Skora Michal Edward (Orcid ID: 0000-0002-9121-1318)

Evidence of potential establishment of pink salmon *Oncorhynchus gorbuscha* in Scotland

Michał E. Skóra[1,2], J. Iwan Jones[1], Alan F. Youngson[3,4], Sean Robertson[5]

Alan Wells[6], Rasmus B. Lauridsen[7], Gordon H. Copp[8,9,10]

[1]School of Biological and Behavioural Sciences, Queen Mary University of London, London, UK

[2]Professor Krzysztof Skóra Hel Marine Station, Institute of Oceanography, Faculty of Oceanography and Geography, University of Gdańsk, Hel, Poland

[3]Environmental Research Institute, University of the Highlands and Islands, Thurso, Caithness, UK

[4]Caithness District Salmon Fishery Board, Thurso, Caithness, UK

[5]Scottish Fisheries Coordination Centre, Freshwater Fisheries Laboratory, Faskally, UK (formerly Kyle of Sutherland District Salmon Fisheries Board, Ardgay, Sutherland, UK)

[6]Fisheries Management Scotland, Edinburgh, UK

[7]Game and Wildlife Conservation Trust, Salmon & Trout Research Centre, Wareham, Dorset, UK

[8]Center for Environment, Fisheries and Aquaculture Science, Lowestoft, Suffolk, UK

[9]Centre for Conservation Ecology, Bournemouth University, Poole, Dorset, UK

[10]Environmental and Life Sciences Graduate Program, Trent University, Peterborough, ON, Canada

Correspondence Michał Skóra, Queen Mary University of London, The River Lab, East Stoke, Wareham, BH20 6BB, UK. Email: m.skora@qmul.ac.uk

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Abstract

In spring 2022, pink salmon *Oncorhynchus gorbuscha* smolts were recorded in the UK. Fish were caught in the Rivers Thurso and Oykel in Scotland between 13 and 17 March. To our knowledge, this is the first observation of *O. gorbuscha* smolts in Europe outside the Scandinavian and Kola peninsulas including other tributaries of the White and Barents Seas. It also provides evidence of successful spawning in 2021, completion of the freshwater phase of the life cycle, and indicates the possibility for potential establishment of an *O. gorbuscha* population in Great Britain.

Key words invasive species, pink salmon, River Oykel, River Thurso, smolt

Statement of Significance

Pink salmon *Oncorhynchus gorbuscha* (Walbaum 1792) are invasive in the North Atlantic, with an irregular but increasing distribution since 2017. The implications for Atlantic salmon *Salmo salar* L. 1758 and other native fish species are unknown. In Scottish rivers, spawning of *O. gorbuscha* was observed in August 2017 and egg trials indicate full resorption of the yolk-sac in alevins by the end of November that year (Knight & Shaw; 2018; Armstrong *et al*., 2018). Upon emergence in late autumn, juveniles were anticipated to descend to sea immediately, where the low food availability in coastal waters during winter was expected to result in poor recruitment, preventing the establishment of a self-sustaining population (Armstrong *et al*., 2018). The present study indicates that *O. gorbuscha* smolts run to sea in spring, having overwintered in fresh water, and that *O. gorbuscha* are successfully utilising spawning grounds in Scotland. *Oncorhynchus gorbuscha* may be beginning to establish self-sustaining populations in Scottish rivers, potentially indicating vulnerability of other suitable rivers in Great Britain.

Among anadromous Pacific salmonids, pink salmon *Oncorhynchus gorbuscha* (Walbaum 1792) is the smallest yet most abundant species. The native distribution of *O. gorbuscha* ranges from rivers in North America from the Beaufort Sea (near the River Mackenzie) to California (River Sacramento) and rivers in Asia from the Laptev Sea (River Lena) to the Sea of Japan (River Tumen and Hokkaido: Heard, 1991). *Oncorhynchus gorbuscha* typically has a 2-year life cycle, with odd and even year reproductive broodlines that do not hybridise, where either one or both can occur within a river system (Heard, 1991). They dominate commercial offshore salmon catches in the North Pacific, both numerically and in terms of mass (NPAFC, 2020). *Oncorhynchus gorbuscha* was deliberately introduced by USSR/Russia into White Sea tributaries to increase fish production over five decades in the second half of the 20th century. Between 1956 and 1979 the stocking material originated mainly from the southern part of the range, i.e. from south Sakhalin Island (Niemelä *et al*., 2016 with the references therein). Despite these massive stockings, which resulted in high landings in the 1970s, *O. gorbuscha* did not establish permanent self-sustaining populations. However, in the years 1985–1999, material for stocking the White Sea tributaries was sourced from the River Ola, which is located further north than Sakhalin Island. These later introductions resulted in *O. gorbuscha* successfully establishing permanent, self-reproducing odd-year populations in the White Sea tributaries.

Oncorhynchus gorbuscha vagrants from the initial releases into the White Sea rivers were first captured in the Great Britain in the 1960s (Shearer & Trewavas, 1960). In the subsequent 56 years, the numbers of *O. gorbuscha* recorded were low and irregular, often as a single observation per year (Armstrong *et al*., 2018). In 2017, the number of fish reported (caught by rod and line, captured as bycatch or targeted netting, observed alive, or found dead) increased unexpectedly, with 139 specimens reported from Scotland and numerous other records across Great Britain and Ireland, including as far south as the River Frome, Dorset (Copp, 2017; Armstrong *et al*., 2018; Millane *et al.*, 2019). This sudden increase was also reported in other North Atlantic countries (e.g. Iceland, Sweden, Denmark, and Germany) with the highest number of records from Norway (Sivebæk, 2017; Mo *et al*., 2018; Sandlund *et al*. 2019; Staveley & Bergendahl, 2022; G. Guðbergsson, & M. Freese, pers. comm.)

and the most southerly being a male captured in the River Canche, Pas-de-Calais in France (Beaulaton *et al.*, 2017).

In 2019, the number of fish recorded in the UK was lower than in 2017 (19 specimens in Scotland). A similar decline was also seen in many other southern intrusions (Ireland, Sweden, Denmark, and Germany). However, the total number of reported fish increased in Norway from 11,483 to 15,721 (river catches) with most catches concentrated in the rivers of Finnmark and Troms (Berntsen *et al*., 2020; Diaz Pauli *et al*., 2022). A notable increase in *O. gorbuscha* records was also reported for Greenland and Iceland (Nielsen *et al*., 2020; G. Guðbergsson, pers. comm), which might be explained by the higher sea surface temperatures prevailing in higher latitudes at that time (Nielsen *et al*., 2020).

In 2021, the total number of *O. gorbuscha* entering North Atlantic tributaries was the highest recorded, especially in Norway where more than 112,000 fish were caught in fresh water (Diaz Pauli *et al*., 2022). The increase was also noted in the Great Britain and Ireland: 171 *O. gorbuscha* were reported in Scotland (FMS; 2022: Figure 1) with records as far south as the River Tamar (Devon/Cornwall border) in England.

Spawning of *O. gorbuscha* in Scotland in 2017 was observed in the Rivers Spey, Ness, Dee (Armstrong *et al*., 2018) and Thurso (A.F. Youngson, pers. obs.). Field observations of the development of eyed eggs kept in incubation chambers in the Spey and Ness documented the hatching of alevins (initiated on 23 September 2017), high mortality before hatching (≈ 98.5 and 97.0%, respectively) and no survival to the stage with complete absorption of yolk-sac (Ness DSFB, 2017; Knight & Shaw, 2018). Based on these observations, combined with the results of rearing eggs collected from the River Dee under controlled conditions in different temperatures, Armstrong *et al*. (2018) concluded that the warmer water temperatures of Scottish rivers compared with North Norwegian rivers would result in *O. gorbuscha* smolts migrating to the sea at the beginning of winter. As the arrival of *O. gorbuscha* juveniles in the marine environment would coincide with a period of low productivity, Armstrong *et al*. (2018) suggested that establishment of *O. gorbuscha* populations in the Britain and Ireland is

unlikely. Whilst the possibility of smolts migrating to the sea in spring was not excluded, it was suggested that this would require *O. gorbuscha* spawning later than was observed (in mid-August) in 2017.

The high number of *O. gorbuscha* reported for some Scottish rivers in 2021 provided the opportunity to investigate the potential that smolt migration occurred in spring. Based on the number of fish recorded in 2021 and in previous years, knowledge of and accessibility to the spawning grounds, and practical constraints due to the size of rivers, the Thurso and Oykel were selected to survey *O. gorbuscha* smolts in spring 2022 (Figure 1).

Regarding the River Thurso, a few adult fish were present in 2017 (10 were caught by rod, three were found dead), and some were known to have spawned. No fish were reported in 2019, whereas, in 2021, most of the *O. gorbuscha* captured in Scotland (73 specimens) were from the Thurso. In 2021, *O. gorbuscha* spawning began around 10 August and petered out at the beginning of September. The Thurso was very shallow in 2021, making it unusually easy to obtain a more precise record of *O. gorbuscha* numbers, which in July were substantial, coinciding with a large number of Atlantic salmon *Salmo salar* L. 1758 holding position in the lowest pool in the main river (six *O. gorbuscha* were reported caught by anglers there). A further 67 *O. gorbuscha* were removed from the river by targeted netting during and after spawning. About 80 *O. gorbuscha* redds were constructed up to 8.5 km from the tidal limit, although the number of redds is probably an under-estimate due to merging of neighbouring redds. No carcasses were identified post-spawning. In total, the run of *O. gorbuscha* adults was estimated to be in the range of 200–250 individuals.

Oncorhynchus gorbuscha were reported in the River Oykel in 2017, 2019 and 2021 with one, five and seven specimens recorded, respectively. Amongst the fish caught in 2021, two specimens were caught by rod and a single female was captured by targeted netting on 20 August, when a shoal of six fish comprising both sexes was identified by drone. In August 2019 after a report of *O. gorbuscha* spawning activity a redd was excavated by hand, and *O. gorbuscha* eggs found to be present which

demonstrated that these fish were spawning in the Oykel. Some trial redds were found in 2021 in a similar location to where redds were dug in 2019. Post-spawning carcasses of two *O. gorbuscha* were found on 11 and 13 August 2021.

In March 2022, 72-h fishing surveys were carried out, using both nets and electrofishing, with the aim of catching *O. gorbuscha* smolts. The nets (0.5 mm mesh size) were 6-meter long, conical, and with either small, 1×1 m, or large, 2×1 m, net entrances (Table 1). The nets were positioned in the thalweg, some distance below where *O. gorbuscha* had spawned the previous year, three nets 6.7 km above the tidal limit in the Thurso and a single net 2.4 km above the tidal limit in the Oykel. The net frames were stabilised by attaching the sides to angle iron driven into the riverbed, which comprised cobbles and gravel, and tethered with ropes to the riverbank. The water depth did not exceed 0.5 m, half the height of the net entrance. Nets were checked in the River Thurso twice per day and in the River Oykel once per day. Electrofishing was carried out upstream (during the first and last day) and downstream (last day) of where the nets were deployed, and covered an area of ≈ 150 m^2 (Table 1) along the shallower river margins.

In total, 95 and 25 *O. gorbuscha* smolts were netted in the Rivers Thurso and Oykel, respectively. All the specimens had absorbed the yolk-sack. (Figure 2). Additionally, in both rivers *S. salar* and brown trout *Salmo trutta* L. 1758 parr, and European eel *Anguilla anguilla* (L. 1758) were captured. Three-spined stickleback *Gasterosteus aculeatus* L. 1758 were noted in the Thurso and single adults of river lamprey *Lampetra fluviatilis* (L. 1758) and brook lamprey *Lampetra planeri* (Bloch 1784) in the Oykel. No juvenile *O. gorbuscha* were captured by electrofishing, but in both rivers, *S. salar* and *S. trutta* parr were captured along with minnow *Phoxinus phoxinus* (L. 1758) in the Oykel. Captured *O. gorbuscha* juveniles were euthanised humanely and retained for measurement of fork length (FL, to the nearest mm below) and weight (in mg). The *O. gorbuscha* smolts were between 27 and 33 mm FL (mean 30.3), and weighed between 83 and 177 mg wet weight (mean 129.8).

To date, there have been no reports of *O. gorbuscha* smolts caught in Scottish rivers nor in other recently invaded rivers outside Scandinavia and Russia. The observations of smolt migration presented here provide the first evidence of successful completion of the freshwater phase of the life-cycle in Great Britain, and may suggest the possibility that self-sustaining populations of this species could become established. Despite very limited 'blind' effort, a significant number of *O. gorbuscha* smolts were caught in both systems where netting took place. It is impossible to calculate the actual number of smolts produced but it is fair to extrapolate from the data presented that recruitment had been significant.

Oncorhynchus gorbuscha smolts have been recorded in Norway as far south as 60°N (near Bergen) in the River Eio (Sandlund *et al*., 2019). According to our knowledge, at around 58°N, the juveniles caught in Scotland are the most southerly observations of successful reproduction of *O. gorbuscha* in the North Atlantic. Nevertheless, it is possible that reproduction could occur further south; future smolt surveys will be required to determine the southern limit of successful *O. gorbuscha* reproduction in Great Britain. Although the numbers of *O. gorbuscha* in the North Atlantic appear to be increasing rapidly, thereby increasing the likelihood of populations establishing in Great Britain, the number of adults may vary inter-annually due to the fluctuations in marine conditions between years.

Based on observations of incubated eggs in the River Spey (Scotland), the time to fry emergence has been estimated to be 1075 degree-days (Knight & Shaw, 2018). Much shorter periods (in degree-days) have been reported for the species in its native range, determined under natural environment and controlled conditions (Heard, 1991): 950–970 (Bams, 1972), 900–980 (Bailey, 1980), 889–1000 (Sheridan, 1962). Time to hatching (in degree-days) is also reportedly variable, lasting from 100–162 (Sheridan, 1962), 450–500 (unpublished data from Sandlund *et al*., 2018) to 610 degree-days (Gjedrem & Gunnes, 1978). The timing of capture of *O. gorbuscha* smolts in the Rivers Thurso and Oykel in comparison with estimated time from spawning to hatching (based on degree-days) indicates

that juvenile *O. gorbuscha* may remain in the river for a prolonged period before migration (Figure 3) rather than migrating immediately upon hatching, as was previously suggested (Armstrong *et al*. 2018).

In the northeast of Sakhalin Island, *O. gorbuscha* smolts start migrating when the water temperature reaches 4–5°C, with the highest numbers observed between 5 and 10°C (Kirillov *et al*. 2018). A similar temperature was noted (5.1°C) when smolts initiated migration in the Indera River (White Sea) with a peak in the range 6.2–8.8°C (Niemelä *et al*., 2016 after Zubchenko *et al*. 2004). The mean daily water temperature in the Thurso (5.7–6.4°C) and Oykel (4.6–5.5°C) during the period of fishing varied and was on a downward trend (Figure 3). As smolt migration at higher latitudes starts when water temperature increases to about 5°C, it is not possible to indicate when the migration of smolts started in the rivers studied here, nor how long it lasted. Although there is no evidence of *O. gorbuscha* migrating in autumn or winter, migration may have started in January or earlier (Figure 3). The duration of the *O. gorbuscha* smolt run depends on the region, water temperature and water level, mainly lasting seven days but can last up to two and half months (Kirillov *et al*., 2018; Pavlov *et al*., 2015).

The *O. gorbuscha* smolts collected in the Thurso and Oykel had resorbed their yolk-sac. This contrasts with the situation in the species' native range, where many *O. gorbuscha* juveniles emerge as alevins with residual yolk (Heard, 1991). Heard (1991) reported the yolk-sac to persist until the start of downstream migration, with the proportion of individuals with yolk decreasing as downstream migration progressed. Considering the time interval between spawning and the capture of *O. gorbuscha* smolts (Figure 3), this may suggest that the captured *O. gorbuscha* had been actively feeding whilst in the river.

Initial risk assessment of the potential impacts of *O. gorbuscha* on native species assumed that *O. gorbuscha* would migrate downstream more or less immediately after emergence, as reported in the native range (Copp, 2017), so "there is likely to be little competition for food with juvenile life stages of native fishes and the difference in size of emerging alevins against native salmonid fry and

parr in the late summer period would suggest such competition is unlikely." (p. 45 of Cowx, 2019). The results of the present study suggest that interactions with *S. salar* fry could take place.

The incursions of *O. gorbuscha* into the rivers of Great Britain and Ireland in recent years has generated great concern, with particular regard to possible implications for *S. salar* stocks. These incursions have coincided with a period of decline in *S. salar* populations in the North Atlantic (ICES, 2021). Interactions with *O. gorbuscha* may put further pressure on *S. salar* at a number of stages in their life-cycle, both in the freshwater and marine environment. Furthermore, other freshwater species may be affected through the fertilization of rivers with marine derived nutrients by returning adult *O. gorbuscha*. Based on the present study, it can be concluded that actions towards removing *O. gorbuscha* before they spawn are necessary in order to reduce the number of *O. gorbuscha* smolts entering the sea, as these offspring could return to natal rivers in Scotland. Such concerted actions to remove *O. gorbuscha* at a regional, national, and international level have been advocated by Norwegian scientists (VKM, 2020).

In conclusion, *O. gorbuscha* has made the first steps towards becoming established in Great Britain. Since 2017, with every reproductive cycle adult O. *gorbuscha* have entered British rivers in order to breed: spawning has taken place in each reproductive year. Contrary to expectations, these spawning can produce viable offspring capable of migrating to the sea at the smolt stage in spring, thus completing the freshwater stage of the life-cycle in Scotland. It is not known if these Scottish smolts survive to adulthood and successfully return to breed in their natal rivers, although in the current period of range expansion of *O. gorbuscha* in the North Atlantic it is clear that homing behaviour has yet to become the norm; Scottish smolts may eventually breed in rivers elsewhere and vice versa, with vagrant adults helping to support the colonisation of Scottish rivers. Only time will tell if the species establishes a self-sustaining population in Great Britain.

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Authors contribution

M.E.S., J.I.J. and G.H.C. conceptualized the study, M.E.S., A.F.Y. and S.R. participated in fieldwork, A.W. delivered data on fish records in Scotland, M.E.S. wrote and J.I.J., G.H.C., R.B.L, A.F.Y., S.R. and A.W. edited the manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Fishing was carried out under consent of Marine Scotland (App. Ref CSM-22-027).

ORCID

Michał E. Skóra https://orcid.org/0000-0002-9121-1318

J. Iwan Jones https://orcid.org/0000-0002-7238-2509

Rasmus B. Lauridsen https://orcid.org/0000-0002-7100-1161

Alan Wells https://orcid.org/0000-0003-0419-8141

Gordon H. Copp https://orcid.org/0000-0002-4112-3440

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Table 1. The location, environmental features, and methods used in fishing for pink salmon *Oncorhynchus gorbuscha* smolts in the Scottish rivers in 2022

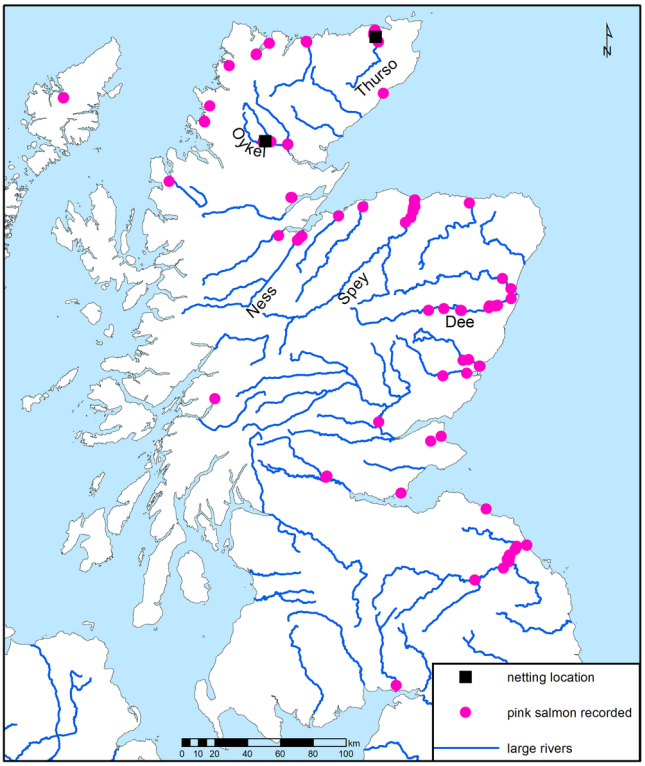
parameters	River Thurso	River Oykel
geographic position	58°33.385'N, 3°30.650'W	57°58.468'N, 4°38.377'W
dates of fishing	13–16 March	14–17 March
water temp. [°C] min-max	5.7–6.4	4.6–5.5
pH / conductivity [$\mu S \cdot cm^{-1}$]	6.35 / 168	6.5 / 190
number and size of nets	2 small, 1 large	1 large
dates of electrofishing	13, 16 March	14, 17 March
electrofishing equipment	Electrafish, DC, 240V, Honda generator	Electracatch, WFC-8, DC, <400V, battery

Figure captions

Figure 1. Map of Scotland indicating location of fish surveys and records of pink salmon *Oncorhynchus gorbuscha* in Scottish rivers in 2021. Pink salmon were also recorded in England, Wales and Ireland in 2021 (not shown).

Figure 2. Pink salmon *Oncorhynchus gorbuscha* smolts caught in the River Oykel on 15 March 2022

Figure 3. Mean daily water temperatures in the Rivers Thurso and Oykel near to the netting locations between 1 August 2021 and 1 April 2022. Horizontal bars indicate the timing of spawning of pink salmon *Oncorhynchus gorbuscha* observed in the River Thurso, the earliest to latest estimated dates of hatching and fry emergence in the Thurso based on degree days of incubation of pink salmon eggs according to different authors (Sheridan, 1962; Gjedrem & Gunnes, 1978; Bams, 1979; Bailey, 1980; Knight & Shaw, 2018; unpublished data from Sandlund *et al*., 2019), and the timing of surveys of pink salmon smolts



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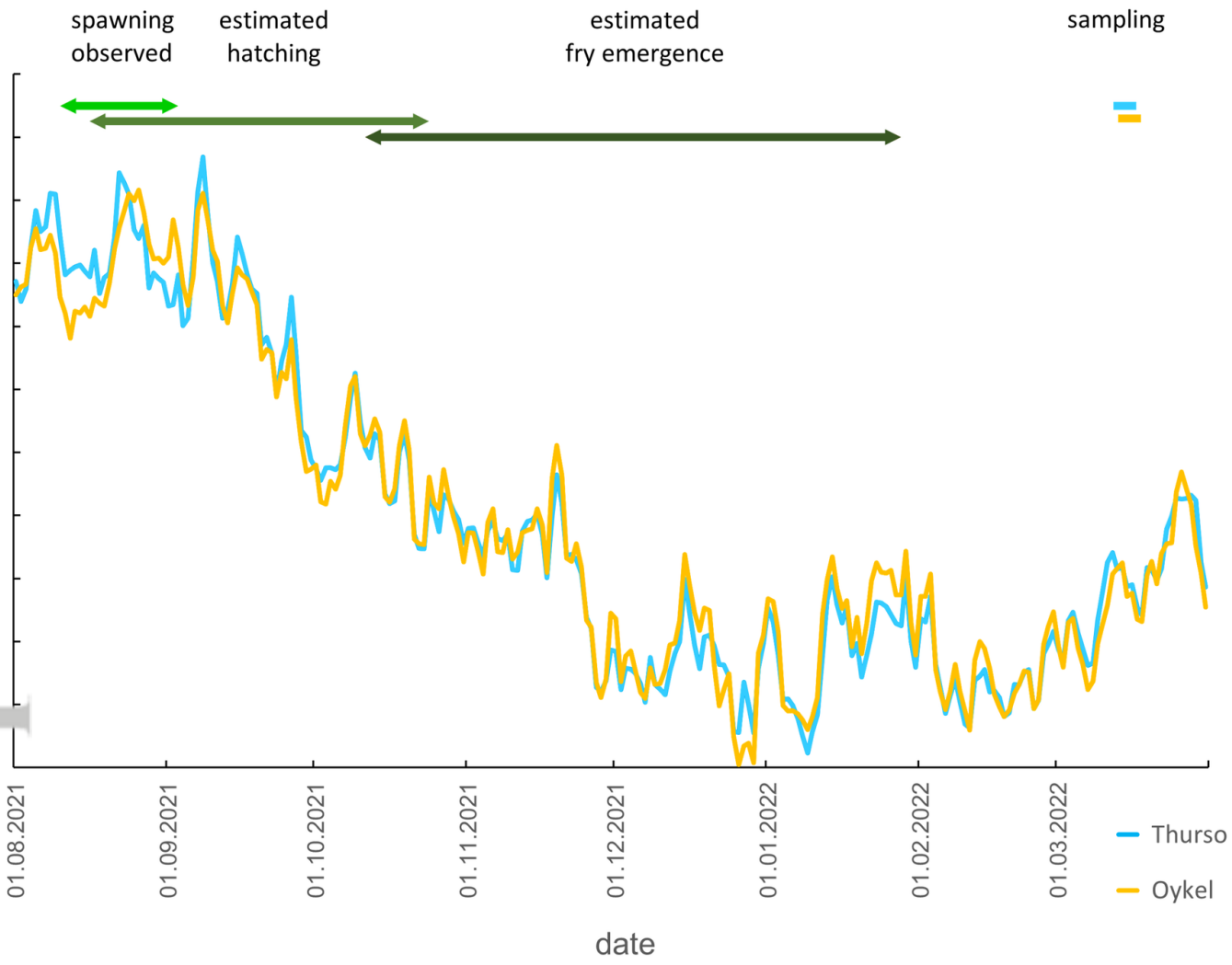
JFB_15304_Skora et al_pink salmon smolts in Scotland_Figure 2.tiff



JFB_15304_Skora et al_pink salmon in Scotland_Figure 3_improved.tif