe have shifted from clean- and cold water species such as vendace (*Coregonus albula*, Salmonidae), whitefish (*C. lavaretus*, Salmonidae) and burbot towards domination by warm water species such as pikeperch (*Sander lucioperca*, Percidae) and bream (*Abramis brama*, Cyprinidae) (Kangur *et al.* 2007). Although population declines have been recorded, burbot populations do not seem to be overall at risk in northern Europe (Anonymous 2002; Kullander 2002; Tammi *et al.* 2003). Burbot occur in the coastal waters of the Baltic Sea and inland rivers and lakes in this region. Burbot are common but probably declining in Finland (Anttila 1973; Rask *et al.* 1995; Pulliainen *et al.* 1999; Tammi *et al.* 1999; Anonymous 2008), Sweden (Herrmann *et al.* 1993; Olofsson *et al.* 1995) and Estonia (Pihu and Turovski 2003; Kangur *et al.* 2007).

Burbot occur in lakes and rivers, and in coastal waters of the Baltic Sea in Lithuania (Kesminas and Virbickas 2000; Balkuvienė *et al.* 2003; Repecka 2003), although there is some evidence that climate change is associated with the decline of burbot in some areas. In the Curonian lagoon, warmer winters have had negative effects on burbot reproduction (Švagždys 2002). The status of burbot in Denmark and Norway is unknown, but in both the countries, burbot inhabits rivers and lakes (Jensen 1988; Hesthagen *et al.* 1998; Følsvik and Brevik 1999; Tammi *et al.* 2003; Carl *et al.* 2007). There is some evidence that the species is threatened by pollution in parts of its range. Organotin compound levels in burbot muscle tissue showed an obvious trend, being higher in freshwaters situated in urban and rural areas in southern Norway than those in lakes in more isolated and remote areas in central and northern Norway (Følsvik and Brevik 1999). Similarly, elevated levels of polybrominated diphenyl ethers (PBDEs) were found in burbot from lakes Røgden and Mjøsa (Mariussen *et al.* 2008). There are recreational fisheries for burbot in Denmark and Norway.

In Finland, burbot populations have declined or have been extirpated in 16% of the lakes due to eutrophication (Anttila 1972; Tammi *et al.* 1999). For example, in Lake Hiidenvesi, which is the second largest lake (30.3 km^2) in southern Finland, few adult burbot occur in the least eutrophic basin (Olin and Ruuhijärvi 2005), but burbot larvae were found in four of the five lake basins (Kjellman *et al.* 2000). Farther north, to the Bothnian Bay, sterility in adult burbot was caused by effluents from pulp mills (Pulliainen *et al.* 1999). The River Kyrönjoki, emptying into the Northern Quark of the Gulf of Bothnia, is episodically acidified due to excavation and drainage of sulphuric soil layers in the catchment area. The diadromous burbot of the river currently reproduce in the estuary and the resident population of the river has vanished (Hudd *et al.* 1983; Urho *et al.* 1998). The decline in burbot catches in the area was due to the acidification-limited survival of burbot larvae (Kjellman 2003). In southern Finnish lakes, burbot larvae were found in lakes having pH between 5.6 and 7.1 (50% probability of occurrence), while no larvae were found below or above this range (Urho *et al.* 1998). In southern and central Finnish lakes, Rask *et al.* (1995) estimated that acidic precipitation was associated with the extinction of 180–380 burbot populations and negatively affected 110–220 more. However, in the northernmost Finnish Lapland, no clear effects of acidification on burbot and Eurasian minnow (*Phoxinus phoxinus*, Cyprinidae) were found in 13 rivers caused by the sulfur emissions from Russian Kola Peninsula (Erkinaro *et al.* 2001).

Pollution has undoubtedly contributed to declines in other burbot populations in Finland. For example, the sea area close to Helsinki has been one of the most polluted along the Finnish coast. Anttila (1973) reported that the local whitefish, burbot and northern pike populations had decreased or disappeared, while populations of many cyprinid species have increased. The water quality has improved since 1975 (Kauppila *et al.* 2005), but Lappalainen & Pesonen (2000) showed that the recovery in local fish communities has been very slow and that burbot have not returned to the area.

Winter drawdown (*c.* 1.7 m) of Lake Koitere in Finland had negative effects on burbot (Tarvainen *et al.* 2006). In two other Finnish reservoirs, burbot was the most abundant species for *c.* 10 years after filling (Koivisto *et al.* 2005). Since that time, the burbot stocks decreased and other fish species became more dominant; northern pike in Lake Kalajärvi and roach (*Rutilus rutilus*, Cyprinidae) in Lake Kyrkösjärvi. In eight regulated lakes the combined proportion of littoral fish species including young burbot was much lower than in five reference lakes (Sutela and Vehanen 2008). However, other variables such as nutrient level and lake size besides the winter drawdown may have affected the fish community simultaneously. Similar shifts in fish domination and the final decline of burbot have also been noted in several other reservoirs elsewhere (Mutenia 1985; Jensen 1988; Avakyan *et al.* 2002).

Similarly, acidification, pollution and invasive species are associated with declines in burbot populations in Sweden. Acidification has negatively affected burbot in rivers and lakes in Sweden (Herrmann *et al.* 1993; Olofsson *et al.* 1995; Norberg *et al.* 2008). Svärdson (1976) suggested that the decline in burbot catches in Lake Vättern during 1957–73 was associated with concentrations of polychlorinated biphenyls (PCBs). The decline in burbot was concurrent with an increase in the abundance of ruffe (*Gymnocephalus cernuus*, Percidae). Introduced signal crayfish (*Pacifastacus leniusculus*, Astracidae) have been suggested as negatively affecting burbot and other benthic fishes in Sweden (Josefsson and Andersson 2001 and references therein). Although damming of rivers has been shown to affect burbot populations elsewhere, burbot were observed both to ascend and descend through two human-made fishways in the River Emån in southern Sweden (Calles 2005).

Eastern Europe

Burbot populations in Poland are vulnerable due to damming and pollution (Brylinska *et al.* 2002; Penczak and Kruk 2005; Kruk 2007a,b). In the Warta River, damming affected negatively burbot both in tail- and backwaters (Penczak and Kruk 2005). Burbot and wels (*Silurus glanis*, Siluridae) are becoming extirpated as a result of impoundment and accompanying effects. The high variation in flow and increased poaching when the river bed is uncovered can lead to local extinction (Kruk and Penczak 2003). Rheophilic burbot, stone loach (*Barbatula barbatula*, Balitoridae), gudgeon (*Gobio gobio*, Cyprinidae), chub (*Squalius cephalus*, Cyprinidae) and dace (*Leuciscus leuciscus*, Cyprinidae) are most abundant in the upper section of the river. These species are nearly absent in the middle section, which is the most polluted, and occur in comparatively low numbers in the downstream section, which is moderately disturbed (Kruk 2007a). The main reasons for the recorded declines in fish biomasses were water pollution and impoundment of the river (Kruk 2004).

Burbot populations in Slovakia occur in the River Danube (Copp *et al.* 1994). Due mainly to pollution and damming, these populations are also vulnerable (Holcik 2003). In the Czech Republic, burbot populations occur in the rivers Morava and Ohre (Slavík and Bartoš 2002; Lusk *et al.* 2004; Jurajda *et al.* 2006). Although these populations are vulnerable to the effects of damming and pollution, the constructions of fishways have had positive effects on burbot in the Czech Republic (Slavík and Bartoš 2002). The decline of burbot in Slovenia is thought to be caused by river regulation, in combination with pollution (Veenvliet 2000; Šlejkovec *et al.* 2004). Burbot occur in the River Drava, Lake Cerknica, Rak Creek and the lower reach of Cerkniščica Creek. Fishing for burbot is prohibited in Slovenia. Burbot are rare or endangered in Bulgaria (River Danube: Vassilev and Pehlivanov

2005) and vulnerable in Hungary (Biró *et al.* 2003; Anonymous 2005).

Russia, Mongolia and China

Burbot are common in much of the species' range in Russia but populations have declined or have been extirpated in some places due to damming, eutrophication, competition from invasive species and pollution (Zhadin and Gerd 1963; Kirillov 1988; Volodin 1994; Chereshnev 1996; Reshetnikov *et al.* 1997; Zhulidova *et al.* 2002; Allen-Gil *et al.* 2003; Andrianova *et al.* 2006; Kotegov 2007). Known burbot populations occur in the rivers Kolyma, Anadyr and Penzhina and rivers near Novosibirsk in Siberia; rivers on Sakhalin and the Shantar Islands; and in Lake Baikal. Burbot were extirpated from Lake Gusinoe as a result of eutrophication and the occurrence of invasive species that occupied the same trophic niche as burbot (Pisarsky *et al.* 2005). Similarly, burbot populations have either declined or disappeared from some Russian reservoirs (Avakyan *et al.* 2002; Andrianova *et al.* 2006). For example, in the Sheksninskii Pool of Rybinskoe Reservoir, emergency dumping of sewage effluent reduced the reproduction potential of burbot by about half (Volodin 1994). By contrast, despite a considerable technogenic load to Lake Kostomuksha, pike, roach, bleak (*Alburnus alburnus*, Cyprinidae) and burbot have survived in the lake (Sidorov *et al.* 2003).

The status of burbot is unknown in Mongolia and China. Populations in Mongolia have been recorded in Buir Lake and the Khalkhin River in the Amur drainage, the Selenge and Orkhon river basins, and in Hövsgöl, Ugii, Terhiyn Tsagaan lakes (Dulmaa 1999; Ocock *et al.* 2006). In western China, burbot occurs in Erqishi River system, where it is commercially fished. Besides this river system, burbot occurs also in Lake Ulungur (Walker and Yang 1999).

Alaska and north of Great Slave Lake, Canada

Burbot are endemic to most watersheds in Alaska and to many of the arctic drainages of Canada, although specific information on distribution is lacking for many areas. Fluvial populations have been documented in large glacial systems in Alaska, such as the Yukon (Evenson 1993), Kuskokwim (Andrews and Peterson 1983), Susitna (Sundet and Wenger 1984) and Copper rivers (Schwanke and Bernard 2005) as well as in many clear, run-off rivers draining into the Arctic Ocean (Bendock 1979). Lacustrine populations have also been documented throughout northern, central and south central Alaska (Bendock 1979; Lafferty *et al.* 1991). In northern Canada, burbot populations are distributed in suitable habitats in the continental portions of the Northwest and Yukon Territories exclusive of most northern portions and are thought to be absent from the Canadian Archipelago (Scott and Crossman 1973). Fluvial populations along the Canadian Arctic coast have been documented from the Mackenzie River east as far as the Coppermine River. Burbot from these populations and from arctic coastal populations in Alaska are known to enter the brackish waters of the Arctic Ocean (Walters 1955).

Overall, habitats supporting burbot populations in this region are unperturbed and healthy and burbot are widely distributed and abundant. In addition, many of the lake and river systems are remote and receive little fishing pressure. Therefore, few populations have been impacted to a level leading to substantial population declines.

However, in Alaska, there have been a number of road-accessible lacustrine populations impacted by sport fisheries that have led to substantial reductions in abundance. Harvest of burbot increased, on average, *c.* 30% annually from 1977 to 1983, coinciding with an increase in human population following construction of the Trans Alaska Pipeline. Statewide sport harvests peaked in 1985 exceeding 27 000 burbot, but recent harvests have typically been <10 000 (Howe *et al.* 1995; Jennings *et al.* 2007). The majority of this harvest was taken from numerous small-to-moderate-sized lakes throughout central and south central Alaska and from the Tanana River. Stock assessments of lacrustine populations in the mid-1980s (Bernard *et al.* 1993) led to estimates of sustainable yield for many of the lakes that were either being, or likely would be, exceeded with existing regulations (Parker *et al.* 1989). Consequently, more restrictive regulations were adopted for many of the lakes that reduced the daily creel limit. In addition, baited set-lines were prohibited as a legal method of sport fishing for most lakes in central Alaska. These restrictive regulations were effective at maintaining yields at sustainable levels. Concurrent with the assessments of Alaskan lakes, an assessment programme for fluvial populations of burbot indicated that the river populations were very large compared to harvest and that seasonal movements of mature burbot mitigated the impacts of fisheries that were concentrated spatially and temporally (Evenson 1993, 2000). Therefore,

Published 2009

the restrictive regulations put in place for the lake populations were not enacted for the river populations.

Lota lota maculosa of North America south of Great Slave Lake, Canada (Table 1)

Western Canada south of Great Slave Lake

Burbot are endemic to western Canada, typically east of the coastal range (McPhail and Lindsey 1970; Scott and Crossman 1973, 1998). In British Columbia (BC), burbot are common in most of the large drainages; typically flowing southwest to the Pacific Ocean and North to the Arctic Ocean (McPhail and Carveth 1993; Nelson and Paetz 1992). There are a few records of burbot from the lower Fraser River west of the coast range. However, these burbot are thought to have emigrated from east of the coast range and the population has never established at a self-sustaining level (McPhail and Carveth 1993). In Alberta, Saskatchewan and Manitoba burbot are also common in most of the large drainages that flow north to the Arctic Ocean, east to Hudson Bay and southwest to the Atlantic Ocean. Burbot in these drainages are more common in large, deep lakes as well as many of the larger river systems (Nelson and Paetz 1992). Although burbot are common in many of the Rocky Mountain foothill streams, they are rare in the Rockies (Nelson and Paetz 1992).

It is unlikely that the overall range of burbot in western Canada has changed significantly in the last century (McPhail 1997; McPhail and Paragamian 2000; Van Schubert and Newman 2000; Spence and Neufeld 2002; Reddecopp *et al.* 2003; Lheidli T'enneh First Nation 2007; Prince 2007). Although some populations appear to be stable (Arndt and Baxter 2006), little is known about the status of most populations and many of those that have been evaluated show evidence of declines (Paragamian *et al.* 2000; Prince 2001, 2007; Ahrens and Korman 2002; Bisset and Cope 2002). Recreational interest is strong in most of BC today (Lheidli T'enneh First Nation 2007; British Columbia (BC) Ministry of Environment 2008; Prince and Cope 2008). However, in Alberta and Saskatchewan, most captures are incidental in the recreational pursuit of other sport fish. (K. Bodden, Alberta Minstry of Sustainable Resource Development [AMSRD], personal communication; M. Cope and T. Johnston, Saskatchewan Ministry of Environment, personal communication. Sport fishing regulations in Alberta contain an exemption for wastage of burbot, in which anglers are not legally required to retain harvested burbot for consumption (Alberta Sustainable Resource Development 2008). These incidental catches of burbot in Alberta waters can exceed 25 000 kg year^{-1}. In Manitoba, burbot were removed from some lakes as part of a 'rough fish' removal programme (Anonymous 1964).

Populations in BC, Alberta, Saskatchewan and Manitoba are thought to be generally secure, but have not been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The only exception is the Kootenay Lake and River population in BC, which has been Red Listed (S1) by BC's Conservation Data Centre (BC CDC). However, this assessment, should be interpreted with caution. The combined effects of low regard for burbot as a sport fish in many regions (Ford *et al.* 1995), a lack of standardized methods for completing population assessments (Bernard *et al.* 1993; Paragamian 2000a; Prince 2007; Neufeld 2008), and decompression-related mortality when retrieving burbot from depth (Gitschlag 1986; Bruesewitz and Coble 1993; Neufeld and Spence 2004) have resulted in few stock assessments targeting burbot. This lack of trend information for many burbot stocks has left some populations vulnerable to overfishing (Prince 2007, Prince 2008; K. Bodden, AMSRD, personal communication). In addition, burbot are even more susceptible to overfishing because much of the angling effort typically occurs over spawning or feeding congregations (Martin 1976; Ahrens and Korman 2002; Prince 2008).

Remedial actions for overfishing have typically included closure of the fishery, either entirely or for the spawning period when burbot are most vulnerable, or reductions in the daily harvest quota (Martin 1976; Prince 2007; Prince 2008; B. Jantz, C. Spence, and C. Williamson, BC Ministry of Environment, personal communication;. Although there are many examples of these remedial techniques in both BC and Alberta (Alberta Sustainable Resource Development 2008; British Columbia (BC) Ministry of Environment 2008; K. Bodden, AMSRD, personal communication), little targeted monitoring has been performed to assess the response. In Alberta, many of the fisheries that have been impacted by harvest have not seen a major resurgence in angler numbers typically seen when other species recover.

Dams may have had a negative effect on burbot populations in the region. Although some reservoirs in southern BC appear to have healthy burbot populations (Arndt and Baxter 2006), winter drawdown for power production and flood control has been hypothesized as a significant risk factor to burbot reproductive success (BC Hydro 2005a,b). In particular, burbot eggs deposited from shoal spawning events may become dewatered during spring drawdown, resulting in high egg mortality. On Duncan Reservoir in BC, Spence & Neufeld (2002) found that 17% of tagged adult burbot were entrained in the space of 5 months and remained alive after entrainment. No fish passage upstream exists for burbot at Duncan Dam. Although the population trend has not been established, densities in Duncan reservoir are much lower than nearby reservoirs (Arndt and Baxter 2006; Neufeld 2006). The lower population density in Duncan Reservoir may be associated with its drawdown regime.

The burbot population in Kootenay Lake, BC collapsed starting in the early 1970s and studies since 1998 indicate that few, if any, adult burbot remain today (Spence 1999; Neufeld 2005). Modelling results suggest recruitment failure was the most likely cause of collapse and angling pressure resulted in removing the remaining adults. Recruitment failure was most highly associated with decreases in mean summer density of copepods, which are thought to be an important food item for larval burbot (Ryder and Pesendorfer 1992; Hardy *et al.* 2008). Although alternate hypotheses have been proposed, it is likely that decreases in copepod density are linked to increases in introduced mysis shrimp (*Mysis relicta*, Mysidae), which are copepod predators and competitors, in combination with reductions in lake productivity after construction of upstream dams (Duncan and Libby Dams: Zyblut 1967; Northcote 1972; Binsted and Ashley 2006). Remediation for the decrease in copepods has included adding nutrients to Kootenay Lake as part of a larger ecosystem rehabilitation project (Ashley *et al.* 1999; Schindler *et al.* 2007). This lake fertilization project has resulted in increased copepod densities close to levels at the time of historic recruitment. Although suitable conditions for larval survival may now exist, few adult burbot remain in this population today (Spence 1999; Neufeld 2005) and there is little chance it will recover on its own.

USA Pacific Northwest to the Great Lakes States

Burbot are endemic to the northern tier of states of the Pacific Northwest east to the Laurentian Great Lakes bounding the border with Canada, ranging as far south as Kansas, Iowa, Nebraska and Wyoming (McPhail and Lindsey 1970). This area includes the upper Mississippi, Missouri, Saskatchewan and Columbia River systems. They are also found in large deep lakes and reservoirs (Brown 1971; Wydoski and Whitney 2003; Hubert *et al.* 2008). The southern extent of their range is limited to below Gavins Point Dam in Nebraska (Bouc 1987). Burbot are also uncommon in Iowa but found in border rivers (Harlan *et al.* 1987) and in Kansas, there are only a few records from the Missouri and Kansas rivers (Cross 1967). To the north, burbot are endemic to the Missouri River and its tributaries in North and South Dakota, Montana and to the upper Columbia of Washington (Wydoski and Whitney 2003).

In Washington, there were no regulations to manage burbot until 1998. The species is generally not a popular gamefish and there is no evidence of overharvest (Bonar *et al.* 1997). Burbot are seldom found in Oregon and the species is not included in Oregon's fishing regulations.

In Idaho, burbot are found only in the Kootenai River of the upper Columbia (Simpson and Wallace 1982). Prior to the construction of Libby Dam in 1972, the annual harvest of burbot from the Kootenai River by sport anglers, particularly during winter setline fishing, and commercial fishers in Idaho may have been in the tens of thousands of kg (Paragamian *et al.* 2000). Three commercial fishers alone harvested an estimated 2150 kg in 1958 (Idaho Department of Fish and Game [IDFG] Regional Archives, unpublished data). During 1979–82, the estimated burbot harvest declined to <250 fish per year (Partridge 1983). Burbot regulations in Idaho were not restrictive until 1983, when a two-fish limit was adopted. This limit was followed until 1992 when the fishery was closed because the burbot population was nearing collapse (Paragamian *et al.* 2000). The burbot population in the Kootenai River continued to diminish despite closure of the fishery (Paragamian 2000a). The primary reasons for the loss of burbot recruitment in the Kootenai River are likely the increased winter temperatures and discharge from the dam (Paragamian 2000a; Paragamian *et al.* 2005), which are in part responsible for disruption or delay in burbot spawning migration and spawning synchrony (Paragamian and Wakkinen 2008). Winter discharges in the Kootenai River are now three to four times that of pre-Libby Dam conditions and water temperatures post-Libby Dam are warmer by up to 4 °C (Partridge 1983). In Montana, Skaar *et al.* (1996) reported entrainment of fishes through Libby Dam, where burbot were the second most abundant species through the turbines.

In Wyoming, burbot are generally limited to the cooler water of high elevation lakes and rivers including the Wind/Bighorn watershed, Boysen Reservoir, the main stem of the Wind River and several natural lakes and tributaries (Hubert *et al.* 2008). Burbot have been extirpated from the Tongue River in Wyoming as a result of construction of the Tongue River Reservoir in Montana and past pollution (Eiserman 1964). Hubert *et al.* (2008) believed that the low densities of burbot in Wyoming were due to the cumulative effects of exploitation and entrainment to canals. Emigration of burbot from reservoirs and fluvial portions of some watersheds in Wyoming is due to water diversion structures and canals and thought to be limiting stock numbers (Hubert *et al.* 2008). Hubert *et al.* (2008) also indicated that large numbers of burbot emigrate annually from natural lakes that have been modified for water storage by construction of dams. Hubert *et al.* (2008) also cited the diversion of water during the irrigation season between the Wind River Diversion Dam and the mouth of the Little Wind River and in Bull Lake Creek as major factors of burbot mortality. Most burbot in Wyoming are believed to die at the end of the irrigation season. Extreme winter drawdowns of Bull Lake, Wyoming were implicated as a source for failed reproduction by exposing sand and gravel habitat leaving only silt habitat for burbot spawning (Bergersen *et al.* 1993). Concerns about burbot populations due to increasing angler exploitation and overharvest of stocks led the Wyoming Game and Fish Department to implement more restrictive regulations during the late 1940s through the 1960s, such as shorter fishing seasons, lower creels limits, restrictions on minimum length and a closure of the special winter fisheries on lakes where burbot spawn (Krueger and Hubert 1997).

Burbot decreased in the angler creel and electrofishing surveys during 1998–2007 in North Dakota, below Garrison Dam on the Missouri River (P. Bailey, North Dakota Game and Fish Department, personal communication), but the reason for the decline is not known. However, burbot numbers in the creel were apparently higher in the late 1990s during higher water and an abundant smelt entrainment. Anglers fish for post-spawning burbot as they enter tributaries of the Missouri River in North Dakota (Quinn 2000) and burbot remain vulnerable to exploitation. By contrast, burbot are not popular in South Dakota and there are no regulations to manage them, although they are common in lakes Oahe and Sharpe (Quinn 2000). In Nebraska, Hesse (1993) recommended that burbot be protected and fishing closed because they were found to be vulnerable to angler harvest during the spawning season. In Iowa and Kansas, burbot are of little consequence in the fisheries. The species is uncommon in these states, likely due to upper water temperature limits (Harlan *et al.* 1987).

Great Lake States of USA

Burbot are found in hundreds of inland lakes and streams throughout Minnesota (P. Jacobson, Minnesota Department of Natural Resources [MNDNR]), personal communication). Although fish communities in Minnesota inland lakes are assessed using standard gillnet surveys, burbot catch is so infrequent that temporal trends are difficult to discern in most lakes. However, for Mille Lacs Lake, the survey data clearly showed a greater-than-80% decrease in burbot abundance during 1979–2007 (T. Jones, MNDNR, personal communication). The trend toward warmer water temperatures beginning in 1980 is suspected of causing this decline in burbot abundance in Mille Lacs Lake (T. Jones and P. Jacobson, MNDNR, personal communications). On the basis of the reports by anglers, burbot abundance in Lake of the Woods has substantially declined over the last 20 years (D. Topp, MNDNR, personal communication). Reasons for this decrease are unclear.

Burbot are widespread throughout the inland waters of northern Wisconsin, where they occur in hundreds of lakes and streams (J. Lyons, Wisconsin Department of Natural Resources [WIDNR], personal communication). By contrast, burbot are generally rare in the southern inland waters of Wisconsin. As burbot are not regularly caught by WIDNR biologists during their standard assessment surveys of inland waters, reliable information on temporal trends in burbot abundance from these standard surveys is not available (J. Lyons, WIDNR, personal communication). Burbot are regularly seen beneath the ice by winter anglers on Lake Winnebago. By the early 1960s, a programme to remove 'rough fish' from Lake Winnebago had begun (M. Schrage, WIDNR, personal communication). Fyke nets were set under the ice to catch these rough fish. The removal programme targeted freshwater drum (*Aplodinotus grunniens*, Sciaenidae);

however, burbot represented a substantial portion of the fyke-net catch. The removal programme was terminated in the early 1980s. Commercial harvest of burbot from Lake Winnebago plummeted between the early 1960s and the early 1980s and this decrease was attributable to the rough fish removal programme (M. Schrage, WIDNR, personal communication). According to the results of special surveys targeting burbot in the early 2000s, the burbot population in Lake Winnebago has fully recovered from the effects of the rough fish removal programme.

Burbot are found in inland waters of both the Lower Peninsula and Upper Peninsula of Michigan (L. Wang, Michigan Department of Natural Resources, personal communication). Just as in Wisconsin and Minnesota, no special regulations are imposed on anglers fishing for burbot. Also, the status of burbot in the inland waters of Michigan remains unknown because burbot are not effectively sampled by the regular fish surveys.

Laurentian Great Lakes

Burbot occur in all of the Great Lakes, but in Lake Erie the species is restricted to the colder and deeper eastern portion of the lake (Scott and Crossman 1973; Trautman 1981). Burbot populations collapsed in four of the five Laurentian Great Lakes between 1930 and the early 1960s (Stapanian *et al.* 2008). Collapses in Lakes Michigan, Huron and Ontario were associated with sea lamprey (*Petromyzon marinus*, Petromyzontidae) predation, whereas the collapse in Lake Erie was likely due to a combination of over-exploitation, decreased water quality and habitat degradation. Burbot population density in Lake Superior has remained relatively low and stable since 1978.

Since the decline of burbot, many changes occurred in the Great Lakes, including reductions in sea lamprey through control efforts, reductions in alewives, stocking native and non-native salmonines, and controls on commercial fishing. Perhaps the most important management effort, in terms of its influence on the fishery of the Great Lakes, has been sea lamprey control (Smith and Tibbles 1980). Sea lamprey abundance has been dramatically reduced in all five of the Great Lakes as a result of control efforts.

Alewife (*Alosa pseudoharengus*, Clupeidae) predation has been implicated in the decline of certain Great Lakes fish stocks, mainly by preying on their pelagic fry (Smith 1970; Brandt *et al.* 1987; Eck and Wells 1987; Brown *et al.* 1987; Luecke *et al.* 1990; O'Gorman and Stewart 1999). Eshenroder & Burnham-Curtis (1999) concluded that when alewives are abundant in the Great Lakes, they inhibit the natural succession of native species in the Great Lakes.

Intensive salmonine stocking in the 1960s and 1970s and the subsequent predation led to reductions in alewife abundances in Lakes Michigan, Huron and Ontario (Madenjian *et al.* 2002; Madenjian *et al.* 2005a,b; Mills *et al.* 2003; Dobiesz *et al.* 2005). However, alewife abundance in Lake Ontario has remained considerably higher than alewife abundances in Lakes Michigan and Huron (O'Gorman and Stewart 1999; Madenjian *et al.* 2003). Alewife abundance in Lake Erie has remained low, owing mainly to the species' intolerance to the adverse water temperature regimes that exist under typical winter conditions in Lake Erie (Ryan *et al.* 1999).

Recovery of burbot populations occurred in Lakes Michigan and Huron during the 1980s and in Lake Erie during the 1990s (Stapanian *et al.* 2006, 2008). Control of sea lampreys was a requirement for recovery of burbot populations in these three lakes. Declines in alewife abundance appeared to be a second requirement for burbot recovery in Lakes Michigan and Huron (Stapanian *et al.* 2008). High populations of adult lake trout (*Salvelinus namaycush*, Salmonidae) in the Great Lakes have been shown to serve as a buffer species against sea lamprey predation and thus contribute to the recovery of other native species, including burbot in Lakes Huron and Erie (Swink and Fredericks 2000; Stapanian and Madenjian 2007) and lake whitefish (*Coregonus clupeaformis*, Coregonidae) (Madenjian *et al.* 2002). This buffering effect facilitated recovery of the burbot populations in Lakes Huron and Erie (Stapanian *et al.* 2008). Although sea lampreys have been controlled in Lake Ontario, alewives are probably still too abundant to permit burbot recovery (Stapanian *et al.* 2008).

USA east and south of the Laurentian Great Lakes

Burbot are endemic to the northern tier of states in the eastern USA bordering Canada west to the Great Lakes, and occur in isolated populations or appear in historic records from several other states as far south as Maryland and Kentucky. Although this region supports burbot populations in multiple waters, burbot are rarely included in agency assessments and status and abundance trends of populations or changes in distribution patterns are largely unknown. As in much of their range in North America, burbot are generally not highly valued by anglers in this region. However, some exceptions occur, in several waters in Maine (Roy 2001) and New Hampshire (Quinn 2000).

In the northernmost states of the region, burbot typically occur in large, deep lakes and associated tributaries, but their distribution further south is primarily associated with large river systems (Whitworth *et al.* 1968; Cooper 1983; Halliwell *et al.* 2001; Hartel *et al.* 2002). In Maine, burbot are widely distributed in lakes and ponds, particularly in the northern regions of the state, and are also found in the headwaters of the Kennebec, Penobscot and St. John Rivers (Roy 2001). Burbot are also widely distributed in the colder lakes of New Hampshire, primarily in the central and northern regions of the state, and have been reported from all of the state's major watersheds, with riverine populations most prevalent in the northern part of the state (Scarola 1973; New Hampshire Fish and Game Department (NHFGD) 2005). In Vermont, burbot are most common in rivers and streams in the northern part of the state, but also occur in some lakes of that region as well as tributaries to Lake Champlain and the Connecticut River (Langdon *et al.* 2006). Burbot in the Connecticut River extend south into Massachusetts and Connecticut, where they are considered rare (Whitworth *et al.* 1968; Hartel *et al.* 2002). Burbot have also been reported from the Housatonic River drainage in both Massachusetts and Connecticut (Whitworth *et al.* 1968; Hartel *et al.* 2002).

Burbot are widely distributed in New York State, occurring in both lakes and river systems (Smith 1985). Lake populations of burbot in New York include Lake Champlain, Oneida Lake, some of the Finger Lakes, as well as other smaller lakes, chiefly in the St. Lawrence and Susquehanna drainages. Jackson *et al.* (2008) attributed the recent decline in burbot abundance in Oneida Lake to global climate warming. Burbot are also found above downstream barriers in the Raquette River system of the St. Lawrence and in the headwaters of the Susquehanna and Allegheny rivers (Robins and Deubler 1955; Smith 1985).

Isolated records of burbot in the Susquehanna River exist from both Pennsylvania (Cope 1879) and Maryland (Kazyak and Raesley 2003). In Pennsylvania, burbot are a species of special concern and also occasionally found in the Susquehanna River (Argent *et al.* 2000), but modern records of burbot from Pennsylvania are primarily restricted to the headwaters of the Allegheny River (Cooper 1983). In Kentucky, the burbot has been sporadically reported in the lower Ohio River system, but no evidence of reproduction exists for burbot (Clay 1975; Burr and Warren 1986).

Canada north and east of the Laurentian Great Lakes

Burbot are found throughout eastern Canada as far north as the Arctic drainage, that of Hudson Bay and east to Newfoundland and Labrador (Scott and Crossman 1973). In Ontario, burbot numbers were thought to be stable, at least into the early 1960s (MacKay 1963), and Scott (1967) characterized burbot as common in deep lakes and large rivers of the province. Burbot populations are secure in Québec, New Brunswick and Newfoundland and Labrador. Burbot are not highly regarded in eastern Canada, although a few commercial fisheries exist. During 1930–72, commercial fishers on Lake of the Woods in Minnesota, USA and Ontario, Canada annually harvested from 82 565 to over 400 000 burbot (Muth and Smith 1974). Burbot have been removed from some lakes in Ontario as part as part of 'rough fish' removal programmes (Smedley 1998). A removal programme in Lake Simcoe resulted in catches of almost 6000 kg in 1954, but the programme was discontinued due to a lack of identified use for the fish (MacCrimmon and Skobe 1970). The lack of popularity of burbot in eastern Canada and the disdain for the species by anglers fishing for more popular sportfish is partially responsible for the lack in interest regarding their status. In Ontario, burbot are often caught coincidentally while angling for lake trout (MacKay 1963).

Synthesis of causes for decline and mitigating measures

Habitat change, especially from dam construction and pollution, was overwhelmingly the most important reason for declines in burbot abundance in rivers and streams worldwide. Dams have been shown to change habitat complexity, alter river discharge and temperatures on a temporal and spatial scale, and have contributed to the decline of many species of fish (Stanford *et al.* 1996). Overfishing is still a problem in some areas and undoubtedly contributed to declines in burbot abundance at the local level. However, overfishing does not appear to be limiting burbot populations worldwide. Further, the comparatively poor swimming stamina of burbot (Jones *et al.* 1974) may limit its movement of burbot from one water body to another due to water velocity gradients across culverts or other structures. In lakes, adverse effects of exotic species and pollution appear to be the main factors for decreases in burbot abundance. In the Laurentian Great Lakes, invasions of exotic fishes have apparently led to substantial increases in both mortality of adult burbot and mortality of burbot fry.

Mitigation measures for burbot populations impacted by dams are lacking. A conservation strategy (Kootenai Valley Resource Initiative (KVRI) Burbot Committee 2005; Ireland and Perry 2008) was prepared to outline measures necessary to rehabilitate the burbot population of the Kootenai River. The Conservation Strategy indicated that operational discharge changes at Libby Dam are required during winter to provide suitable conditions for burbot migration. Paragamian *et al.* (2005) and Paragamian & Wakkinen (2008) recommended that discharge for burbot pre-spawning migration and spawning should range from 113–300 $m^3\ s^{-1}$ and average 176 $m^3\ s^{-1}$ for a minimum of 90 days (mid-November through mid-February) in the Kootenai River. Temperature should decline to <5 °C by the first week in November and maintained from 1 to 4 °C for the duration of December through February, which includes the migration and spawning season. However, implementation has not occurred and unless it occurs, it is likely burbot in the Kootenai River will be extirpated (Paragamian *et al.* 2008). However, in the interim, development involving artificial propagation technology may serve to reestablish burbot stocks (Jensen *et al.* 2008).

The specialization of burbot to cold, oligotrophic conditions may make it more vulnerable to anthropogenic change. Warmer water temperatures, due either to discharge from dams or climate change, have been noted in declining burbot populations at the southern extent of their range. Some of these declines appear to be due to warmer summer water temperatures thought to reflect climate change (Jackson *et al.* 2008). Although Columbia Lake at the extreme upper end of the Columbia River drainage is not the southern bound of burbot range in western North America, this shallow lake is at the extreme side of temperature tolerance for burbot survival (Ford *et al.* 1995; Taylor 2002). By contrast, Horton & Strainer (2008) considered possible benefits of dams that cooled riverine habitats below and provided lacustrine habitats within impoundments. Although no historical distribution data existed for burbot, Horton & Strainer (2008) hypothesized burbot numbers in a section of the Missouri River below dams of three upstream reservoirs increased because the upstream reservoirs provided comparatively cooler summer water temperatures downstream.

Our review also suggests that burbot populations are fully capable of recovering from over-exploitation once fishing pressure has been relaxed. For example, once more restrictive regulations were placed on burbot fisheries, burbot populations in Alaskan lakes exhibited recoveries. These regulation changes included reducing the daily limit and prohibiting the use of baited set-lines. The Lake Winnebago case history provided another example of burbot populations recovering from over-exploitation. Once the rough fish removal programme was terminated in the early 1980s, the burbot population in Lake Winnebago exhibited a strong recovery during the late 1980s and through the 1990s. By contrast, total protection of burbot in Kootenay Lake, BC from fishing has not led to population restoration.

The case histories for the Laurentian Great Lakes clearly illustrate that burbot populations can recover when appropriate fisheries management actions are taken. As previously mentioned, the burbot populations in Lakes Michigan, Huron, Erie and Ontario had collapsed by 1960, due in part to high populations of sea lamprey and alewife. Chemical control of sea lampreys began in the late 1950s and was effective in reducing sea lamprey abundance in all five Great Lakes (Christie and Goddard 2003; Mullett *et al.* 2003). To reduce alewife abundance in Lakes Michigan, Huron and Ontario, large-scale salmonine stocking programmes were launched as early as 1965 by Great Lakes fishery managers (Madenjian *et al.* 2008). These salmonine stocking programmes led to dramatic increases in salmonine abundances, which in turn led to dramatic increases in the consumption of alewives by salmonines. These salmonine stocking programmes were effective in substantially reducing alewife abundance in Lakes Michigan, Huron and Ontario (Madenjian *et al.* 2008). A decrease in the abundance of the sea lamprey led to recovery of the burbot population in Lake Erie, and decreases in the abundances of both sea lamprey and alewife led to recovery of the burbot populations in Lakes Michigan and Huron (Stapanian *et al.* 2008). Thus, management action to control these two invasive fish species was instrumental in the recovery of burbot populations in three of the Laurentian Great Lakes. Apparently, alewife abundance in Lake Ontario is still too high to allow for burbot recovery in that lake (Stapanian *et al.* 2008). Increasing the lakewide biomass of salmonines to further reduce alewife abundance should eventually result in a recovered burbot population in Lake Ontario (Madenjian *et al.* 2008).

Although burbot are widespread in distribution, they are locally sensitive to disturbances of habitat conditions and fish community structure. Capacity for recovery when appropriate management actions are taken indicates that threatened populations recover. Burbot appear to serve as an excellent indicator species in much of their range, and monitoring of populations could provide valuable insights into the magnitude of perturbations resulting from both intentional and unintentional actions. Burbot in marginal habitats may also serve as an early indicator of the impacts of climate change on coldwater fish species. However, because burbot are not held in high regard as a sport or commercial species in much of their range, information on population status is frequently limited or nonexistent. The ability to measure responses to recovery efforts and identify future threats will be dependent on expanded efforts to assess burbot status in waters where they occur. Thus, it will be important to develop standardized methods to assess stock status of burbot populations in consideration of juvenile and adult abundance.

Acknowledgements

We thank the many researchers who provided vital information from agency archives and to the reviewers of this manuscript that provided important guidance. The Bonneville Power Administration provided partial funding for this investigation. E. Braig, M. Bur, O. Gorman and F. Neave reviewed earlier drafts. This article is Contribution Number 1537 of the Great Lakes Science Center.

References

Addis, P.B. (1990) Omega-3 fatty acid content of Lake Superior fish. *Minnesota Extension Service, Home Economics Publication* HE-FO-5618-B, University of Minnesota, Minneapolis-St. Paul.

Ahrens, R. and Korman, J. (2002) What happened to the West Arm burbot stock in Kootenay Lake? Use of an age-structured population model to determine the possible causes for recruitment failure. Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 30 pp.

Alberta Sustainable Resource Development. (2008) 2008–2009 Alberta Guide to Sportfishing Regulations. Alberta Sustainable Resource Development, Sports Scene Publications Inc., Edmonton, Alberta, Canada, 99 pp.

Allen-Gil, S.M., Ford, J., Lasorsa, B.K., Monetti, M., Vlasova, T. and Landers, D.H. (2003) Heavy metal contamination in the Taimyr Peninsula, Siberian Arctic. *The Science of the Total Environment* **301**, 119–138.

Andrews, E.R. and Peterson, R. (1983) Wild resource use of the Tuluksak River drainage by residents of Tuluksak, 1980–1983. Alaska Department of Fish and Game, Division of Subsistence, Juneau. *Technical Paper* **87**, 47 pp.

Andrianova, A.V., Zavoruev, V.V., Zadelennov, V.A., Lopatin, V.N., Mikhaleva, T.V. and Shchur, L.A. (2006) Assessment of the present-day state of cooling-basin ecosystem at the Berezovskaya State Regional Power Plant, Krasnoyarsk Territory. *Water Resources* **33**, 176–186.

Anonymous. (1964) Rough fish removal. Fishing. *Fisheries Branch Province of Manitoba* **4**, 8–10.

Anonymous. (2002) *Red Data Book of the Baltic and Nordic Region. Red Lists of Fish*. Version Dec 2002:1. Available at: http://www.artdata.slu.se/filer/BaltNord_RL_Fish.pdf [last accessed May 2009].

Anonymous. (2005) *BQE Report Fish. Ministry of Environment and Water, Hungary*. Available at: http://www.eu-wfd.info/ecosurv/report/ECOSURV final BQE report FISH english res.pdf [last accessed May 2009].

Anonymous. (2008) Commercial marine fishery 2007. *Riista- ja Kalataloustilastoja* **3**, 62.

Anttila, R. (1972) Helsingin edustan merialueen kalatalousselvitys 1969–1972. 233 pp and 14 appendices. Helsinki. (In Finnish).

Anttila, R. (1973) Effect of sewage on the fish fauna in the Helsinki area. *Oikos Supplement* **15**, 226–229.

Argent, D.G., Carline, R.F. and Staufer, J.R. Jr (2000) A method to identify and conserve rare fishes in Pennsylvania. *Journal of the Pennsylvania Academy of Science* **74**, 3–12.

Arndt, S. (2001) Summary of Winter Creel Surveys for Columbia and Windermere Lakes from 1995–2001. Report prepared for Columbia Basin Fish and Wildlife Compensation Program, Nelson, British Columbia, 34 pp.

Arndt, S. and Baxter, J. (2006) Status of burbot (*Lota lota*) in Arrow Lakes Reservoir. Report prepared for Columbia Basin Fish and Wildlife Compensation Program, Nelson, British Columbia, 35 pp.

Arndt, S.K.A. and Hutchinson, J. (2000) Characteristics of a tributary-spawning population of burbot from Columbia Lake. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, MD, pp. 48–60.

Ashley, K., Thompson, L.C., Sebastian, D., Lasenby, D.C., Smokorowski, K.E. and Andrusak, H. (1999) Restoration of Kokanee Salmon in Kootenay Lake, a large intermontane lake, by controlled seasonal application of limiting nutrients. In: *Aquatic Restoration in Canada* (eds T.P. Murphy and M. Munawar). Backhuys Publishers, Leiden, the Netherlands, pp. 127–170.

Avakyan, A.B., Litvinov, A.S. and Riv'er, I.K. (2002) Sixty years' experience in operating the Rybinsk Reservoir. *Water Resources* **29**, 1–11.

Bailey, M.M. (1972) Age, growth, reproduction, and food of the burbot, *Lota lota* (Linnaeus), in southwestern Lake Superior. *Transactions of the American Fisheries Society* **101**, 667–674.

Balkuvienė, G., Kesminas, V. and Virbickas, T. (2003) Fish diversity and growth in lakes of Aukštaitija National Park. *Acta Zoologica Lituanica* **13**, 355–371.

Barrett, J.H., Locker, A.M. and Roberts, C.M. (2004) The origins of intensive marine fishing in medieval Europe: the English evidence. *Proceedings of the Royal Society of London Series B-Biological Sciences* **271**, 2417–2421.

British Columbia (BC) Ministry of Environment. (2008) *2008–2009 British Columbia Freshwater Fishing Regulations Synopsis*. Monday Tourism Publications Limited, Victoria, BC, 96 pp.

BC Hydro. (2005a) Duncan Dam Water Use Plan Project Consultative Report. Report prepared for the BC Hydro Duncan Dam Water Use Plan Project, Burnaby, British Columbia, 30 pp.

BC Hydro. (2005b) Columbia River Water Use Plan Project, Volume 1 of 2, Consultative Report. Report prepared for the BC Hydro Columbia River Water Use Plan Project, Burnaby, British Columbia, 919 pp.

Becker, G. (1983) *Fishes of Wisconsin*. The University of Wisconsin Press, Madison, WI.

Bendock, T.N. (1979) Inventory and cataloging of Arctic area waters. Alaska Department of Fish and Game, Juneau. Federal Aid in Fish Restoration Project F-9-11. *Annual Report of Progress* **20**, 64 pp.

Bergersen, E.P., Cook, M.F. and Baldes, R. (1993) Winter movements of burbot (*Lota lota*) during an extreme drawdown in Bull Lake, Wyoming, USA. *Ecology of Freshwater Fish* **2**, 141–145.

Bernard, D.R., Parker, J.F. and Lafferty, R. (1993) Stock assessment of burbot populations in small and moderate-size lakes. *North American Journal of Fisheries Management* **13**, 657–675.

Bianco, P.G. and Ketmaier, V. (2001) Anthropogenic changes in the freshwater fish fauna of Italy, with reference to the central region and *Barbus graellsii*, a newly established alien species of Iberian origin. *Journal of Fish Biology* **59**(Suppl. A), 190–208.

Binsted, G.A. and Ashley, K.I. (2006) Phosphorus Loading to Kootenay Lake from the Kootenay and Duncan rivers and Experimental Fertilization Program. Report prepared for the British Columbia Conservation Foundation and Kootenai Tribe of Idaho, Bonners Ferry, Idaho, 38 pp.

Biró, P., Specziar, A. and Keresztessy, K. (2003) Diversity of fish species assemblages distributed in the drainage area of Lake Balaton (Hungary). *Hydrobiologia* **506–509**, 459–464.

Bisset, J.E. and Cope, R.S. (2002) Goat River Burbot Spawner Enumeration Program, Creston, B.C. Report prepared for Columbia-Kootenay Fisheries Renewal Partnership, Cranbrook, British Columbia, 36 pp.

Bonacina, C. (2001) Lake Orta: the undermining of an ecosystem. *Journal of Limnology* **60**, 53–59.

Bonar, S., Brown, L.G., Mongillo, P.E. and Williams, K. (1997) *Status of Burbot in Washington*. Washington Department of Fish and Wildlife, Olympia, WA.

Bouc, K. (1987) The Fish Book. *Nebraskaland Magazine*, Lincoln, Nebraska, **65**, 1–130.

Brandt, S.B., Mason, D.M., MacNeill, D.B., Coates, T. and Gannon, J.E. (1987) Predation by alewives on larvae of yellow perch in Lake Ontario. *Transactions of the American Fisheries Society* **116**, 641–646.

Branion, H. (1930) The marketing of ling (burbot). *Transactions of the American Fisheries Society* **60**, 199–203.

Brown, C.J.D. (1971) *Fishes of Montana*. Big Sky Books, Bozeman, MT.

Brown, E.H. Jr., Argyle, R.L., Payne, N.R. and Holey, M.E. (1987) Yield and dynamics of destabilized chub (Coregonus spp.) populations in Lakes Michigan and Huron, 1950–84. *Canadian Journal of Fisheries and Aquatic Sciences* **44**, s371–s383.

Bruesewitz, R.E. and Coble, D.W. (1993) Effects of deflating the expanded swim bladder on survival of burbot. *North American Journal of Fisheries Management* **13**, 346–348.

Brylinska, M., Chybowski, L. and Boguszewski, A. (2002) Reproductive biology of burbot, *Lota lota*, in Lake Hancza, Poland. *Folia Zoologica* **51**, 141–148.

Burr, B.M. and Warren, M.L. Jr (1986) A distributional atlas of Kentucky fishes. *Kentucky Nature Preserves Commission Scientific and Technical Series* **4**, 398 pp.

Cahn, A.R. (1936) Observations on the breeding of the lawyer, *Lota maculosa*. *Copeia* **1936**, 163–165.

Calles, O. (2005) *Re-establishment of connectivity for fish populations in regulated rivers*. PhD thesis, Karlstad University, Karlstad, Sweden, 56 pages and 6 appendices.

Carl, H., Berg, S., Møller, P.R., Nielsen, J. and Rasmussen, G. (2007) Status for Atlas over danske ferskvandsfisk.

Version II. Zoologisk Museum og Danmarks Fiskeriundersøgelser. Available at: http://www.fiskeatlas.dk [last accessed May 2009].

Cavender, T.M. (1986) Review of the fossil history of North American freshwater fishes. In: *The Zoogeography of North American Freshwater Fishes* (eds C.H. Hocut and E.O. Wiley). John Wiley and Sons, New York, NY, pp. 699–724.

Chereshnev, I.A. (1996) Annotated list of Cyclostomata and Pisces from the fresh waters of the arctic and adjacent territories. *Journal of Ichthyology* **36**, 566–577.

Christie, G.C. and Goddard, C.L. (2003) Sea Lamprey International Symposium (SLIS II): advances in the integrated management of sea lamprey in the Great Lakes. *Journal of Great Lakes Research* **29**(Suppl. 1), 1–14.

Clady, M.D. (1976) Distribution and abundance of larval ciscoes, *Coregonus artedii*, and burbot, *Lota lota*, in Oneida Lake. *Journal of Great Lakes Research* **2**, 234–247.

Clay, W.M. (1975) *The Fishes of Kentucky*. Kentucky Department of Fish and Wildlife Resources, Frankfort.

Cooper, E.L. (1983) *Fishes of Pennsylvania and the Northeastern United States*. Pennsylvania State University Press, University Park.

Cooper, G.P. and Fuller, J.L. (1945) A biological survey of Moosehead Lake and Haymock Lake, Maine. Maine Department of Inland Fisheries and Game, Augusta. *Fisheries Survey Report* **6**, 160 pp.

Cope, E.D. (1879) *Lota maculosa* in the Susquehanna river. *American Naturalist* **13**, 457.

Copp, G.H., Guti, G., Rovny, B. and Cern, J. (1994) Hierarchical analysis of habitat use by 0 + juvenile fish in Hungarid/Slovak flood plain of the Danube River. *Environmental Biology of Fishes* **40**, 329–340.

Cross, F. (1967) *Handbook of Fishes of Kansas*. University of Kansas Museum. State Printer, Topeka.

De Nie, H.W. (1997) Bedreigde en kwetsbare zoetwatervissen in Nederland - voorstel voor een rode lijst. Documentatierapport, Stichting Atlas verspreiding Nederlandse Zoetwatervissen. 74 pp. Available at: http://home.wxs.nl/~hwdenie/redlist1997.pdf [last accessed May 2009].

Dillen, A., Martens, S., Baeyens, R. and Coeck, J. (2005) Onderzoek naar de biologie van de kwabaal (*Lota lota L.*), ter voorbereiding van het herstel van de soort in het Vlaamse Gewest. Rapport van het Instituut voor Natuurbehoud IN.R.2005.04, Brussel. 154 pp. Available at: http://www.inbo.be/docupload/2895.pd [last accessed May 2009].

Dillen, A., Vught, I., De Charleroy, D., Monnier, D. and Coeck, J. (2008) A preliminary evaluation of reintroductions of burbot in Flanders, Belgium. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 179–183.

Dobiesz, N.E., McLeish, D.A., Eshenroder, R.L., Bence, J.R., Mohr, L.C., Ebener, M.P., Nalepa, T.F., Woldt, A.P., Johnson, J.E., Argyle, R.L. and Makarewicz, J.C. (2005) Ecology of the Lake Huron fish community, 1970–1999. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 1432–1451.

Dulmaa, A. (1999) Fish and fisheries in Mongolia. In: Fish and Fisheries at Higher Altitudes: Asia (ed T. Petr), Food and Agriculture Organization of the United Nations (FAO) Fisheries Technical Paper No. 385, Rome, Italy, pp. 187–236.

Eck, G.W. and Wells, L. (1987) Recent changes in Lake Michigan's fish community and their probable causes, with emphasis on the role of the alewife (*Alosa pseudoharengus*). *Canadian Journal of Fisheries and Aquatic Sciences* **44**, 53–60.

Edsall, T.A., Kennedy, G.W. and Horns, W.H. (1993) Distribution, abundance, and resting microhabitat of burbot on Julian's Reef, southwestern Lake Michigan. *Transactions of the American Fisheries Society* **122**, 560–574.

Eiserman, F. (1964) A fisheries survey of lakes and streams in the Tongue River drainage. Wyoming Game and Fish Commission, Cheyenne. *Fisheries Technical Report* **12**, 88 pp.

Erkinaro, H., Erkinaro, J., Rask, M. and Niemelä, E. (2001) Status of zoobenthos and fish populations in subarctic rivers of the northernmost Finland: possible effects of acid emissions from Russian Kola Peninsula. *Water, Air and Soil Pollution* **130**, 831–836.

Eshenroder, R.L. and Burnham-Curtis, M.K. (1999) Species succession and sustainability of the Great Lakes fish community. In: *Great Lakes Fisheries and Policy Management: A Binational Perspective* (eds W.W. Taylor and C.P. Ferreri). Michigan State University Press, East Lansing, MI, pp. 145–184.

Evenson, M.J. (1993) *A Summary of Abundance, Catch per Unit Effort, and Mean Length Estimates of Burbot Sampled in Rivers of Interior Alaska, 1986–1992*. Alaska Department of Fish and Game, Anchorage. Fishery Data Series 93-15.

Evenson, M.J. (2000) Reproductive traits of burbot in the Tanana River, Alaska. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, MD, pp. 61–70.

Evenson, M.J. and Hansen, P. (1991) *Assessment of Harvest Characteristics of the Tanana River Burbot Sport Fishery in 1990 using a Postal Questionnaire*. Alaska Department of Fish and Game, Anchorage. Fisheries Data Series 91–67.

Fladung, E., Scholten, M. and Thiel, R. (2003) Modelling the habitat preferences of preadult and adult fishes on the shoreline of the large, lowland Elbe River. *Journal of Applied Ichthyology* **19**, 303–314.

Følsvik, N. and Brevik, E.M. (1999) Levels of organotin compounds in burbot (*Lota lota*) from Norwegian lakes. *Journal of High Resolution Chromatography* **22**, 177–180.

Ford, B.S., Higgins, P.S., Lewis, A.F. *et al.* (1995) Literature reviews of the life history, habitat requirements and mitigation/compensation strategies for selected fish species in the Peace, Liard and Columbia river drainages of British Columbia. *Canadian Manuscript Report of Fisheries and Aquatic Sciences* **2321**, 342.

Ghan, D. (1990) *Ecology of larval and juvenile Burbot (Lota lota): abundance and distribution patterns, growth, and an analysis of diet and prey selection*. Masters thesis, University of Toronto, Toronto, Ontario Canada, 99 pp.

Gitschlag, G.R. (1986) A collapsible trap for underwater fish tagging. *Bulletin of Marine Science* **39**, 719–722.

Hackney, P.A. (1973) *Ecology of the Burbot (Lota lota)* with special reference to its role in the Lake Peonage Fish Community. Doctoral dissertation, University of Toronto, Toronto, Ontario Canada.

Halliwell, D.B., Whittier, T.R. and Ringler, N.H. (2001) Distributions of lake fishes of the northeast USA – III. Salmonidae and associated coldwater species. *Northeastern Naturalist* **8**, 189–206.

Hardy, R., Paragamian, V.L. and Neufeld, M.D. (2008) Zooplankton communities and burbot relative abundance of some oligotrophic lakes of Idaho, USA and British Columbia, Canada. In: *Burbot: Ecology, Management and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 79–89.

Harlan, J.R., Speaker, E.B. and Mayhew, J. (1987) *Iowa Fish and Fishing*. Iowa Department of Natural Resources, State of Iowa Printer, Des Moines, IA.

Harsányi, A. and Aschenbrenner, P. (1992) Die Rutte *Lota lota* (Linnaeus, 1758) – Biologie und Aufzucht. *Fischer und Teichwirt* **10**, 372–376.

Hartel, K.E., Halliwell, D.B. and Launer, A.E. (2002) *Inland Fishes of Massachusetts*. Massachusetts Audubon Society, Lincoln, MA.

Hayes, S.J., Bue, F.J., Borba, B.M. *et al.* (2008) *Annual Management Report Yukon and Northern Areas 2002–2004*. Alaska Department of Fish and Game, Anchorage. Fishery Management Report 08-36.

Herrmann, J., Degerman, E., Gerhardt, A., Johansson, C., Lingdell, P.-E. and Muniz, I.P. (1993) Acid-stress effects on stream biology. *Ambio* **22**, 298–307.

Hesse, L.W. (1993) The status of burbot in the Missouri River.2. Burbot (*Gadidae Lota lota*). *Transactions of the Nebraska Academy of Science* **20**, 67–71.

Hesthagen, T., Langeland, A. and Berger, H.M. (1998) Effects of acidification due to emissions from the Kola Peninsula on fish populations in lakes near the Russian border in Northern Norway. *Water, Air, and Soil Pollution* **102**, 17–36.

Hewson, L.C. (1955) Age, maturity, spawning, and food of burbot (*Lota lota*) in Lake Winnipeg. *Journal of the Fisheries Research Board of Canada* **12**, 930–940.

Hoffman, N. and Fischer, P. (2002) Temperature preference and critical limits of burbot: implications for habitat selection and ontogenetic habitat shift. *Transactions of the American Fisheries Society* **13**, 1164–1172.

Hokanson, K.E.F. (1977) Temperature requirements of some percids and adaptations to the seasonal temperature cycle. *Journal of the Fisheries Research Board of Canada* **34**, 1524–1550.

Holcik, J. (2003) Changes in the fish fauna and fisheries in the Slovak section of the Danube River: a review. *Annals of Limnology – International Journal of Limnology* **39**, 177–195.

Horton, T.B. and Strainer, A.C. (2008) Distribution and population characteristics of burbot in the Missouri River, Montana based on hoop-net, cod trap and slat trap captures. In: *Burbot: Biology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium **59**, Bethesda, MD, pp. 201–211.

Howe, A.L., Fidler, G. and Mills, M.J. (1995) *Harvest, Catch, and Participation in Alaska Sport Fisheries during 1994*. Alaska Department of Fish and Game, Anchorage. Fishery Data Series 95-24.

Howes, G.J. (1991) Biogeography of Gadoid fishes. *Journal of Biogeography* **18**, 595–622.

Hubbs, C.L. and Shultz, L.P. (1941) Contributions to the ichthyology of Alaska with description of two new fishes. *Occasional Papers of the Museum of Zoology*, University of Michigan, Ann Arbor, MI.

Hubert, W., Dufek, D., Deromedi, J., Johnson, K., Roth, S. and Skates, D. (2008) Burbot in the Wind River Drainage of Wyoming: knowledge of stocks and management issues. In: *Burbot: Biology, Management, and Culture* (eds /miscellaneoustext> V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 187–200.

Hudd, R., Urho, L. and Hildén, M. (1983) Occurrence of burbot, *Lota lota* L., larvae at the mouth of the Kyrönjoki in Quarken, Gulf of Bothnia. *Aquillo Series of Zoology* **22**, 127–130.

Ireland, S.C. and Perry, P.N. (2008) Burbot restoration in the Kootenai River basin: using agency, tribal, and community collaboration to develop and implement a conservastion strategy. In: *Burbot: Biology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 251–256.

Jackson, J.R., VanDeValk, A.J., Forney, J.L., Lantry, B.F., Brooking, T.E. and Rudstam, L.G. (2008) Long-term trends in Burbot abundance in Oneida Lake, New York: life at the southern edge of the range in an era of climate change. In: *Burbot: Ecology, Management and Culture* (eds V.L. Paragamian and D.H. Bennett). American

Fisheries Society, Symposium 59, Bethesda, MD, pp. 131–152.

Jennings, G.B., Sundet, K. and Bingham, A.E. (2007) *Participation, Catch, and Harvest in Alaska Sport Fisheries during 2004*. Alaska Department of Fish and Game, Anchorage. Fishery Data Series 07-40.

Jensen, J.W. (1988) Crustacean plankton and fish during the first decade of a subalpine, man-made reservoir. *Nordic Journal of Freshwater Research* **64**, 5–53.

Jensen, N.R., Williams, S.R., Ireland, S.C., Siple, J.T., Neufeld, M.D. and Cain, K.D. (2008) Preliminary captive burbot spawning observations. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 155–165.

Johnsson, C., Sällsten, G., Schütz, A., Sjörs, A. and Barregård, L. (2004) Hair mercury levels versus freshwater fish consumption in household members of Swedish angling societies. *Environmental Research* **96**, 257–263.

Jones, D.R., Kiceniuk, J.W. and Bamford, O.S. (1974) Evaluation of the swimming performance of several species of fish from the Mackenzie River. *Journal of the Fisheries Research Board of Canada* **31**, 1641–1647.

Josefsson, M. and Andersson, B. (2001) The environmental consequences of alien species in the Swedish lakes Mälaren, Hjälmaren, Vänern and Vättern. *Ambio* **30**, 514–521.

Jude, D.J., Heufelder, G.R. and Tin, H.T. (1979) Adult, juvenile, and larval fish in the vicinity of the J.H. Campbell Power Plant, eastern Lake Michigan, 1978. Great Lakes Research Division, University of Michigan, Ann Arbor. *Special Report* **73**.

Jurajda, P., Reichard, M. and Smith, C. (2006) Immediate impact of an extensive summer flood on the adult fish assemblage of a channelized lowland river. *Journal of Freshwater Ecology* **21**, 493–501.

Kangur, K., Park, Y.-S., Kangur, A., Kangur, P. and Lek, S. (2007) Patterning long-term changes of fish community in large shallow Lake Peipsi. *Ecological Modelling* **203**, 34–44.

Kauppila, P., Weckström, K., Vaalgamaa, S., Korhola, A., Pitkänen, H., Reuss, N. and Drew, S. (2005) Tracing pollution and recovery using sediments in an urban estuary, northern Baltic Sea: are we far from ecological reference conditions? *Marine Ecology-Progress Series* **290**, 35–53.

Kazyak, P.F. and Raesley, R.L. (2003) *Key to the Freshwater Fishes of Maryland*. Maryland Biological Stream Survey, Annapolis, MD.

Keith, P. and Allardi, J. (1996) Endangered freshwater fish: the situation in France. In: *Conservation of Endangered Freshwater Fish in Europe* (eds A. Kirchhofer and D. Hefti). Birkhäuser Verlag, Basel, Switzerland, pp. 35–54.

Keith, P. and Marion, L. (2002) Methodology for drawing up a Red List of threatened freshwater fish in France. *Aquatic Conservation-Marine and Freshwater Ecosystems* **12**, 169–179.

Kesminas, V. and Virbickas, T. (2000) Application of an adapted index of biotic integrity to rivers of Lithuania. *Hydrobiologia* **422/423**, 257–270.

Kirchhofer, A., Breitenstein, M. and Zaugg, B. (2007) Rote Liste der Fische und Rundmäuler der Schweiz. Bundesamt für Umwelt, Bern, und Schweizer Zentrum für die Kartographie der Fauna, Neuenburg. Umwelt-Vollzug Nr. 0734. 64 pp. Available at: http://www.bafu.admin.ch/publikationen/publikation/00071/index.html?lang=de&show_kat=/publikationen/00011 [last accessed May 2009].

Kirillov, A.F. (1988) Burbot, *Lota lota*, of Vilyuysk Reservoir. *Journal of Icthyology* **28**, 49–55.

Kjellman, J. (2003) *Growth and recruitment of Burbot (Lota lota)*. PhD thesis, University of Helsinki, Vaasa, Finland, 25 pp and 6 appendixes.

Kjellman, J., Lappalainen, J., Vinni, M., Uusitalo, L., Sarén, J. and Lappalainen, S. (2000) Occurrence of burbot larvae in a eutrophic lake. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication 1, Bethesda, MD, pp. 105–110.

Koivisto, A.-M., Bonde, A. and Aroviita, J. (2005) The status and development of the artificial lakes of the River Kyrönjoki Part I: the status and development of the artificial lakes of the River Kyrönjoki – based on physical–chemical parameters, mercury content in fish and the benthic fauna. *Regional Environment Publications* **406**, 53–66 (in Finnish).

Kootenai Valley Resource Initiative (KVRI) Burbot Committee. (2005) Kootenai River/Kootenay Lake Burbot Conservation Strategy. Report prepared by Kootenai Tribe of Idaho and S.P. Cramer and Associates, Bonners Ferry, Idaho, 77 pp.

Kotegov, B.G. (2007) Special features of fish species composition and community structure in small rivers of the Udmurt Republic. *Russian Journal of Ecology* **38**, 253–261.

Krueger, K.L. and Hubert, W.A. (1997) Assessment of lentic burbot populations in the Big Horn/Wind River drainage, Wyoming. *Journal of Freshwater Ecology* **12**, 453–463.

Kruk, A. (2004) Decline in migratory fish in the Warta River, Poland. *Ecohydrology and Hydrobiology* **4**, 147–155.

Kruk, A. (2007a) Role of habitat degradation in determining fish distribution and abundance along the lowland Warta River, Poland. *Journal of Applied Ichthyology* **23**, 9–18.

Kruk, A. (2007b) Long-term changes in fish assemblages of the Widawka and Grabia Rivers (Poland): pattern recognition with a Kohonen artificial neural network.

Annales de Limnologie – International Journal of Limnology **43**, 253–269.

Kruk, A. and Penczak, T. (2003) Impoundment impact on populations of facultative riverine fish. *Annales de Limnologie – International Journal of Limnology* **39**, 197–210.

Kullander, S.O. (2002) Svenska fiskar: Förteckning över svenska fiskar. Worldwide Web elektronisk publikation; Naturhistoriska riksmuseet. Available at: http://www.nrm.se/download/18.4e32c81078a8d9249800010214/svenska+fiskar.pdf [last accessed May 2009].

Lafferty, R., Parker, J.F. and Bernard, D.R. (1991) *Stock Assessment and Biological Characteristics of Burbot in Lakes of Interior Alaska during 1990*. Alaska Department of Fish and Game, Anchorage. Fishery Data Series 91-57.

Langdon, R.W., Ferguson, M.T. and Cox, K.M. (2006) *Fishes of Vermont*. Vermont Department of Fish and Wildlife, Waterbury, VT.

Lappalainen, A. and Pesonen, L. (2000) Changes in fish community structure after cessation of waste water discharge in a coastal bay area west of Helsinki, northern Baltic Sea. *Archive of Fishery and Marine Research* **48**, 226–241.

Lawler, G.H. (1963) The biology and taxonomy of the burbot, *Lota lota*, in Heming Lake, Manitoba. *Journal of the Fisheries Research Board of Canada* **20**, 417–433.

Lheidli T'enneh First Nation. (2007) *Omineca Burbot Creel, Habitat and Population Assessment Project; Results of Surveys of Sport-Ice Fisheries and Assessments of Burbot (Lota lota) Populations in Saxton, Nukko, Eaglet, Cluculz and Norman lakes*. Report prepared for British Columbia Ministry of Environment, Prince George, British Columbia, 32 pp.

Luecke, C., Rice, J.A., Crowder, L.B., Yeo, S.E. and Binkowski, F.P. (1990) Recruitment mechanisms of bloater in Lake Michigan: an analysis of the predatory gauntlet. *Canadian Journal of Fisheries and Aquatic Sciences* **47**, 524–532.

Lusk, S., Hanel, L. and Luskova, V. (2004) Red List of the ichthyofauna of the Czech Republic: development and present status. *Folia Zoologica* **53**, 215–226.

MacCrimmon, H.R. and Skobe, E. (1970) *The Fisheries of Lake Simcoe*. Ontario Department of Lands and Forests, Toronto, ON.

MacKay, H.H. (1963) *Fishes of Ontario*. Ontario Department of Lands and Forests, The Bryant Press Limited, Toronto, ON.

Madenjian, C.P., Fahnenstiel, G.L., Johengen, T.H. *et al.* (2002) Dynamics of the Lake Michigan food web, 1970–2000. *Canadian Journal of Fisheries and Aquatic Sciences* **59**, 736–753.

Madenjian, C.P., Holuszko, J.D. and Desorcie, T.J. (2003) Growth and condition of alewives in Lake Michigan, 1984–2001. *Transactions of the American Fisheries Society* **132**, 1104–1116.

Madenjian, C.P., Höök, T.O., Rutherford, E.S., Mason, D.M., Croley II, T.E., Szalai, E.B. and J. R. Bence, J.R. (2005a) Recruitment variability of alewives in Lake Michigan. *Transactions of the American Fisheries Society* **134**, 218–230.

Madenjian, C.P., Hondorp, D.W., Desorcie, T.J. and Holuszko, J.D. (2005b) Sculpin community dynamics in Lake Michigan. *Journal of Great Lakes Research* **31**, 267–276.

Madenjian, C.P., O'Gorman, R., Bunnell, D.B. *et al.* (2008) Adverse effects of alewives on Laurentian Great Lakes fish communities. *North American Journal of Fisheries Management* **28**, 263–282.

Maitland, P.S. and Lyle, A.A. (1990) Practical conservation of British fishes: current action on six declining species. *Journal of Fish Biology* **37**(Suppl. A), 255–256.

Maitland, P.S. and Lyle, A.A. (1996) Threatened freshwater fishes of Great Britain. In: *Conservation of Endangered Freshwater Fish in Europe* (eds A. Kirchhover and D. Hefti). Birkhäuser Verlag, Basel, Switzerland, pp. 9–21.

Mariussen, E., Fjeld, E., Breivik, K., Steinnes, E., Borgen, A., Kjellberg, G. and Schlabach, M. (2008) Elevated levels of polybrominated diphenyl ethers (PBDEs) in fish from Lake Mjøsa, Norway. *The Science of the Total Environment* **390**, 132–141.

Marlborough, D. (1970) The status of the burbot *Lota lota* (L.) (Gadidae) in Britain. *Journal of Fish Biology* **2**, 217–222.

Martin, A. (1976) *Kootenay Lake Burbot Fishery*. British Columbia Fish and Wildlife Miscellaneous Report, Nelson, British Columbia, 14 pp.

McCart, P.J. (1986) Fish and fisheries of the Mackenzie system. In: *The Ecology of River Systems* (eds B.R. Davies and K.F. Walker). Springer Publishing, New York, NY, pp. 493–516.

McPhail, J.D. (1997) A review of burbot (*Lota lota*) life history and habitat use in relation to compensation and improvement opportunities. *Canadian Manuscript Report of Fish Aquatic Science* **2397**, 37.

McPhail, J.D. and Carveth, R. (1993) *Field Key to the Freshwater Fishes of British Columbia*. Fish Museum, Department of Zoology, University of British Columbia, Vancouver, BC.

McPhail, J.D. and Lindsey, C.C. (1970) Freshwater fishes of northwestern Canada and Alaska. *Bulletin of the Fisheries Research Board of Canada* **173**, 295–300.

McPhail, J.D. and Paragamian, V.L. (2000) Burbot biology and life history. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, Maryland, USA, pp. 11–23.

Miller, D.D. (1970) *A life history study of the burbot in Ocean Lake and Torrey Creek, Wyoming*. Master's thesis, University of Wyoming, Laramie.

Mills, E.L., Casselman, J.M., Dermott, R. *et al.* (2003) Lake Ontario: food web dynamics in a changing ecosystem (1970–2000). *Canadian Journal of Fisheries and Aquatic Sciences* **60**, 471–490.

Mullett, K.M., Heinrich, J.W., Adams, J.V., Young, R.J., Henson, M.P., McDonald, R.B. and Fodale, M.F. (2003) Estimating lake-wide abundance of spawning-phase sea lampreys (*Petromyzon marinus*) in the Great Lakes: extrapolating from samples streams using regression models. *Journal of Great Lakes Research* **29**(Suppl. 1), 240–252.

Mutenia, A. (1985) Fish stocks and fishing in the Lokka and Porttipahta reservoirs, northern Finland. In: *Habitat Modification and Freshwater Fisheries* (ed. J.S. Alabaster). Food and Agriculture Organization of the United Nations, London, UK, pp. 195–201.

Muth, K. and Smith, L.L. Jr (1974) *The burbot fishery in Lake of the Woods*. University of Minnesota, Agricultural Experimental Station Technical Bulletin **296-174**, St. Paul, MN.

NatureServe. (2009) *NatureServe Explorer: An Online Encyclopedia Of Life [Web Application]. Version 7.1*. NatureServe, Arlington, VA. Available at: http://www.natureserve.org/explorer [last accessed May 2009].

Nelson, J.S. and Paetz, M.J. (1992) *Fishes of Alberta*. University of Alberta Press, Edmonton, AB.

Neufeld, M. (2005) Kootenay Sturgeon and Burbot Recovery Progress in British Columbia, 2004–2005. Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 49 pp.

Neufeld, M.D. (2006) Kootenay Burbot Recovery Projects in British Columbia, 2005–06. Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 24 pp.

Neufeld, M.D. (2008) Moyie Lake Burbot: Population Assesment 2007. Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 24 pp.

Neufeld, M. and Spence, C. (2004) Evaluation of a simple decompression procedure to reduce decompression trauma in trap caught burbot. *Transactions of the American Fisheries Society* **133**, 1241–1244.

New Hampshire Fish and Game Department (NHFGD). (2005) New Hampshire Wildlife Action Plan. Available at: http://www.wildlife.state.nh.us/Wildlife/wildlife_plan.htm [last accessed May 2009].

Nikčević, M., Hegediš, A., Mićković, B., Živadinović, D. and Andjus, R.K. (2000) Thermal acclimation capacity of the burbot *Lota lota* L. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, MD, pp. 71–77.

Norberg, M., Bigler, C. and Renberg, I. (2008) Monitoring compared with paleolimnology: implications for the definition of reference condition in limed lakes in Sweden. *Environmental Monitoring and Assessment* **146**, 295–308.

Northcote, T.G. (1972) Some effects of mysid introduction and nutrient enrichment on a large oligotrophic lake and its salmonids. *Verhandlungen Internationale Vereinigung für theoretische und angewandte Limnologie (Proceedings of the International Association of Theoretical and Applied Limnology)* **18**, 1096–1106.

O'Gorman, R. (1983) Distribution and abundance of larval fish in the nearshore waters of western Lake Huron. *Journal of Great Lakes Research* **9**, 14–22.

O'Gorman, R. and Stewart, T.J. (1999) Ascent, dominance, and decline of the alewife in the Great Lakes: food web interactions and management strategies. In: *Great Lakes Fisheries Policy and Management: A Binational Perspective* (eds W.W. Taylor and C.P. Ferreri). Michigan State University Press, East Lansing, MI, pp. 489–513.

Ocock, J., Baasanjav, G., Baillie, J.E.M., Erbenebat, M., Kottelat, M., Mendsaikhan, B. and Smith, K. (2006) *Mongolian Red List of Fishes*. Regional Red List Series Vol. 3. Zoological Society of London, London, UK, (in English and Mongolian).

Olin, M. and Ruuhijärvi, J. (2005) Fish communities in the different basins of L. Hiidenvesi in 1997–2001: effects of trophic status and basin morphology. In: *Lake Hiidenvesi – Studies on a Clay-Turbid and Eutrophic MultiBasin Lake* (ed. S. Repka). *Archiv Für Hydrobiologie Special Issues Advances Limnology* **59**, 125–140.

Olofsson, E., Melin, E. and Degerman, E. (1995) The decline of fauna in small streams in the Swedish mountain range. *Water, Air and Soil Pollution* **85**, 419–424.

Paragamian, V.L. (2000a) The effects of variable flows on burbot spawning migrations in the Kootenai River, Idaho, USA, and British Columbia, Canada. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, MD, pp. 111–123.

Paragamian, V.L. (2000b) Preface. In: *Burbot: Biology, Ecology, and Management* (eds. V.L. Paragamian and D.W. Willis), American Fisheries Society, Fisheries Management Section, Publication Number 1. Bethesda, Maryland, pp 7.

Paragamian, V.L. and Wakkinen, V.D. (2008) Seasonal movement and the interaction of temperature and discharge on burbot in the Kootenai River, Idaho, USA, and British Columbia, Canada. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society Symposium 59, Bethesda, MD, pp. 55–77.

Paragamian, V.L., Whitman, V., Hammond, J. and Andrusak, H. (2000) Collapse of the burbot fisheries in Kootenay Lake, British Columbia Canada, and the Kootenai River, Idaho, USA, post-Libby Dam. In: *Burbot: Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis).

American Fisheries Society, Fisheries Management Section, Publication Number 1, Bethesda, MD, pp. 155–164.

Paragamian, V.L., Hardy, R. and Gunderman, B. (2005) Effects of regulated discharge on burbot migration. *Journal of Fish Biology* **66**, 1199–1213.

Paragamian, V.L., Pyper, B.J., Daigneault, M.J., Beamesderfer, R.P. and Ireland, S.C. (2008) Population dynamics and extinction risk of burbot in the Kootenai River, Idaho, USA and British Columbia, Canada. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium **59**, Bethesda, MD, pp. 213–234.

Parker, J.F., Lafferty, R., Potterville, W.D. and Bernard, D.R. (1989) *Stock Assessment and Biological Characteristics Of Burbot in Lakes of Interior Alaska, 1988*. Alaska Department of Fish and Game, Juneau, AK. Fishery Data Series 98.

Partridge, F. (1983) *Kootenai River Fisheries Investigations*. Idaho Department of Fish and Game, Boise, ID. Job Completion Report, Project F-73-R-5.

Penczak, T. and Kruk, A. (2005) Patternizing of impoundment impact (1985–2002) on fish assemblages in a lowland river using the Kohonen algorithm. *Journal of Applied Ichthyology* **21**, 169–177.

Pietschmann, V. (1934) *Lota hulai*, eine neue fischart aus dem Wiener Becken. *Palentological Zoology* **16**, 48–52.

Pihu, E. and Turovski, A. (2003) Burbot, *Lota lota* (L.). In: *Fishes of Estonia* (eds E. Ojaveer, E. Pihu and T. Saat). Estonian Academy Publishers, Talinn, Estonia, pp. 267–271.

Pinnegar, J.K. and Engelhard, G.H. (2008) The 'shifting baseline' phenomenon: a global perspective. *Reviews in Fish Biology and Fisheries* **18**, 1–16.

Pisarsky, B.I., Hardina, A.M. and Naganawa, H. (2005) Ecosystem evolution of Lake Gusinoe (Transbaikal region, Russia). *Limnology* **6**, 173–182.

Powell, M., Paragamian, V.L. and Dunnigan, J. (2008) Mitochondrial variation in Western North American burbot with special reference to the Kootenai River in Idaho and Montana, USA. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 3–28.

Prince, A. (2001) Local knowledge of Columbia River fisheries in British Columbia, Canada. Report prepared for the Columbia-Kootenay Fisheries Renewal Partnership, Cranbrook, British Columbia, 50 pp.

Prince, A. (2007) East Kootenay burbot population assessment. Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 25 pp.

Prince, A. and Cope, R.S. (2008) North Moyie Lake creel survey (January – March 2008). Report prepared for the Ministry of Environment, Environmental Stewardship Division, Fish and Wildlife Section, Cranbrook, B.C., by Westslope Fisheries Ltd., 21pp.

Prince, A. and Cope, R.S. (2008) North Moyie Lake Creel survey (January–March 2008). Report prepared for the British Columbia Ministry of Environment, Nelson, British Columbia, 22 pp.

Pulliainen, E., Korhonen, K. and Huuskonen, M. (1999) Developmental disorders in the gonads of burbot in the Bothnian Bay: extent of the problem and links with other reproductive disorders in fish. Ministry of the Environment, Lapland Regional Environmental Centre and North Ostrobothnia Regional Environment Centre. Jyväskylä, Finland. *The Finnish Environment Report* **322**, 101 (in Finnish with English abstract).

Quinn, S. (2000) The status of recreational fisheries for burbot in the United States. In: *Burbot Biology, Ecology, and Management* (eds V.L. Paragamian and D.W. Willis). American Fisheries Society, Fisheries Management Section, Publication No. 1, Bethesda, MD, pp. 127–135.

Rask, M., Mannio, J., Forsius, M., Posch, M. and Vuorinen, P.J. (1995) How many fish populations in Finland are affected by acid precipitation? *Environmental Biology of Fishes* **42**, 51–63.

Reddekopp, S., McLoughlin, S. and Murphy, H. (2003) Characteristics of burbot (Lota lota) populations in Lac Des Roches and Birch Lake, British Columbia. Prepared for BC Ministry of Environment, Kamloops, B.C by the British Columbia Conservation Foundation Kamloops, B.C., 23pp.

Repecka, R. (2003) The species composition of the ichthyofauna in the Lithuanian economic zone of the Baltic Sea and the Curonian lagoon and its changes in recent years. *Acta Zoologica Lituanica* **13**, 149–157.

Reshetnikov, Y.S., Bogutskaya, N.G., Vasil'eva, D.E. *et al.* (1997) An annotated check-list of the freshwater fishes of Russia. *Journal of Ichthyology* **37**, 687–736.

Roach, S.M. and Evenson, M.J. (1993) *A Geometric Approach to Estimating and Predicting the Fecundity of Tanana River Burbot*. Alaska Department of Fish and Game, Juneau, AK. Fisheries Data Series 93-38.

Robins, C.R. and Deubler, E.E. Jr (1955) The life history and systematic status of the burbot, *Lota lota lacustris* (Walbaum), in the Susquehanna River System. New York State Museum and Science Service Circular 39, New York State Museum and Science Service, Albany, New York.

Roy, S.A. (2001) Burbot Management Plan. Maine Department of Inland Fisheries and Wildlife, Division of Fisheries and Hatcheries. Available at: http://www.maine.gov/ifw/fishing/species/management_plans/burbot.pdf [last accessesed May 2009].

Rudstam, L.G., Peppard, P.E., Fratt, T.W., Bruesewitz, R.E., Coble, D.W., Copes, F.A. and Kitchell, J.F. (1995) Prey consumption by the burbot (*Lota lota*) population in Green Bay, Lake Michigan, based on a bioenergetics model. *Canadian Journal of Fisheries and Aquatic Sciences* **52**, 1074–1082.

Ryan, P.A., Witzel, L.D., Paine, J. *et al.* (1999) Recent trends in fish populations in eastern Lake Erie in relation to changing lake trophic state and food web. In: *State of Lake Erie (SOLE) – Past, Present and Future* (eds M. Munawar, T. Edsall and I.F. Munawar). Backhuys Publishers, Leiden, the Netherlands, pp. 241–289.

Ryder, R.A. and Pesendorfer, J. (1992) Food, growth, habitat and community interactions of young-of-the-year burbot, *Lota lota* (L.), in a Precambrian Shield lake. *Hydrobiologia* **243/244**, 211–227.

Scarola, J.F. (1973) *Freshwater Fishes of New Hampshire*. New Hampshire Fish and Game Department, Division of Inland and Marine Fishes, Concord, NH, 132 pp.

Schindler, E.U., Andrusak, H., Ashley, K.I. *et al.* (2007) Kootenay Lake Fertilization Experiment: year 14 (North Arm) and year two (South Arm) – 2005. British Columbia Ministry of Environment, Nelson, British Columbia, *Fisheries Project Report RD* **122**, 223 pp.

Schwanke, C.J. and Bernard, D.R. (2005) *Copper River Burbot Stock Assessment, 2003*. Alaska Department of Fish and Game, Anchorage, AK. Fishery Data Series 05-15.

Scott, W.B. (1967) *Freshwater Fishes of Eastern Canada*, 2nd edn. University of Toronto Press, Toronto, Ontario Canada.

Scott, W.B. and Crossman, E.J. (1973) Freshwater fishes of Canada. *Bulletin of the Fisheries Research Board of Canada* **184**, Ottawa, Ontario, Canada.

Scott, W.B. and Crossman, E.J. (1998) *Freshwater Fishes of Canada*. Galt House Publications, Oakville, ON.

Sidorov, V.S., Nemova, N.N., Vysotskaya, R.U. and Taksheev, S.A. (2003) Variability of the integrated biochemical index in fish exposed to technogenic water of mining and ore-processing works. *Russian Journal of Ecology* **34**, 242–247.

Simpson, J. and Wallace, R. (1982) *Fishes of Idaho*. The University Press of Idaho, Moscow, ID.

Skaar, D., DeShazer, J., Garrow, T., Ostrowski, T. and Thornburg, B. (1996) *Quantification of Libby Reservoir Levels Needed to Maintain or Enhance Reservoir Fisheries*. Report prepared for Bonneville Power Administration. Montana Department of Fish, Wildlife, and Parks Completion Report, Project 83-467, Kalispell, Montana.

Slavík, O. and Bartoš, L. (2002) Factors affecting migrations of burbot. *Journal of Fish Biology* **60**, 989–998.

Šlejkovec, Z., Bajc, Z. and Doganoc, D.Z. (2004) Arsenic speciation patterns in freshwater fish. *Talanta* **62**, 931–936.

Smedley, J. (1998) The lovely ling. *Ontario Out of Doors* **29**, 29–30.

Smith, S.H. (1970) Species interaction of the alewife in the Great Lakes. *Transactions of the American Fisheries Society* **99**, 754–765.

Smith, C.L. (1985) *The Inland Fishes of New York State*. New York State Department of Environmental Conservation, Albany, NY. 522 pp.

Smith, B.R. and Tibbles, J.J. (1980) Sea lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan, and Superior: history of invasion and control, 1936–78. *Canadian Journal of Fisheries and Aquatic Sciences* **37**, 1780–1801.

Spence, C.R. (1999) Kootenay Lake Burbot Studies; Progress 1998–1999. Report prepared for British Columbia Ministry of Environment, Nelson, British Columbia 42 pp.

Spence, C. and Neufeld, M. (2002) Radio telemetry studies of Duncan Reservoir burbot. Report prepared for British Columbia Ministry of Environment, Nelson, British Columbia 21 pp.

Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A. and Coutant, C.C. (1996) A general protocol for restoration of regulated rivers. *Regulated Rivers: Research and Management* **12**, 391–413.

Stapanian, M.A. and Kakuda, Y. (2008) Some effects of freezing techniques on burbot meat. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 257–270.

Stapanian, M.A. and Madenjian, C.P. (2007) Evidence that lake trout served as a buffer against sea lamprey predation on burbot in Lake Erie. *North American Journal of Fisheries Management* **27**, 238–245.

Stapanian, M.A., Madenjian, C.P. and Witzel, L.D. (2006) Evidence that sea lamprey control led to recovery of the burbot population in Lake Erie. *Transactions of the American Fisheries Society* **135**, 1033–1043.

Stapanian, M.A., Madenjian, C.P., Bronte, C., Ebener, M., Lantry, B.F. and Stockwell, J. (2008) Status of burbot populations in the Laurentian Great Lakes: a synthesis. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 111–130.

Sundet, R.L. and Wenger, M.N. (1984) Resident fish distribution and population dynamics in the Susitna River below Devil Canyon. Alaska Department of Fish and Game, Anchorage. *Susitna Hydro Aquatic Studies Report Series* **2**, 75 pp.

Sutela, T. and Vehanen, T. (2008) Effects of water-level regulation on the nearshore fish community in boreal lakes. *Hydrobiologia* **613**, 13–20.

Švagždys, A. (2002) Growth and abundance of burbot in the Curonian lagoon and determinatives of burbot abundance. *Acta Zoologica Lituanica* **12**, 58–64.

Svärdson, G. (1976) Interspecific population dominance in fish communities of Scandinavian lakes. *Report Institute of Freshwater Research, Drottningholm* **55**, 144–171.

Swink, W.D. and Fredericks, K.T. (2000) Mortality of burbot from sea lamprey attack, and initial analyses of burbot blood. In: *Burbot Biology, Ecology and Management* (eds V.L. Paragamian and D. Willis). American

Fisheries Society, Fisheries Management Section Publication Number 1, Bethesda, MD, pp. 147–154.

Tack, P.I., Ingalls, R., Klocke, J.F., Baeder, H., Cederquist, D.C., Musser, E. and Ohlson, M.A. (1947) Preparation, utilization, and vitamin concentrations of the burbot *Lota lota maculosa* (Lesherer). *Michigan Agricultural Experimental Station Bulletin* **29**, 286–302.

Tammi, J., Lappalainen, A., Mannio, J., Rask, M. and Vuorenmaa, J. (1999) Effects of eutrophication on fish and fisheries in Finnish lakes: a survey based on random sampling. *Fisheries Management and Ecology* **6**, 173–186.

Tammi, J., Appelberg, M., Beier, U., Hesthagen, T., Lappalainen, A. and Rask, M. (2003) Fish status survey of Nordic lakes: effects of acidification, eutrophication and stocking activity on present fish species composition. *Ambio* **32**, 98–105.

Tarvainen, A., Verta, O.-M., Marttunen, M., Nykänen, J., Korhonen, T., Pönkkä, H. and Höytämö, J. (2006) Effects and the development opportunities of the regulation of Lake Koitere. *Finnish Environment* **37/2006**, 116 (in Finnish). Available at: http://www.ymparisto.fi/download.asp?contentid=59752&lan=FI [last accessed May 2009].

Taylor, J. (2002) Juvenile Burbot Sampling in Columbia and Windermere Lakes, Summer 2002. Report prepared for the Columbia Basin Fish and Wildlife Compensation Program, Nelson, British Columbia, 12 pp.

Tolonen, A. and Lappalainen, J. (1999) Origin of the burbot (*Lota lota* (L.)) in an Arctic ice-fishing competition – a case study. *Journal of Applied Ichthyology* **15**, 122–126.

Trautman, M.B. (1981) *The Fishes of Ohio*, 2nd edn. The Ohio State University Press, Columbus, OH.

Urho, L., Lappalainen, J., Kjellman, J. and Hudd, R. (1998) Occurrence of burbot (*Lota lota*) larvae in relation to pH. In: *Biology and Management of Burbot* (eds V.L. Paragamian and D.D. MacKinlay). American Fisheries Society, Fisheries Management Section Publication Number 1, Bethesda, MD, pp. 5–10.

Van Houdt, J.K., Hellemans, B. and Volckaert, F.A.M. (2003) Phylogenetic relationships among Palearctic and Nearctic burbot (*Lota lota*): Pleistocene extinctions and recolonization. *Molecular Phylogenetics and Evolution* **29**, 599–612.

Van Houdt, J.K.J., DeCleyn, L., Perretti, A. and Volckaert, F.A.M. (2006) Discriminating glacial races of burbot (*Lota lota*) by means of PCR-RF-SSCP (PRS) analysis of the mitochondrial control region. *Molecular Ecology Notes* **6**, 554–558.

Van Schubert, R.M. and Newman, T.J. (2000) A Winter Study of Age, Growth, Movement Patterns and Angler Harvest of Burbot (*Lota lota*) in Eaglet Lake, British Columbia. Report prepared for the British Columbia Ministry of Environment, Prince George, British Columbia.

Vassilev, M.V. and Pehlivanov, L.Z. (2005) Checklist of Bulgarian freshwater fishes. *Acta Zoologica Bulgarica* **57**, 161–190.

Veenvliet, P. (2000) The ichtyofauna of Cerknica polje. *Biota (Slovenia)* **1**, 93–100.

Volodin, V.M. (1994) Status of breeding stocks of burbot, *Lota lota*, in the Sheksninskii reach of Rybinskoe Reservoir before and after the emergency sewage disposal in 1987. *Journal of Ichthyology* **34**, 353–358.

Vught, I., Harzevili, A.S., Auwerx, J. and De Charleroy, D. (2008) Aspects of reproduction and larviculture of burbot under hatchery conditions. In: *Burbot: Ecology, Management, and Culture* (eds V.L. Paragamian and D.H. Bennett). American Fisheries Society, Symposium 59, Bethesda, MD, pp. 167–178.

Walker, K.F. and Yang, H.Z. (1999) Fish and fisheries in Western China. In: *Fish and Fisheries at Higher Altitudes: Asia* (ed. T. Petr). FAO Fisheries Technical Paper No. 385, FAO, Rome. Available at: http://www.fao.org/docrep/003/x2614e/x2614e12.htm#P5_0 [last accessed May 2009].

Walters, V. (1955) Fishes of western Arctic America and eastern Arctic Siberia. *Bulletin of the American Museum of Natural History* **106**, 255–368.

Whitmore, C., Martz, M., Linderman, J.C. Jr, Fisher, R.L. and Bue, D.G. (2008) Annual Management Report for subsistence and commercial fisheries of the Kuskokwim area, 2004. Alaska Department of Fish and Game, Anchorage. *Fishery Management Report* **08–25**, 286 pp.

Whitworth, W.R., Berrien, P.L. and Keller, W.T. (1968) Freshwater fishes of Connecticut. *State Geological and Natural History Survey of Connecticut Bulletin* **101**, 135 pp.

Wolter, C. (2007) Temperature influence on the fish assemblage structure in a large lowland river, the lower Oder River, Germany. *Ecology of Freshwater Fish* **16**, 493–503.

Wydoski, R.S. and Whitney, R.R. (2003) *Inland Fishes of Washington*, 2nd edn. University of Washington Press, Seattle, WA.

Zhadin, V.I. and Gerd, S.V. (1963) *Fauna and flora of the rivers lakes and reservoirs of the U.S.S.R.* Translated from Russian by the Israel Program for Scientific Translations, Jerusalem, Israel, 626 pp.

Zhulidova, A.V., Robarts, R.D., Headley, J.V., Liber, K., Zhulidov, D.A., Zhulidova, O.V. and Pavlov, D.F. (2002) Levels of DDT and hexachlorocyclohexane in burbot (*Lota lota* L.) from Russian Arctic rivers. *The Science of the Total Environment* **292**, 231–246.

Zick, D., Gassner, H., Filzmoser, P., Wanzenbock, J., Pamminger-Lahnsteiner, B. and Tischler, G. (2006) Changes in the fish species composition of all Austrian lakes > 50 ha during the last 150 years. *Fisheries Management and Ecology* **13**, 103–111.

Zyblut, E.R. (1967) *Temporal and spatial changes in distribution and abundance of macrozooplankton in a large British Columbia Lake*. MSc thesis, Department of Zoology, University of British Columbia, Vancouver, BC.