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# Evidence of successful recruitment of non-native pink salmon *Oncorhynchus gorbuscha* in Iceland

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## Abstract

In mid-May 2022, pink salmon *Oncorhynchus gorbuscha* smolts were caught in the rivers Botnsá, Grímsá, and Langá in Iceland. This observation provides the first evidence of successful spawning and the completion of the freshwater phase of the life cycle in Icelandic rivers. It is the most western record of *O. gorbuscha* smolts in Europe, further west than Russia, Norway, and the UK. Smolts originating from Iceland potentially support the recruitment of this species in the North Atlantic and may lead to the establishment of a self-sustaining population in Iceland.

**KEYWORDS**
invasive species, pink salmon, River Botnsá, River Grímsá, River Langá, smolt

Pink salmon *Oncorhynchus gorbuscha* (Walbaum 1792) is the smallest but most abundant of the Pacific salmonids throughout its native range. The species is dominant in commercial offshore salmon catches in the North Pacific (NPAFC, 2020) due to the species' fast growth rate and early maturation. *Oncorhynchus gorbuscha* reproduce naturally in rivers on both sides of the North Pacific; along western North America from the Beaufort Sea to California and along eastern Asia from the Laptev Sea to the Sea of Japan. Riverine spawning migrations of *O. gorbuscha* are often short, and fish can spawn in the intertidal stretches of rivers. After emerging from the gravel, juveniles descend quickly to the sea. Typically, *O. gorbuscha* has a 2-year life cycle, with two, reproductively isolated, separate populations that reproduce in odd or even years and do not normally interbreed but can occur together or alone in particular river systems (Heard, 1991).

During the second half of the 20th century, *O. gorbuscha* was introduced into the rivers draining into the White Sea by USSR/Russia. Initially (1956–1979), fish originated mainly from south Sakhalin Island (Niemelä *et al.*, 2016 with the references therein). These stockings were not successful, and *O. gorbuscha* did not establish self-sustaining populations. Between 1985 and 1999, further stocking of *O. gorbuscha* was carried out using stock material from the River Ola, which is located further north than Sakhalin Island. These latter introductions were successful and resulted in the establishment of self-sustaining, predominantly

odd-year populations in the tributaries of the White Sea (Niemelä *et al*., 2016 with the references therein).

Introductions of *O. gorbuscha* to White Sea tributaries were followed by observations of adults in the North Atlantic, with the first reports ($n = 22$) for Iceland during 1960–1961 (Guðjónsson, 1961). Subsequently, records of *O. gorbuscha* captures in logbooks of angling catches from Icelandic rivers, or reported to the Institute of Freshwater Fisheries, were sporadic and almost exclusively of males, which are easily identified due to their distinctive humped back. This bias toward males in the records may be a consequence of female *O. gorbuscha* being misidentified as Arctic char *Salvelinus alpinus* (L. 1758). Official recording of *O. gorbuscha* vagrants was initiated in Iceland in 2000, with 31 *O. gorbuscha* specimens logged during the next 13 years, often only as a few specimens each year. The highest numbers of fish were observed in 2007 (seven specimens) and 2015 (nine). No *O. gorbuscha* were caught in 2006, 2009–2010, and 2012–2013 (Þórðardóttir & Guðbergsson, 2022). The recording of *O. gorbuscha* in logbooks shows the occurrence of catches in rivers all around the island, with the highest reported catches in East Iceland (Figure 1). The earliest fish were recorded in April, and the latest in September. Most catches were in late July and the beginning of August. Reports of spent females were from the beginning of September indicating the onset of spawning.

In 2017, a sudden increase in *O. gorbuscha* records (52 fish) was observed in Iceland (Þórðardóttir & Guðbergsson, 2022). This increase was consistent with reports from across the northeast Atlantic: >11,400 specimens (not including coastal areas) from Norway (Diaz Pauli *et al*., 2023), 149 from the UK (Armstrong *et al*., 2018, ICES, 2022; G. Davies, personal communication), 36 from Ireland (Millane *et al*., 2019), and 46 from Sweden (Staveley & Bergendahl, 2022). *Oncorhynchus gorbuscha* adults were also reported from fresh waters in Denmark (nine), Germany (three), and France (three: Beaulaton *et al*., 2021; Sivebæk, 2017; Marko Freese, personal communication).

In 2019, the number of adult *O. gorbuscha* recorded in Iceland increased almost fourfold (232 specimens) compared with 2017 (Þórðardóttir & Guðbergsson, 2022). An increase in the numbers of *O. gorbuscha* was also noted in Greenland (76), the Faroe Islands (six: Eliasen & Johannesen, 2021; Nielsen *et al*., 2020), and Norway, where the highest catches were observed (>15,700: Diaz Pauli *et al*., 2023). In contrast to the increases in apparent abundance in northern areas, fewer pink salmon were reported in southern areas in 2019: in the UK (23), Ireland (11), Sweden (five), or their absence: Denmark and France (Beaulaton *et al*., 2021; ICES, 2022; Sivebæk, 2021; Staveley & Bergendahl, 2022; Skóra *et al*., 2023; Gareth Davies & Michael Millane, personal communication), which may be a consequence of higher sea surface temperatures in higher latitudes at that time (Nielsen *et al*., 2020).

In 2021, a further increase in freshwater records of *O. gorbuscha* was observed in both the northern and southern areas of invasion – in Norway (>112,000 specimens), Iceland (339), the UK (186), Ireland (45), Sweden (70), and France (four: Beaulaton *et al*., 2021; Diaz Pauli *et al*., 2023; ICES, 2022; Staveley & Bergendahl, 2022; Þórðardóttir & Guðbergsson, 2022; Skóra *et al*., 2023; Gareth Davies & Michael Millane, personal communication).

The high number of adult *O. gorbuscha* reported in Iceland in 2021 led us to believe that successful reproduction could have occurred in Icelandic rivers, followed by potential smolt migration in the spring of 2022. Therefore, a study was undertaken to verify that successful reproduction had occurred in the rivers of southwest Iceland near Reykjavik, namely the rivers Botnsá, Grímsá, and Langá (Figure 1).

The River Botnsá drains from a lake located 386 m above sea level, with the lower 6 km being accessible to anadromous fishes, at least for native salmonids. Six adult *O. gorbuscha* were caught in this short river in 2021. The River Grímsá is a tributary of the River Hvítá, which has an estuary that extends 5 km from the sea. A total of 10 *O. gorbuscha* were caught in the Hvítá in 2021 but none in the Grímsá, whereas 15 *O. gorbuscha* were identified in the VAKI video fish counter (11 males, four females) in the River Langá, although only a single *O. gorbuscha* was reported by anglers for that river.

In May 2022, fishing surveys using nets and electrofishing were carried out to determine if *O. gorbuscha* smolts were present (as an indicator of successful reproduction). To increase the chance of catching *O. gorbuscha* smolts, four nets (0.5 mm mesh-size), each 6 m long, with either small (1 × 1 m) or large (2 × 1 m) net entrances; two of each net size were positioned side by side close to one riverbank and deployed near the mouth of each river. Nets located in the River Botnsá were subject to tidal influence, whereas those in the rivers Grímsá and Langá were above the tidal limit. Nets were left for 1–3 nights and checked daily. In the River Botnsá, electrofishing of 150–200 $m^2$ along the river margins was carried out once upstream of the nets, twice downstream, and once upstream of the nets in the River Langá (Table 1).

All 605 *O. gorbuscha* smolts captured in the rivers Botnsá, Grímsá, and Langá (Table 1) had absorbed their yolk sacs. Fish were found every time the nets were checked. Parr of Atlantic salmon *Salmo salar* L. 1758 were also captured in the three rivers. Three-spined stickleback *Gasterosteus aculeatus* L. 1758 were noted in the rivers Grímsá and Langá. In the River Botnsá, anadromous brown trout *Salmo trutta* L. 1758 parr and an unidentified single flatfish juvenile were also captured.

Two *O. gorbuscha* smolts were captured during each of the two electrofishing surveys in the River Botnsá. *Salmo salar* parr were captured in both rivers Botnsá and Langá, but *S. trutta* parr were captured in the River Botnsá only.

All captured *O. gorbuscha* smolts were killed humanely and retained for measurement in mm of fork length ($L_F$) and in mg of wet mass ($M_W$). The fish were kept frozen and thawed before measurement. A subsample of *O. gorbuscha* smolts ranged in size between 27 and 33 mm $L_F$ ($n = 105$, mean = 30.9 mm), and between 109 and 218 mg $M_W$ ($n = 103$, mean = 164.4 mg).

Although spent female *O. gorbuscha* have been reported for Icelandic rivers, our study is the first to provide evidence of *O. gorbuscha* successfully completing the freshwater phase of the

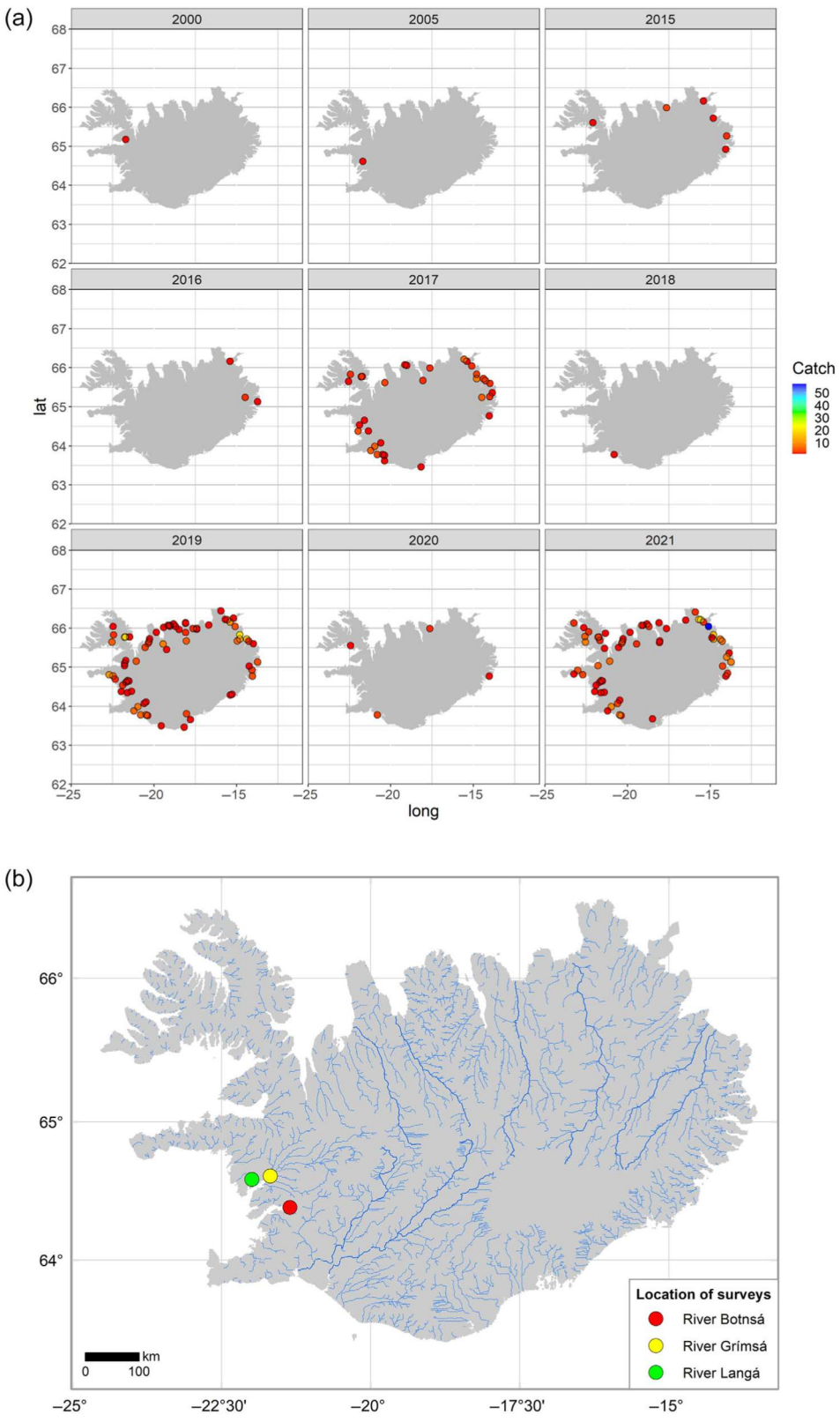


**FIGURE 1** Distribution of pink salmon *Oncorhynchus gorbuscha* in Iceland. (a) Location of rivers in Iceland with reported catches of adult *O. gorbuscha* in 2000, 2005, and annually from 2015 according to Bárðarson *et al.* (2022), and (b) locations of fishing surveys in 2022 to catch smolts of *O. gorbuscha* in three rivers of southwest Iceland

species' life cycle in Iceland. We cannot confirm that successful reproduction did take place in the rivers of northern Iceland, where the highest numbers of *O. gorbuscha* have been recorded. However, the demonstration of successful reproduction in southwestern rivers, despite fewer records of adults in that area, suggests that extensive spawning and recruitment of *O. gorbuscha* may have taken place in Icelandic rivers during 2021. This evidence represents the most western record of *O. gorbuscha* smolts descending to the sea in the North Atlantic. In Norway, *O. gorbuscha* smolts have been recorded as far south as the River Eio (60° N and 7° E) near Bergen (Sandlund

**TABLE 1** Location, water quality variables, capture methods used and numbers of pink salmon *Oncorhynchus gorbuscha* smolts caught in 2022 in three rivers of southwestern Iceland.

| Variables | River Botnsá | River Grímsá | River Langá |
|---|---|---|---|
| Geographic position | 64°23.102′ N, 21°21.196′ W | 64°36.755′ N, 21°41.101′ W | 64°35.282′ N 21°59.520′ W |
| Fishing dates | 17–20 May | 20–21 May | 21–23 May |
| Water temperature [°C] | 9.1 | 7.7 | 6.9 |
| Water pH | 7.11 | 7.20 | 7.04 |
| Water conductivity [μS $cm^{-1}$] | 50.7 | 63.5 | 56.1 |
| Total netting time [h] | 60 | 18.5 | 42 |
| Number of specimens | 550 + 26[†] | 4 | 22 |
| CPUE [number of specimens in four nets·$h^{-1}$] | 9.2 | 0.2 | 0.5 |
| Dates of electrofishing | 18 and 20[‡] May | – | 22 May |
| Covered area [$m^2$] | 200, 150, 150 | – | 150 |
| Number of specimens | 2, 0, 2 | – | 0 |

Abbreviation: CPUE, catch per unit of effort.
[†]Only two nets used.
[‡]Two electrofishing runs that day.

*et al*., 2019), and in Scotland, in the rivers Thurso and Oykel, around 58° N and 3–4° W (Skóra *et al*., 2023).

The onset of *O. gorbuscha* smolt migration occurs when water temperatures exceed 4–5°C, with the highest numbers observed between 5 and 10°C (Kirillov *et al*., 2018; Niemelä *et al*. 2016; Zubchenko *et al*., 2004) Based on water temperatures at the beginning of netting (Table 1), our capture of *O. gorbuscha* smolts occurred close to the peak of their downstream migration.

Similar to the recent evidence of *O. gorbuscha* recruitment in Scotland (Skóra *et al*., 2023), all smolts collected in the three Icelandic rivers had resorbed their yolk sacs. Both observations differ from reports from the native range in the Eastern Pacific (Heard, 1991), where many juvenile *O. gorbuscha* emerge from the gravel with a residual yolk sac that persists until the onset of downstream migration but decreases as the smolts move downstream. Some of the *O. gorbuscha* smolts caught in Iceland had a visibly filled body cavity, evincing active feeding of these fish in the river.

The rate and extent of the *O. gorbuscha* invasion in the North Atlantic have generated much concern about the impacts on native fishes in European countries where large numbers of this species have appeared (e.g., Armstrong *et al*., 2018; Millane *et al*., 2019; Mo *et al*., 2018; Nielsen *et al*., 2020). The spawning time of *O. gorbuscha* (August-September) overlaps with that of some native salmonids: *S. alpinus* (September), *S. salar* (October–December), and *S. trutta* (October–December; starts in northern rivers in September). However, strong selection of *O. gorbuscha* to Atlantic conditions may result in changes in the future (Lennox *et al*., 2023 and the references therein). Among potential implications, the aggressive behavior of *O. gorbuscha* (Quinn, 1999) may disrupt the normal behavior (by wounding, killing, or forcing the latter species to use less suitable positions prior to and during spawning) of both native salmonid parr and spawners, which enter the river earlier than, but spawn after, *O. gorbuscha* (Armstrong *et al*., 2018; Hindar *et al*., 2020, and the references therein). This negative effect may be happening in Iceland, where the incursion of *O. gorbuscha* has coincided with declines in both *S. salar* and *S. alpinus* populations (Svenning *et al*., 2022). In all three rivers, where *O. gorbuscha* smolts were caught, there has been a long-term decline (1987–2021) in the number of *S. salar*; however, such a trend has not been observed in the annual catch (1990–2021) of anadromous *S. trutta* (Þórðardóttir & Guðbergsson, 2022). *Salvelinus alpinus* is not known to occur in the three rivers.

Although *O. gorbuscha* spawning grounds tend to be closer to the sea in the species' native range (Heard, 1991), rivers of the native range are generally longer than those found in Iceland, where the spawning grounds of native salmonids are restricted to the lower sections of rivers. This suggests considerable potential for *O. gorbuscha* to exert impacts on native fishes in Iceland's rivers, during the sea-dwelling phase of their life history and on ecosystem services (Copp, 2017; Cowx, 2019).

The present results indicate that adequate breeding conditions exist in Iceland for *O. gorbuscha*. Future research should determine the origin of *O. gorbuscha* that spawn in Icelandic rivers, for example, as either local recruits or vagrants from Russia and Norway. Owing to the ability of *O. gorbuscha* to migrate great distances, measures to reduce the species' breeding success and abundance should be implemented in Iceland and through concerted international efforts (Hindar *et al*., 2020) with other countries such as Norway and Russia, because increasing stock of *O. gorbuscha* in the North Atlantic may cause pressure on the marine environment, similar to the impact this species has in the North Pacific, where their high abundance can affect the open ocean ecosystem including the seabirds (Springer & van Vliet, 2014; Toge *et al*., 2011).

## AUTHOR CONTRIBUTIONS

Michał E. Skóra, J. Iwan Jones, and Gordon H. Copp conceptualized the study. Michał E. Skóra and Guðni Guðbergsson participated in the fieldwork. Guðni Guðbergsson delivered data on *O. gorbuscha* records

in Iceland. Michał E. Skóra, Guðni Guðbergsson, J. Iwan Jones, and Gordon H. Copp wrote the manuscript.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## DATA AVAILABILITY STATEMENT

The datasets generated and analysed during the current study are available in the Zondero repository https://zenodo.org/record/8380389 and from the corresponding author upon request.

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