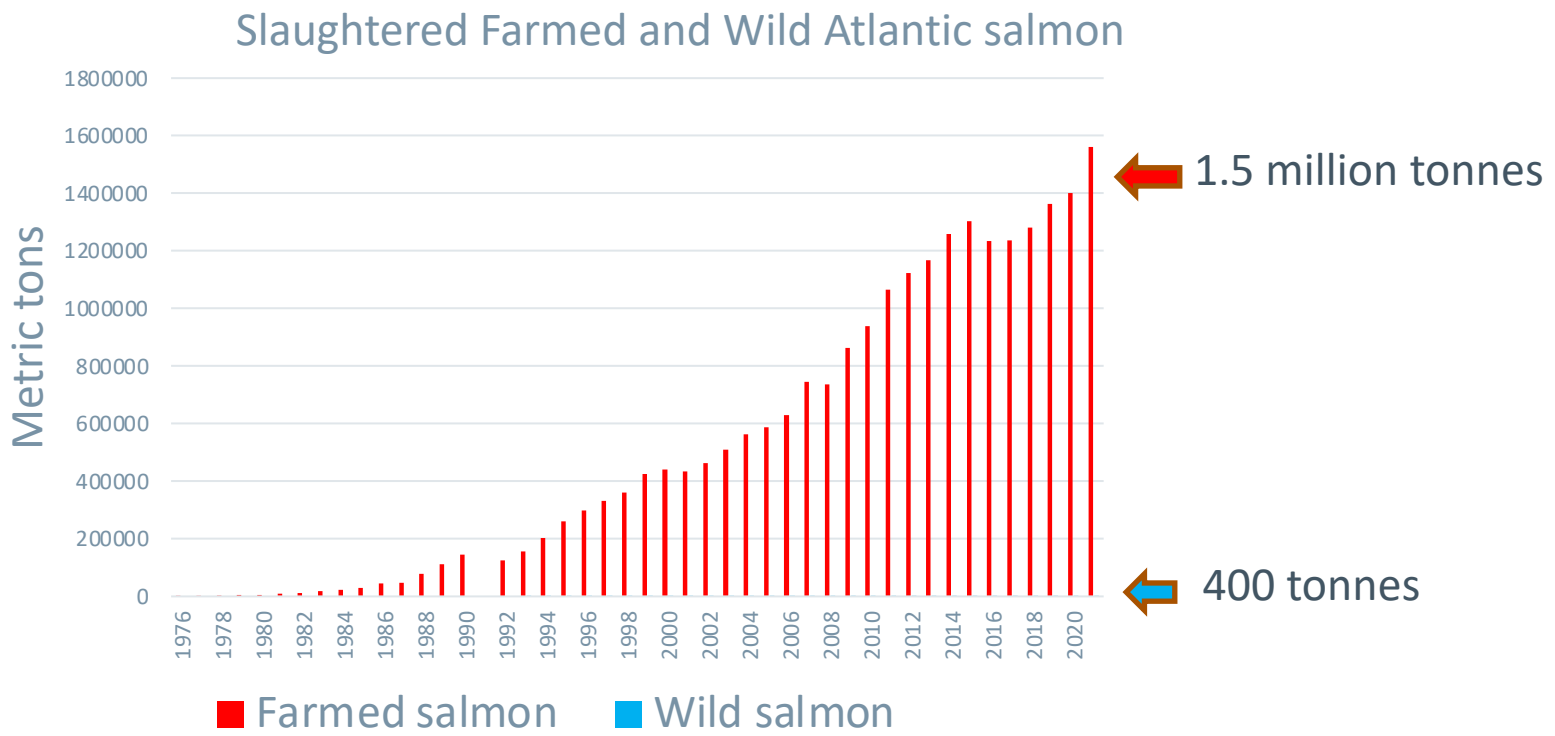
A synthesis of farmed to wild genetic introgression and the consequences for wild Atlantic salmon

Sten Karlsson*, Tonje Aronsen, Geir H. Bolstad, Ola H. Diserud, Peder Fiske, Ingerid J. Hagen, Kjetil Hindar, Eli Kvingedal, Line E. Sundt-Hansen, Grethe Robertsen, Sebastian Wacker

International Year of the Salmon (IYS) Synthesis Symposium, 4-6 October 2022, Westin Bayshore, Vancouver, Canada

Norwegian salmon farming



Wild salmon is outnumbered 3000-fold: Small proportions of escaping from fish farms give large numbers of escapees

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Escapees – In the Rivers

Monitoring program since 1989.

Fig 1b in Diserud et al. 2022. Natural and anthropogenic drivers of escaped farmed salmon occurrence and introgression into wild Norwegian Atlantic salmon populations. ICES Journal of Marine Science, 2022, 79, 1363–1379

ICES Journal of Marine Science (2019), doi:10.1093/icesjms/fsy202

Escaped farmed Atlantic salmon in Norwegian rivers during 1989–2013

O. H. Diserud[1]*, P. Fiske[1], H. Sægrov[2], K. Urdal[2], T. Aronsen[1], H. Lo[3], B. T. Barlaup[4], E. Niemelä[5], P. Orell[6], J. Erkinaro[6], R. A. Lund[7], F. Økland[1], G. M. Østborg[1], L. P. Hansen[8], and K. Hindar[1]

ICES Journal of Marine Science (2019), doi:10.1093/icesjms/fsy207

Domesticated escapees on the run: the second-generation monitoring programme reports the numbers and proportions of farmed Atlantic salmon in >200 Norwegian rivers annually

K. A. Glover[1,2]*, K. Urdal[3], T. Næsje[4], H. Skoglund[5], B. Florø-Larsen[6], H. Otterå[1], P. Fiske[4], M. Heino[1,2,7], T. Aronsen[4], H. Sægrov[3], O. Diserud[4], B. T. Barlaup[5], K. Hindar[4], G. Bakke[1], I. Solberg[4], H. Lo[6], M. F. Solberg[1], S. Karlsson[4], Ø. Skaala[1], A. Lamberg[8], Ø. Kanstad-Hanssen[9], R. Muladal[10], O. T. Skilbrei[11] and V. Wennevik[1]

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Genetic introgression – The method

MOLECULAR ECOLOGY
RESOURCES
Molecular Ecology Resources (2011) 11 (Suppl. 1), 247–253 doi: 10.1111/j.1755-0998.2010.02959.x

SNP GENOTYPING AND APPLICATIONS

Generic genetic differences between farmed and wild Atlantic salmon identified from a 7K SNP-chip

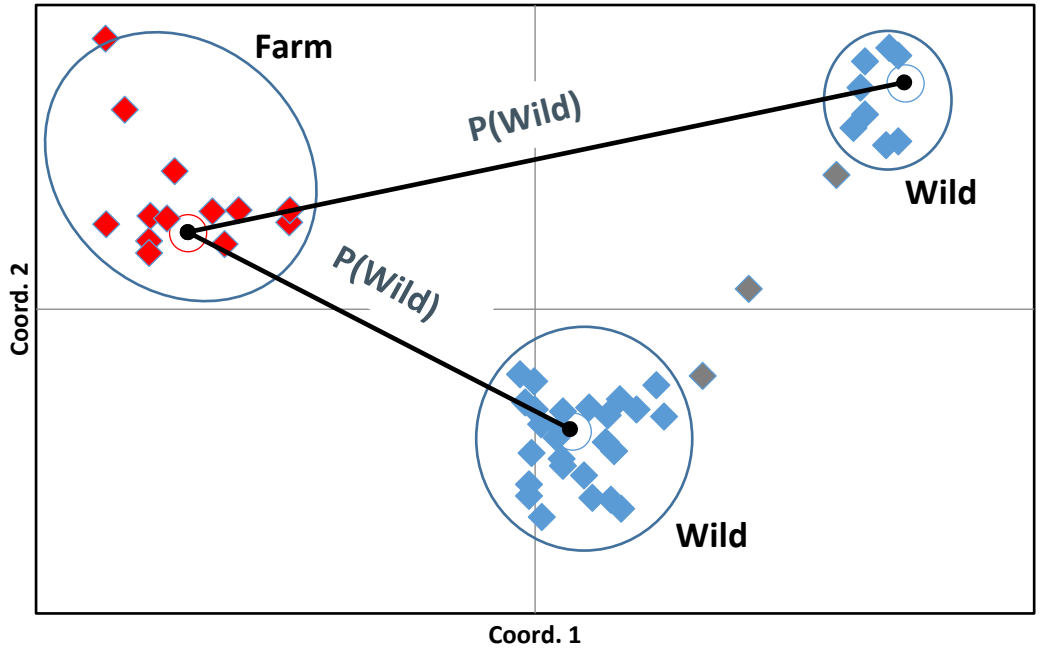
STEN KARLSSON,* THOMAS MOEN,†‡ SIGBJØRN LIEN,‡ KEVIN A. GLOVER¶ and KJETIL HINDAR**
*Nofima Marine, Arboretveien 6, N-1432 Ås, Norway, †Aqua Gen AS, PO Box 1240, N-7462 Trondheim, Norway, ‡Department of Animal and Aquacultural Sciences and Centre for Integrative Genetics, Norwegian University of Life Sciences, Arboretveien 6, N-1432 Ås, Norway, ¶Institute of Marine Research, PO Box 1870 Nordnes, N-5817 Bergen, Norway, **Norwegian Institute for Nature Research (NINA), PO Box 5685 Sluppen, N-7485 Trondheim, Norway

P(wild): Probability of being of wild versus farmed origin

Ecology and Evolution
Open Access

A standardized method for quantifying unidirectional genetic introgression

Sten Karlsson[1], Ola H. Diserud[1], Thomas Moen[2,3] & Kjetil Hindar[1]
[1]Norwegian Institute for Nature Research (NINA), P.O. Box 5685 Sluppen, N-7485 Trondheim, Norway
[2]AquaGen AS, P.O. Box 1240, N-7462 Trondheim, Norway
[3]Centre for Integrative Genetics, Norwegian University of Life Sciences, Arboretveien 6, N-1432 Ås, Norway



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Genetic introgression –in Norway

ICES Journal of Marine Science

ICES Journal of Marine Science (2016), doi:10.1093/icesjms/fsw121

Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations

Sten Karlsson*‡, Ola H. Diserud‡, Peder Fiske, and Kjetil Hindar

- 16 407 adult salmon
- 5155 juveniles
- 109 populations
- Significant introgression in 51 (47%)
- Average introgression 6.4%,

Range 0 – 42%

Highest introgression in farming intensive regions

1926 NINA Rapport

Genetisk påvirkning av rømt oppdrettslaks på ville laksebestander – oppdatert status 2020

Ola H. Diserud, Kjetil Hindar, Sten Karlsson, Kevin A. Glover & Øystein Skaala

80	No genetic changes observed
69	Weak genetic changes indicated
22	Moderate genetic changes shown (4-10 %)
68	Large genetic changes shown (> 10 %)

239 populations evaluated in Norway – only 1/3 unaffected

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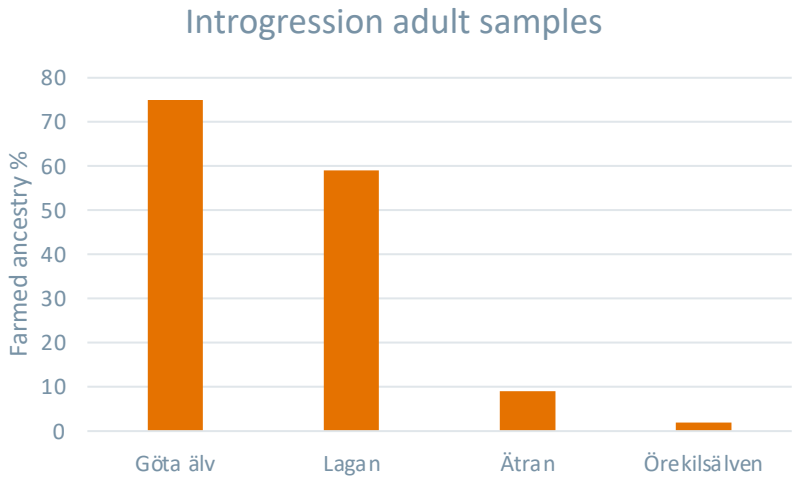
Genetic introgression outside farming range



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AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact
Published December 16

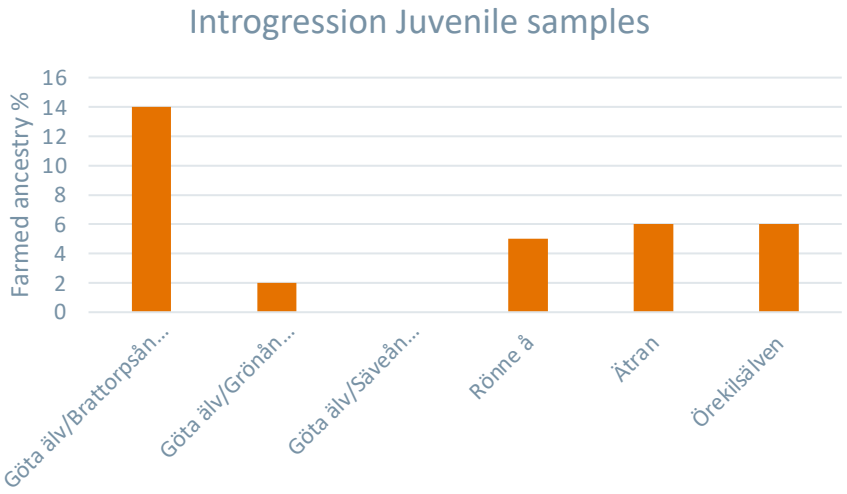
OPEN ACCESS

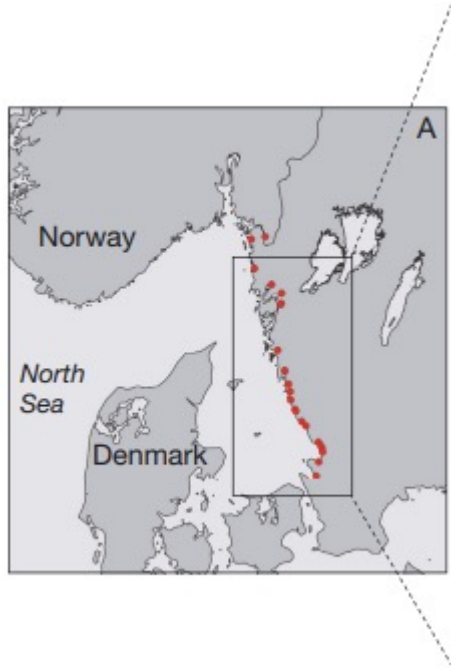
Genetic evidence of farmed straying and introgression in Swedish wild salmon populations

Stefan Palm[1,*], Sten Karlsson[2], Ola H. Diserud[2]

[1]Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Freshwater Research, Stångholmsvägen 2, 178 93 Drottningholm, Sweden
[2]Norwegian Institute for Nature Researc

Genetic introgression from escaped farmed to wild salmon found outside of fish farming range





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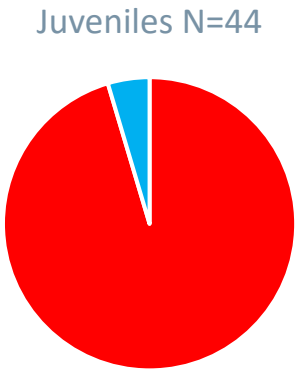
Genetic introgression in trout creeks



Fjell watercourse
95.4 % Genetic introgression
Effective number of breeders = 7

Escaped farmed salmon may enter and spawn in small creeks typically used sea-run brown trout (Salmo trutta)
→ this can potentially amplify the magnitude of genetic introgression

Pulg et al. 2022. Laks i sjøørretbekker – villaks eller oppdrettslaks? NORCE LFI rapport 376. Norwegian Research Center, Bergen

Genetic introgression – Changes in life history and growth rate

nature ecology & evolution
ARTICLES
PUBLISHED: 10 APRIL 2017 | VOLUME: 1 | ARTICLE NUMBER: 0124

Gene flow from domesticated escapes alters the life history of wild Atlantic salmon

Geir H. Bolstad[1]*, Kjetil Hindar[1], Grethe Robertsen[1], Bror Jonsson[2], Harald Sægrov[3], Ola H. Diserud[1], Peder Fiske[1], Arne J. Jensen[1], Kurt Urdal[3], Tor F. Næsje[1], Bjørn T. Barlaup[4], Bjørn Florø-Larsen[5], Håvard Lo[5], Eero Niemelä[6] and Sten Karlsson[1]

4 101 adult individuals, 62 populations, sex, sea age, length, weight, P(wild)

Sea age at maturity reduced in South Norway (East Atlantic Ocean) while mixed results in Northeast (Barents White Sea)

SCIENCE ADVANCES | RESEARCH ARTICLE

ECOLOGY

Introgression from farmed escapees affects the full life cycle of wild Atlantic salmon

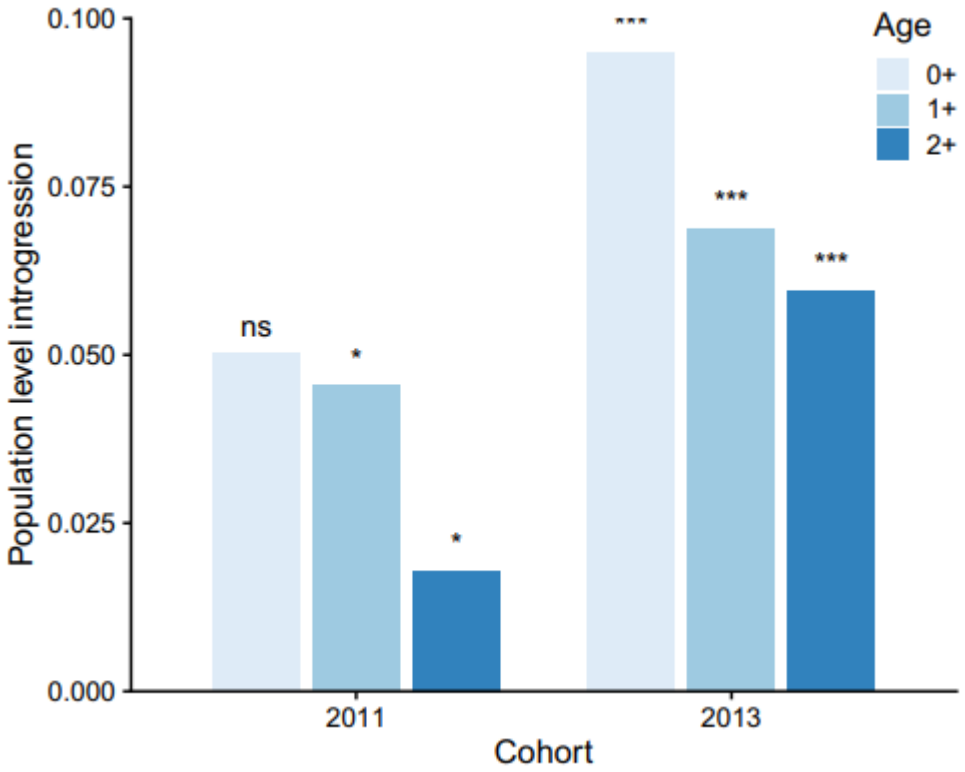
Geir H. Bolstad[1]*, Sten Karlsson[1], Ingerid J. Hagen[1], Peder Fiske[1], Kurt Urdal[2], Harald Sægrov[2], Bjørn Florø-Larsen[3], Vegard P. Sollien[3], Gunnel Østborg[1], Ola H. Diserud[1], Arne J. Jensen[1], Kjetil Hindar[1]

6 926 adult individuals, 105 populations, sex, smolt age, sea age, length, weight, P(wild)

Faster pace of life in South Norway. Younger smolt and sea age, and faster growth in freshwater and seawater life stages

NINA

Natural selection against genetic introgression



Received: 30 June 2020 | Revised: 14 January 2021 | Accepted: 26 February 2021
DOI: 10.1111/eva.13213

ORIGINAL ARTICLE

Evolutionary Applications Open Access WILEY

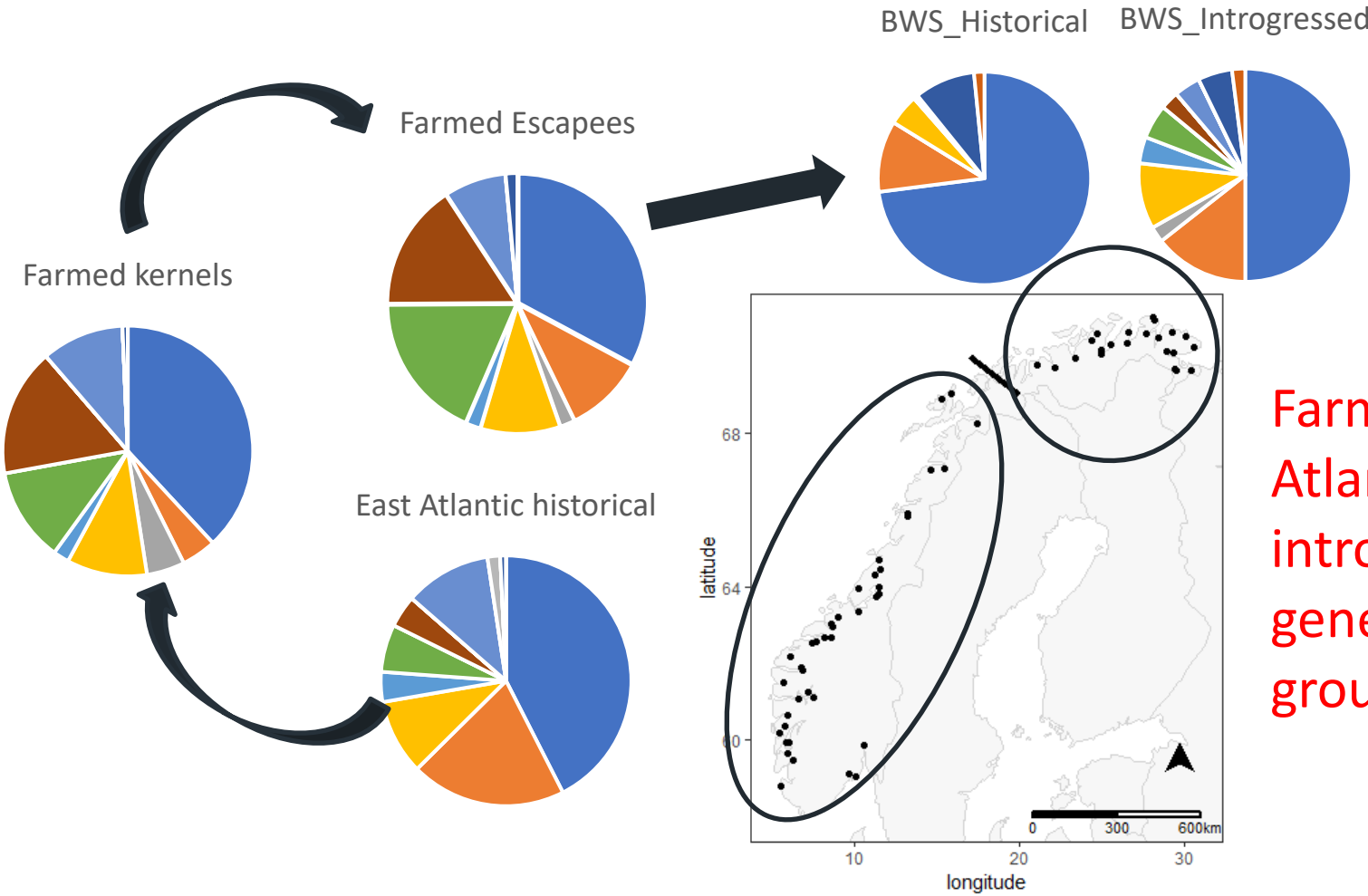
Selection against individuals from genetic introgression of escaped farmed salmon in a natural population of Atlantic salmon

Sebastian Wacker | Tonje Aronsen | Sten Karlsson | Ola Ugedal | Ola H. Diserud | Eva M. Ulvan | Kjetil Hindar | Tor F. Næsje

Level of introgression decreases with age within cohort

NINA

Genetic introgression – mitochondrial gene dispersal



Farmed escapees from the East Atlantic phylogenetic group introduce new mitochondrial genes to the Barents-White Sea group

Wacker et al. MS

Genetic introgression – whole river experiments

The Imsa experiment

Lifetime success of farmed spawners 16% of native spawners

Smolt production reduced compared with stock-recruitment curve

Burishoole Experiments

Lifetime survival of farmedXfarmed offspring 2% of wildXwild offspring

Hybrid groups intermediate and increasing with wild ancestry

Fitness reduction and lower productivity in admixed populations

PROCEEDINGS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Lifetime success and interactions of farm salmon invading a native population

Ian A. Fleming, Kjetil Hindar, Ingrid B. Mjølnerød, Bror Jonsson, Torveig Balstad and Anders Lamberg

Proc. R. Soc. Lond. B 2000 **267**, doi: 10.1098/rspb.2000.1173, published 7 August 2000

PROCEEDINGS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon

Philip McGinnity, Paulo Prodöhl, Andy Ferguson, Rosaleen Hynes, Niall ó Maoiléidigh, Natalie Baker, Deirdre Cotter, Brendan O'Hea, Declan Cooke, Ger Rogan, John Taggart and Tom Cross

Proc. R. Soc. Lond. B 2003 **270**, 2443-2450
doi: 10.1098/rspb.2003.2520

NINA

Genetic introgression – whole river experiments

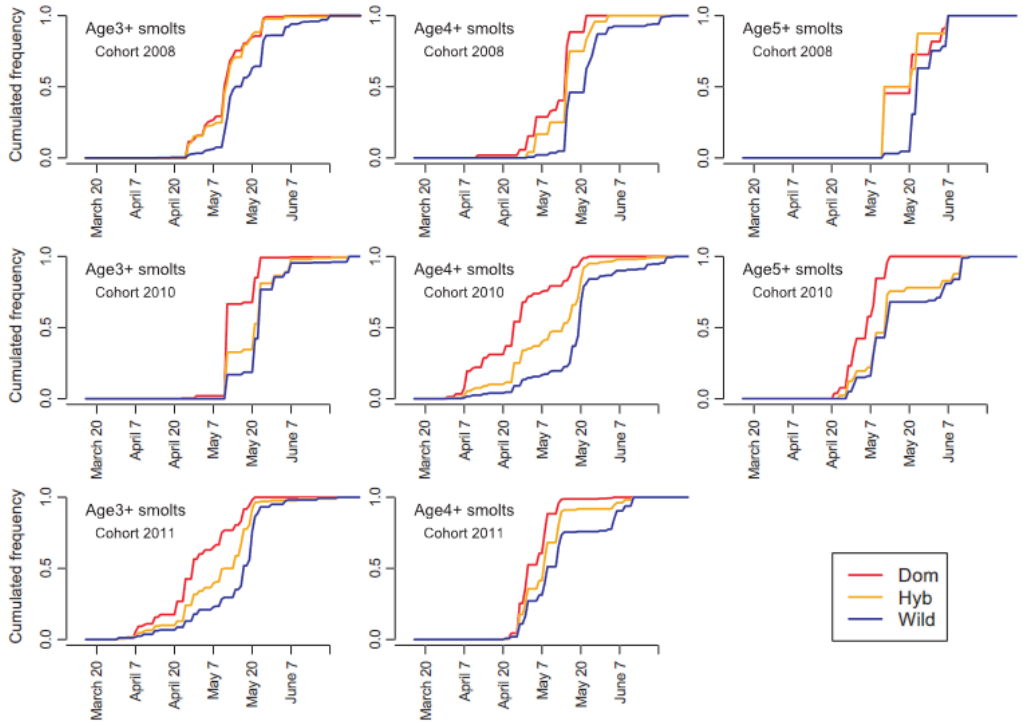
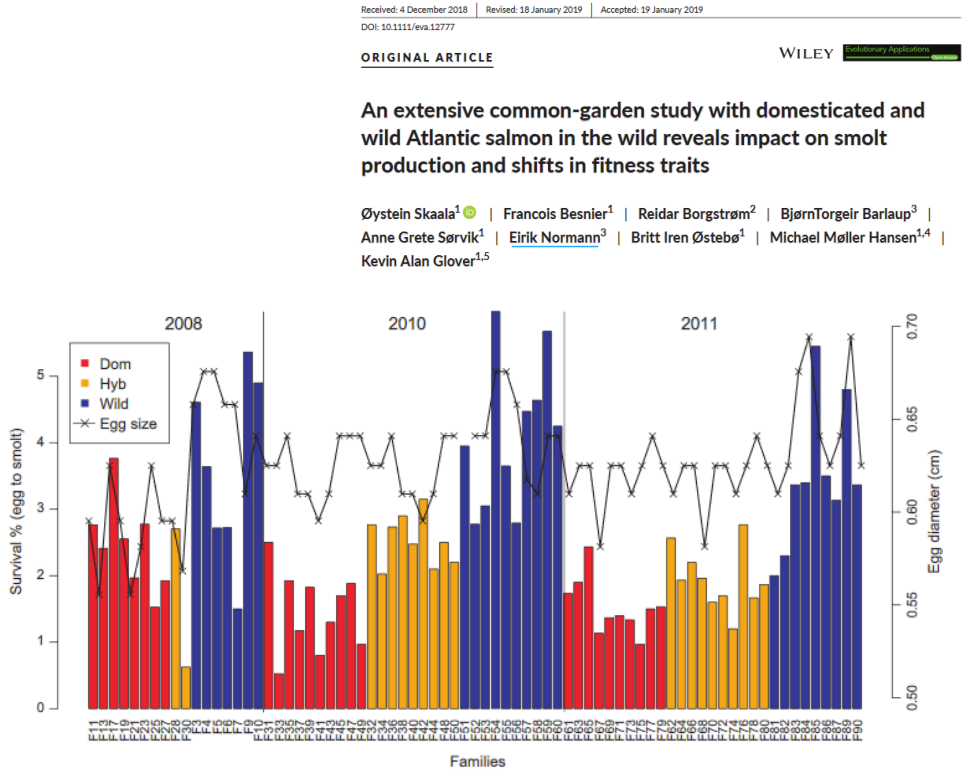


FIGURE 5 Cumulative smolt migration from the River Guddalselva of the C2008, C2010, and C2011 cohorts in regard to smolt age and type (domesticated, hybrid, wild)


Received: 4 December 2018 | Revised: 18 January 2019 | Accepted: 19 January 2019
DOI: 10.1111/eva.12777

ORIGINAL ARTICLE

WILEY Evolutionary Applications

An extensive common-garden study with domesticated and wild Atlantic salmon in the wild reveals impact on smolt production and shifts in fitness traits

Øystein Skaala[1] | Francois Besnier[1] | Reidar Borgstrøm[2] | BjørnTorgeir Barlaup[3] | Anne Grete Sørvik[1] | Eirik Normann[3] | Britt Iren Østebø[1] | Michael Møller Hansen[1,4] | Kevin Alan Glover[1,5]

FIGURE 2 Survival from eyed egg to smolt and egg diameter by cohort in 75 family groups (domesticated, hybrid, and wild), in the River Guddalselva

Farmed and Hybrids have lower survival from eggs to smolt and migrate to sea earlier in the season than wild salmon

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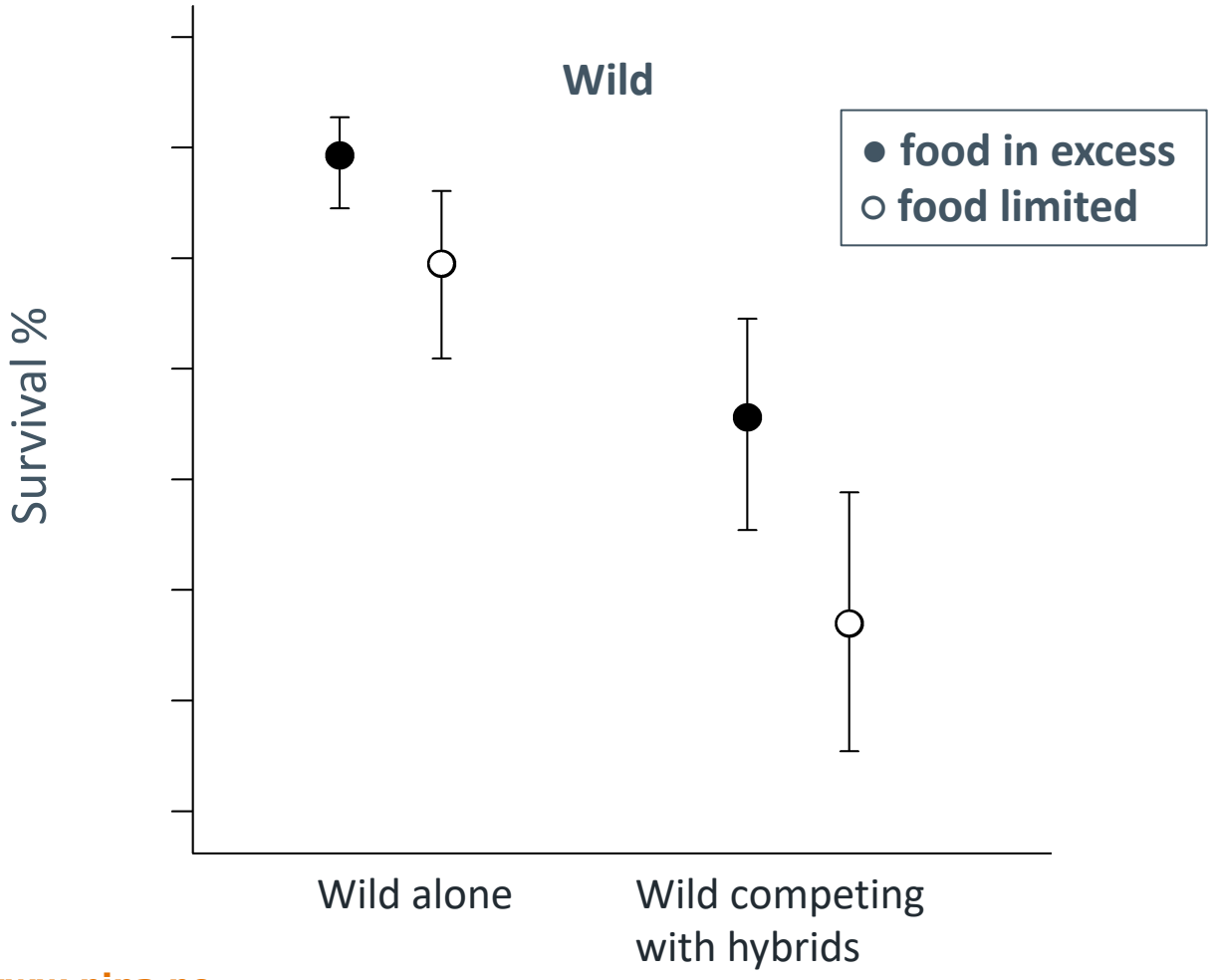
Genetic introgression – Consequences, observations from experiments



ORIGINAL RESEARCH

WILEY Ecology and Evolution

Can variation in standard metabolic rate explain context-dependent performance of farmed Atlantic salmon offspring?

Grethe Robertsen[1] | Donald Reid[2] | Sigurd Einum[3] | Tonje Aronsen[1] | Ian A. Fleming[4] | Line E. Sundt-Hansen[1] | Sten Karlsson[1] | Eli Kvingedal[1] | Ola Ugedal[1] | Kjetil Hindar[1]

Wild salmon outcompeted by hybrids, both at high and low food availability

NINA

Concluding remarks – Genetic introgression

Genetic introgression

- Threatens wild populations – we do not know when or if it will stop
- Is widespread and elevated in farming intensive regions
- Increases individual growth and alters life history
- Reduced fitness and productivity
- Reduced genetic variation and viability

What is the tipping point?

Lessons learned from Atlantic salmon

76 Aquatic species listed by FAO, many hundred potential species -Atlantic salmon a model species

- Basic knowledge
  - Ecology
  - Genetic structure
- Documentation and monitoring programs
  - Origin of wild population used in breeding programs
  - Genetic changes from selective breeding
  - Breeding lines used where and when
  - Monitoring escapees
  - Monitoring genetic introgression

..Foremost prevent escapes

NINA

Cooperation and expertise for a sustainable future

NINA