HOKKAIDO UNIVERSITY

Title	Invasion status of hatchery-origin pink salmon in an unstocked river at the Shiretoko World Natural Heritage Site in northern Japan
Author(s)	Yamada, Taihei; Nobetsu, Takahiro; Urabe, Hirokazu et al.
Citation	Journal of fish biology, 104(5), 1633-1637 https://doi.org/10.1111/jfb.15690
Issue Date	2024-02-19
Doc URL	https://hdl.handle.net/2115/94128
Rights	This is the peer reviewed version of the following article: Yamada, T., Nobetsu, T., Urabe, H., & Nakamura, F. (2024). Invasion status of hatchery-origin pink salmon in an unstocked river at the Shiretoko World Natural Heritage Site in northern Japan. Journal of Fish Biology, 104(5), 1633-1637, which has been published in final form at https://doi.org/10.1111/jfb.15690. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions. This article may not be enhanced, enriched or otherwise transformed into a derivative work, without express permission from Wiley or by statutory rights under applicable legislation. Copyright notices must not be removed, obscured or modified. The article must be linked to Wiley's version of record on Wiley Online Library and any embedding, framing or otherwise making available the article or pages thereof by third parties from platforms, services and websites other than Wiley Online Library must be prohibited.
Type	journal article
File Information	jfb.15690.pdf

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Invasion status of hatchery-origin pink salmon in an unstocked river at the Shiretoko World Natural Heritage Site in northern Japan

Taihei Yamada[1,2*], Takahiro Nobetsu[3], Hirokazu Urabe[4], Futoshi Nakamura[1]

[1]Graduate School of Agriculture, Hokkaido University, Sapporo, Hokkaido, Japan

[2]Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Hokkaido, Japan

[3]Shiretoko Nature Foundation, Rausu, Hokkaido, Japan

[4]Salmon and Freshwater Fisheries Research Institute, Hokkaido Research Organization, Eniwa, Hokkaido, Japan

***Corresponding author**: Taihei Yamada, Faculty of Environmental Earth Science, Hokkaido University, N10 W5, Sapporo, Hokkaido 060-0810, Japan

Email: thymd8@gmail.com

Funding information: This study was supported by JSPS KAKENHI (Grant Numbers 21H03647, 22J11475) and JST SPRING (Grant Number JPMJSP2119).

Ethical statement: Only postspawning carcasses were handled in this study; after otolith removal, the carcasses were returned to near the pickup locations.

Abstract

Hatchery fish and their offspring (including hatchery-wild hybrids) have lower reproductive success than wild fish. Thus, straying of hatchery fish may negatively impact wild populations, depending on the number of wild salmon returning and hatchery strays. We investigated the straying status of hatchery-origin pink salmon (*Oncorhynchus gorbuscha*), which have a higher straying rate than other salmonids, in an unstocked river at the Shiretoko World Natural Heritage Site, Japan. The hatchery strays accounted for 40.0% and 19.0% of the total samples in 2021 and 2022, respectively. These results indicate that hatchery pink salmon have invaded unstocked rivers and potentially genetically affect wild populations.

Keywords: Salmonidae, migration, straying, hatchery salmon, hatchery-wild interactions.

Hatchery releases are conducted worldwide for the conservation and enhancement of various fish species, including anadromous salmonids (Kitada, 2018; Laikre et al., 2010; Naish et al., 2007). However, hatchery fish have lower reproductive success than wild fish, and offspring of hatchery fish (including hatchery-wild hybrids) also display reduced reproductive success (Araki et al., 2007, 2009; Christie et al., 2014). Therefore, the genetic interactions between wild and hatchery fish may negatively impact wild salmonid populations in a stocked river, depending on the number of hatchery strays and wild salmon returning. Spawners of anadromous salmonids often stray to rivers other than where they hatched or were released, especially hatchery fish, which may have high straying rates (Brenner et al., 2012; Jonsson et al., 2003; Quinn, 1993). Hence, even in unstocked rivers, genetic interactions between wild and straying hatchery fish can negatively affect wild fish.

Offspring between hatchery and wild pink salmon (*Oncorhynchus gorbuscha*) tend to have lower reproductive success than offspring of wild fish (Shedd et al., 2022). Because pink salmon generally have higher straying rates than other anadromous salmonids (Hendry et al., 2004; Quinn, 1993), genetic interactions can be common even in unstocked rivers and may negatively impact wild populations, depending on the number of wild salmon returning and hatchery strays. However, studies examining the straying rates of hatchery pink salmon in unstocked rivers have been conducted in limited regions such as Alaska (e.g., Brenner et al., 2012; Knudsen et al., 2021; Shedd et al., 2022). Here, we investigated the straying rate of hatchery pink salmon in an unstocked river on the Shiretoko Peninsula, Hokkaido, northern Japan, in 2021 and 2022. The central part of the Shiretoko Peninsula has been inscribed as a World Natural Heritage Site, in part because of the close linkages between the terrestrial and marine ecosystems supported by pink and chum salmon (*O. keta*) (IUCN, 2005). For example,

these two species are utilized by aquatic invertebrates, stream fishes, and terrestrial animals (Koshino et al., 2013; Shirane et al., 2021; Yamada et al., 2022). While Hokkaido is one of the most active regions in salmon hatchery programs (Morita et al., 2006), a decline in pink salmon returns has been observed in recent years (Saito, 2021). Maintaining healthy wild salmon populations is essential to preserve these valuable ecosystems, and it is necessary to understand the status of straying hatchery-reared pink salmon into unstocked rivers to properly manage pink salmon populations. From 2018 to 2021, the otoliths of all hatchery pink salmon released on the Hokkaido mainland were thermally marked. In short, this study was conducted at an opportune time to examine the invasion status of the hatchery fish.

We selected the Rusa River on the Shiretoko Peninsula, Hokkaido, northern Japan, as the study river (Figure 1). The watershed area, river length, and mean river slope of Rusa River are 9.2 km^2, 5.5 km and 1/7, respectively (Nakayama et al., 2018). Most of the river basin is included in the Shiretoko World Natural Heritage Site. Although hatchery pink salmon were released into this river as recently as May 2019 and April 2012, fish released in those years had already returned in 2020 and 2013, respectively; therefore, these fish were not included in this study. In addition, this river is not currently the target of hatchery programs for pink salmon. All hatchery pink salmon released from the Hokkaido mainland between 2018 and 2021 had thermally marked otoliths. Otolith collection requires destructive sampling; to avoid lethal sampling, we removed otoliths only from postspawning carcasses. Otolith sampling was conducted from September to October 2021 and 2022, the spawning season for pink salmon in this region (Yamada et al., 2024). We collected both sagittal otoliths and recorded the sex of the individuals. After sampling, the otoliths were polished and inspected by three experts using a microscope (BX53, Olympus, Japan) for the presence of hatchery thermal marks. If thermal marks were observed, the

individual release area was identified using a public thermal mark list (http://wgosm.npafc.org/MarkSummary.aspx). The fish with thermal marks were considered hatchery strays, whereas those without thermal marks were considered wild fish.

Hatchery strays accounted for 40.0% and 19.0% of the total samples in 2021 (number of total otolith samples = 130) and 2022 (number of total otolith samples = 84), respectively (Figure 2a; Table S1; Table S2), although we note that errors often arise in otolith thermal marking (Volk et al., 1999). Hatchery salmon from the Hokkaido mainland accounted for 30.0% and 15.5% of the total samples in 2021 and 2022, respectively, while those from the other regions (Etorofu Island and Magadan) accounted for 10.0% and 3.6% in 2021 and 2022, respectively (Figure 2a; Table S1; Table S2). In addition, temporal patterns in the number of carcasses were similar between wild and hatchery fish each year (Figure 2b). These results suggested that hatchery pink salmon invaded wild populations in an unstocked river on the Shiretoko Peninsula during wild fish spawning periods, similar to what was observed in several studies conducted in Alaska (e.g., Brenner et al., 2012; Knudsen et al., 2021; Shedd et al., 2022). In recent years, the distribution of pink salmon as an invasive species has expanded (Lennox et al., 2023; Millane et al., 2019; Mo et al., 2018; Nielsen et al., 2020; Skóra et al., 2023); these trends indicate pink salmon have high dispersal capabilities. On the other hand, contrary to the general understanding that pink salmon have a high straying rate, there is some evidence that pink salmon have a low straying rate and fine-scale homing behaviour (May et al., 2023; Mortensen et al., 2002; Thedinga et al., 2000). Understanding what factors determine the straying rate of pink salmon can contribute to achieving appropriate management of pink salmon.

Hatchery fish and their offspring (including hatchery-wild hybrids) have lower reproductive success than wild fish (Araki et al., 2007, 2009; Christie et al., 2014; Shedd et al.,

104 2022). Therefore, genetic interactions between wild and hatchery fish may negatively impact
105 wild populations, depending on the number of wild salmon returning and hatchery strays. On the
106 other hand, if admixed individuals have a lower return rate than wild fish, then there may be
107 fewer negative impacts on wild populations in the unstocked river. Further investigation is crucial
108 to determine the impact of straying hatchery pink salmon on the wild population. In addition to
109 genetic impacts, there may be additional negative impacts through their spawning behaviour.
110 Since anadromous salmonids spawn their eggs in gravel (Quinn, 2018), high spawner densities
111 can lead to the excavation of previously buried eggs, resulting in increased egg loss and
112 decreased reproductive success (Essington et al., 2000; Fukushima et al., 1998). An increase in
113 spawner density due to high straying rates may result in a high frequency of redd
114 superimposition.

115 While the otoliths of all hatchery pink salmon released in the Hokkaido mainland
116 between 2018 and 2021 were thermally marked, only a portion of the total released fish was
117 marked on the Asian side of the Pacific region other than the Hokkaido mainland. In this study,
118 hatchery fish from outside the Hokkaido mainland were observed; therefore, our results may
119 underestimate the straying status of hatchery pink salmon from regions outside the Hokkaido
120 mainland into the unstocked river. Hence, further studies are needed to assess the status of
121 straying more accurately into unstocked rivers.

122 In Japan, pink salmon stock management has been highly dependent on hatchery
123 programs, but a decline in pink salmon returns has been observed in recent years (Saito, 2021).
124 Considering the high straying rate of hatchery pink salmon observed in the present study and its
125 potential adverse impacts on wild populations, sustainable stock management strategies based on

wild populations should be considered to preserve their valuable ecological functions and continue to receive commercial benefits.

ACKNOWLEDGEMENTS

We thank Megumi Mizoe and Yui Funaki, who helped with the otolith handling. We would like to thank Professor Kentaro Morita for his valuable comments on an earlier draft of the manuscript. We are also grateful to the anonymous reviewer and the Editor for their helpful comments on an earlier draft of the manuscript. This study was supported by JSPS KAKENHI (Grant Numbers 21H03647, 22J11475) and JST SPRING (Grant Number JPMJSP2119).

CONFLICT OF INTEREST

None declared.

AUTHOR CONTRIBUTIONS

Conceptualization, writing: TY, TN, HU, FN. Conducting the research, data interpretation: TY, TN, HU. Preparation figures: TY.

DATA AVAILABILITY STATEMENT

The datasets supporting this article will be deposited in the Figshare repository after acceptance. **Only for peer review**: https://figshare.com/s/ab75976aa10a3a1c03f6

REFERENCES

Araki, H., Cooper, B., & Blouin, M. S. (2007). Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science*, *318*(5847), 100–103. https://doi.org/10.1126/science.1145621

Araki, H., Cooper, B., & Blouin, M. S. (2009). Carry-over effect of captive breeding reduces reproductive fitness of wild-born descendants in the wild. *Biology Letters*, *5*(5), 621–624. https://doi.org/10.1098/rsbl.2009.0315

Brenner, R. E., Moffitt, S. D., & Grant, W. S. (2012). Straying of hatchery salmon in Prince William Sound, Alaska. *Environmental Biology of Fishes*, *94*(1), 179–195. https://doi.org/10.1007/s10641-012-9975-7

Christie, M. R., Ford, M. J., & Blouin, M. S. (2014). On the reproductive success of early-generation hatchery fish in the wild. *Evolutionary Applications*, *7*(8), 883–896. https://doi.org/10.1111/eva.12183

Essington, T. E., Quinn, T. P., & Ewert, V. E. (2000). Intra- and inter-specific competition and the reproductive success of sympatric Pacific salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, *57*(1), 205–213. https://doi.org/10.1139/f99-198

Fukushima, M., Quinn, T. J., & Smoker, W. W. (1998). Estimation of eggs lost from superimposed pink salmon (*Oncorhynchus gorbuscha*) redds. *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(3), 618–625. https://doi.org/10.1139/f97-260

Hendry, A. P., Castric, V., Kinnison, M. T., & Quinn, T. P. (2004). The evolution of philopatry and dispersal: homing versus straying in salmonids. In Andrew P. Hendry & Stephen C. Stearns (Eds.), *Evolution Illuminated: Salmon and Their Relatives* (pp. 52–91). Oxford University Press.

IUCN. (2005). *World heritage nomination – IUCN technical evaluation, Shiretoko (Japan)*. https://whc.unesco.org/document/152000

Jonsson, B., Jonsson, N., & Hansen, L. P. (2003). Atlantic salmon straying from the River Imsa. *Journal of Fish Biology*, *62*(3), 641–657. https://doi.org/10.1046/j.1095-8649.2003.00053.x

Kitada, S. (2018). Economic, ecological and genetic impacts of marine stock enhancement and sea ranching: A systematic review. *Fish and Fisheries*, *19*(3), 511–532. https://doi.org/10.1111/faf.12271

Knudsen, E. E., Rand, P. S., Gorman, K. B., Bernard, D. R., & Templin, W. D. (2021). Hatchery-origin stray rates and total run characteristics for pink salmon and chum salmon returning to Prince William Sound, Alaska, in 2013–2015. *Marine and Coastal Fisheries*, *13*(1), 41–68. https://doi.org/10.1002/mcf2.10134

Koshino, Y., Kudo, H., & Kaeriyama, M. (2013). Stable isotope evidence indicates the incorporation into Japanese catchments of marine-derived nutrients transported by spawning Pacific Salmon. *Freshwater Biology*, *58*(9), 1864–1877. https://doi.org/10.1111/fwb.12175

Laikre, L., Schwartz, M. K., Waples, R. S., & Ryman, N. (2010). Compromising genetic diversity in the wild: unmonitored large-scale release of plants and animals. *Trends in Ecology & Evolution*, *25*(9), 520–529. https://doi.org/10.1016/j.tree.2010.06.013

Lennox, R. J., Berntsen, H. H., Garseth, Å. H., Hinch, S. G., Hindar, K., Ugedal, O., Utne, K. R., Vollset, K. W., Whoriskey, F. G., & Thorstad, E. B. (2023). Prospects for the future of pink salmon in three oceans: From the native Pacific to the novel Arctic and Atlantic. *Fish and Fisheries*. https://doi.org/10.1111/faf.12760

May, S. A., Shedd, K. R., Rand, P. S., & Westley, P. A. H. (2023). Tidal gradients, fine-scale homing and a potential cryptic ecotype of wild spawning pink salmon (*Oncorhynchus gorbuscha*). *Molecular Ecology*, *32*(21), 5838–5848. https://doi.org/10.1111/mec.17154

Millane, M., Walsh, L., Roche, W. K., & Gargan, P. G. (2019). Unprecedented widespread occurrence of Pink Salmon *Oncorhynchus gorbuscha* in Ireland in 2017. *Journal of Fish Biology*, *95*(2), 651–654. https://doi.org/10.1111/jfb.13994

Mo, T. A., Thorstad, E. B., Sandlund, O. T., Berntsen, H. H., Fiske, P., & Uglem, I. (2018). The pink salmon invasion: a Norwegian perspective. *Journal of Fish Biology*, *93*(1), 5–7. https://doi.org/10.1111/jfb.13682

Morita, K., Saito, T., Miyakoshi, Y., Fukuwaka, M. aki, Nagasawa, T., & Kaeriyama, M. (2006). A review of Pacific salmon hatchery programmes on Hokkaido Island, Japan. *ICES Journal of Marine Science*, *63*(7), 1353–1363. https://doi.org/10.1016/j.icesjms.2006.03.024

Mortensen, D. G., Wertheimer, A. C., Maselko, J. M., & Taylor, S. G. (2002). Survival and straying of Auke Creek, Alaska, pink salmon marked with coded wire tags and thermally induced otolith marks. *Transactions of the American Fisheries Society*, *131*(1), 14–26. https://doi.org/10.1577/1548-8659(2002)131<0014:SASOAC>2.0.CO;2

Naish, K. A., Taylor, J. E., Levin, P. S., Quinn, T. P., Winton, J. R., Huppert, D., & Hilborn, R. (2007). An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. In *Advances in Marine Biology* (Vol. 53, Issue 07, pp. 61–194). https://doi.org/10.1016/S0065-2881(07)53002-6

Nakayama, K., Maruya, Y., Matsumoto, K., Komai, K., & Kuwae, T. (2018). Nitrogen fluxes between the ocean and a river basin using stable isotope analysis. *Estuarine, Coastal and Shelf Science*, *212*, 286–293. https://doi.org/10.1016/j.ecss.2018.07.015

Nielsen, J., Rosing-Asvid, A., Meire, L., & Nygaard, R. (2020). Widespread occurrence of pink salmon (*Oncorhynchus gorbuscha*) throughout Greenland coastal waters. *Journal of Fish Biology*, *96*(6), 1505–1507. https://doi.org/10.1111/jfb.14318

Quinn, T. P. (1993). A review of homing and straying of wild and hatchery-produced salmon. *Fisheries Research*, *18*(1–2), 29–44. https://doi.org/10.1016/0165-7836(93)90038-9

Quinn, T. P. (2018). *The behavior and ecology of Pacific salmon and trout* (Second Edi). University of Washington Press.

Saito, T. (2021). An overview of the recent salmon returns in Japan: Poor returns of chum and pink salmon. *North Pacific Anadromous Fish Commission Technical Report*, *17*, 32–34. https://doi.org/10.23849/npafctr17/32.34

Shedd, K. R., Lescak, E. A., Habicht, C., Knudsen, E. E., Dann, T. H., Hoyt, H. A., Prince, D. J., & Templin, W. D. (2022). Reduced relative fitness in hatchery-origin Pink Salmon in two streams in Prince William Sound, Alaska. *Evolutionary Applications*, *15*(3), 429–446. https://doi.org/10.1111/eva.13356

Shirane, Y., Jimbo, M., Yamanaka, M., Nakanishi, M., Mori, F., Ishinazaka, T., Sashika, M., Tsubota, T., & Shimozuru, M. (2021). Dining from the coast to the summit: Salmon and pine nuts determine the summer body condition of female brown bears on the Shiretoko Peninsula. *Ecology and Evolution*, *11*(10), 5204–5219. https://doi.org/10.1002/ece3.7410

Skóra, M. E., Jones, J. I., Youngson, A. F., Robertson, S., Wells, A., Lauridsen, R. B., & Copp, G. H. (2023). Evidence of potential establishment of pink salmon *Oncorhynchus gorbuscha* in Scotland. *Journal of Fish Biology*, *102*(3), 721–726. https://doi.org/10.1111/jfb.15304

Thedinga, J. F., Wertheimer, A. C., Heintz, R. A., Maselko, J. M., & Rice, S. D. (2000). Effects of stock, coded-wire tagging, and transplant on straying of pink salmon (*Oncorhynchus*

gorbuscha) in southeastern Alaska. *Canadian Journal of Fisheries and Aquatic Sciences*, *57*(10), 2076–2085. https://doi.org/10.1139/f00-163

Volk, E. C., Schroder, S. L., & Grimm, J. J. (1999). Otolith thermal marking. *Fisheries Research*, *43*(1–3), 205–219. https://doi.org/10.1016/S0165-7836(99)00073-9

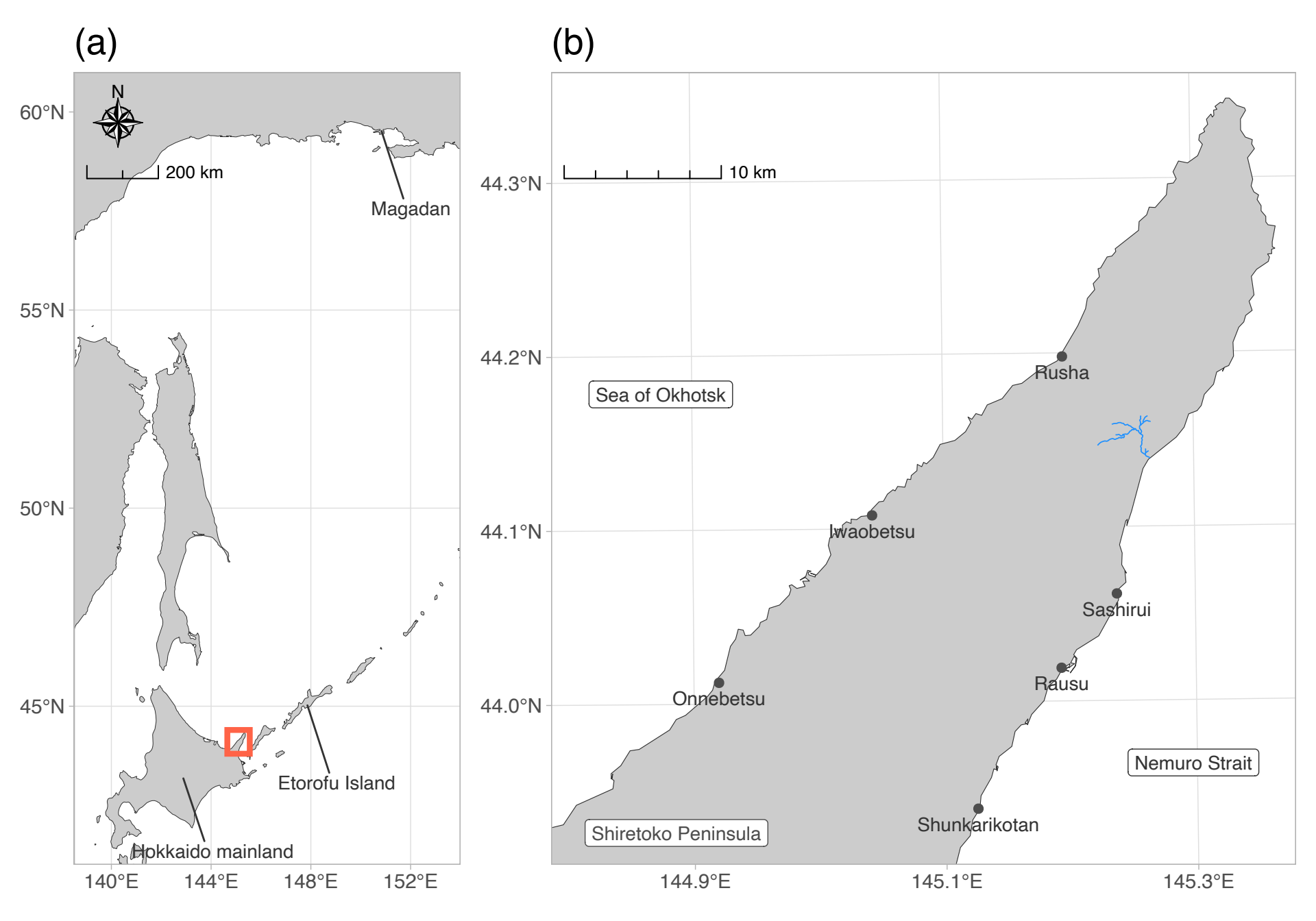
Yamada, T., Katahira, H., Miura, K., & Nakamura, F. (2022). Relationship between salmon egg subsidy and the distribution of an avian predator. *Ecology and Evolution*, *12*(12), e9696. https://doi.org/10.1002/ece3.9696

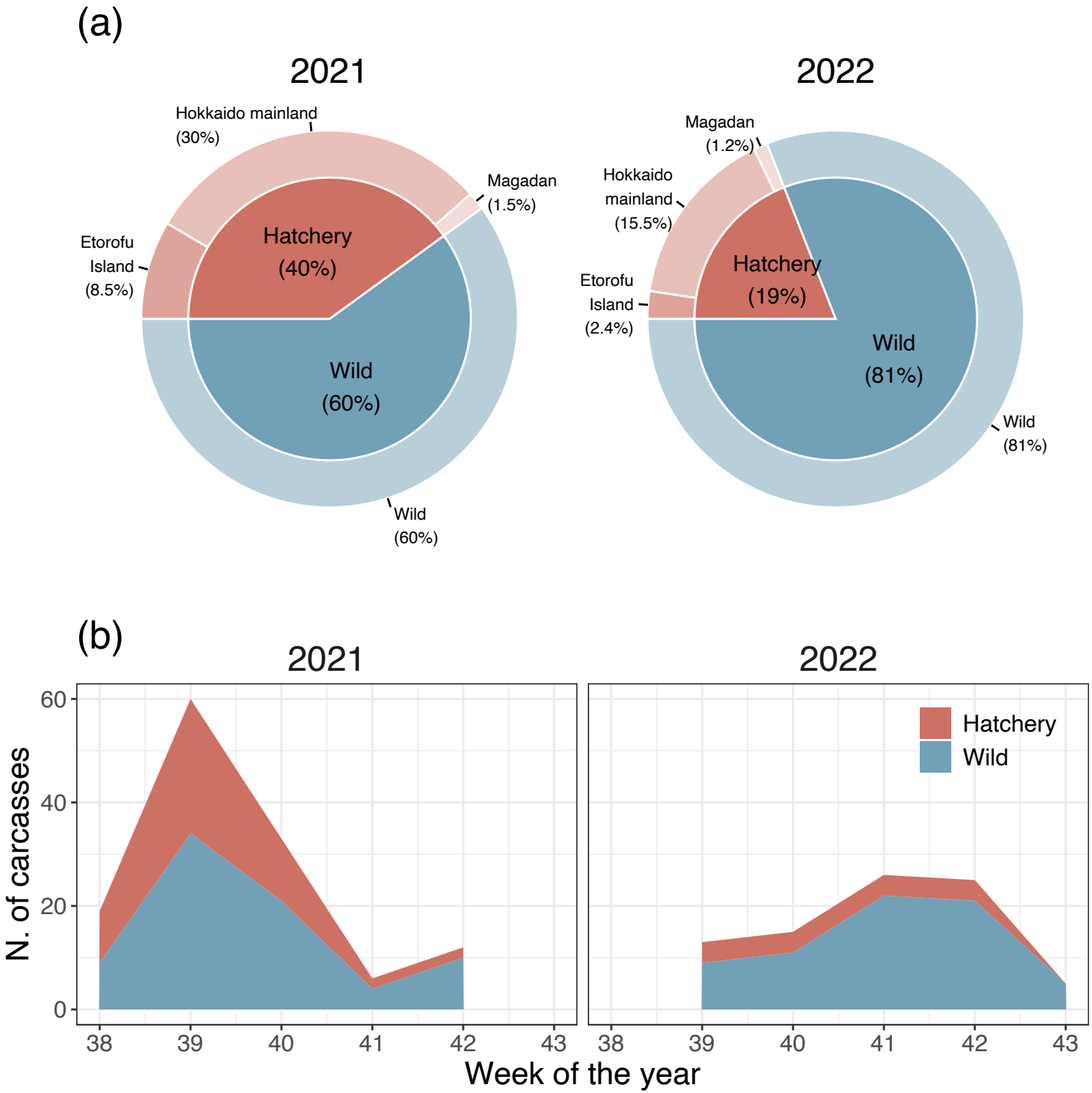
Yamada, T., Urabe, H., & Nakamura, F. (2024). Pink salmon productivity is driven by catchment hydrogeomorphology and can decline under a changing climate. *Freshwater Biology*. https://doi.org/10.1111/fwb.14217

FIGURE CAPTIONS

Figure 1. (a) The location of the study area (shown as an open orange square), the Shiretoko Peninsula in northern Japan. (b) Enlarged view of the study area. The blue line and filled circles indicate the study river (Rusa River) and the sites where hatchery release was conducted in 2020 and 2021 around the study river, respectively.

Figure 2. (a) Relative proportions of carcass origin for each year surveyed (n = 130 in 2021, n = 84 in 2022). The internal circle refers to the origin of the individual (hatchery or wild); the external ring refers to the regions where individuals were released. (b) Weekly trends in the number of carcasses found by origin for each year.


(a)
N
200 km
Magadan
60°N
55°N
50°N
45°N
Etorofu Island
Hokkaido mainland
140°E
144°E
148°E
152°E
(b)
10 km
44.3°N
44.2°N
44.1°N
44.0°N
Sea of Okhotsk
Rusha
Iwaobetsu
Sashirui
Rausu
Onnebetsu
Nemuro Strait
Shunkarikotan
Shiretoko Peninsula
144.9°E
145.1°E
145.3°E


(a)
2021
Hokkaido mainland
(30%)
Magadan
(1.5%)
Etorofu
Island
(8.5%)
Hatchery
(40%)
Wild
(60%)
Wild
(60%)
2022
Magadan
(1.2%)
Hokkaido
mainland
(15.5%)
Etorofu
Island
(2.4%)
Hatchery
(19%)
Wild
(81%)
Wild
(81%)
(b)
2021
2022
Hatchery
Wild
N. of carcasses
0
20
40
60
38
39
40
41
42
43
Week of the year