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The National Electrofishing Programme for Scotland (NEPS) 2021

Scottish Marine and Freshwater Science Vol 14 No 2

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marine scotland

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The National Electrofishing Programme for Scotland (NEPS) 2021

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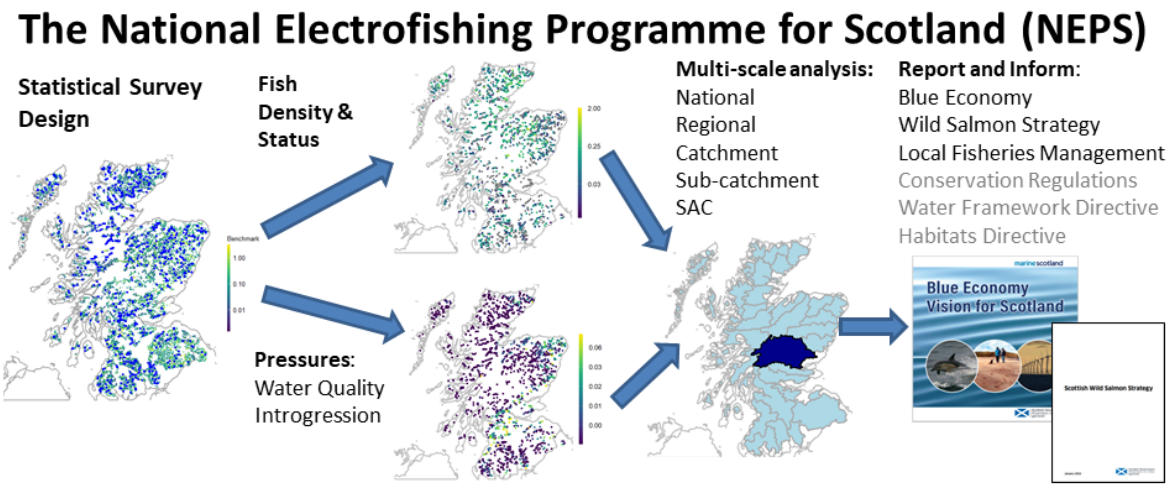
Executive Summary

The National Electrofishing Programme for Scotland (NEPS) was established in 2018. The foundation of the programme is a statistical survey design that ensures collection of unbiased, spatially representative data on the abundance of freshwater fish and the pressures that affect them, including water quality and genetic introgression from farm escapes. Survey design, data storage, analysis and reporting are provided by Marine Scotland. Data collection is undertaken by a network of professional local fisheries managers. NEPS data can be analysed at a range of spatial scales (national, regional, catchment, sub-catchment, site). The current assessment method provides a scientifically robust basis for assessing the status of salmon, identifying potential pressures, supporting local management decision making and policy imperatives (e.g. Blue Economy Vision for Scotland, Wild Salmon Strategy). With further work, similar assessment approaches could support a range of reporting requirements including Habitats Directive, Water Framework Directive and Conservation Regulations, depending on available resource. NEPS provides the evidence base necessary to plan conservation, restoration and management of Atlantic salmon and with further development, other freshwater fish species including brown trout and European eel. The latest data show that densities of salmon fry (0+) in 2021 were lower than 2018, but higher than 2019 and were overall healthy at a national scale. In contrast salmon parr (≥1+) densities were extremely low at around 60% of their target level. However, there was also substantial regional variability. In the case of salmon parr, healthy (Grade 1) populations were only found in the north. Comparison of mean juvenile densities from NEPS with regional rod catch data indicated broadly coherent spatial and temporal relationships. This consistency between abundance indicators used in different assessment methods is reassuring when making management decisions.

Water quality data highlighted potential pressures from nutrient pollution, particularly in the north-east, central belt and Ayrshire coast, while anthropogenic acidification impacts appear to remain a localised problem in the south-west of Scotland. High nutrient loads and eutrophication impacts are likely to become an increasing problem under climate change when combined with low summer flows and high temperatures.



Introduction

Atlantic salmon (hereafter salmon) are a diadromous species (those spending time in marine and freshwater environments) of high economic, conservation and cultural importance that are protected by international management agreements (North Atlantic Salmon Conservation Organisation; NASCO) and legislation at national (The Conservation of Salmon (Scotland) Regulations) and international levels (The European Commission Habitats Directive, 92/43 EEC). Scotland accounts for ca. 75% of wild salmon production in the UK (ICES, 2021). Brown trout (hereafter trout) are a UK Biodiversity Action Plan priority fish species that exhibit a wide range of life history strategies including freshwater resident and diadromous forms (sea trout). Wild freshwater fisheries, which are dominated by salmon and trout, account for around £79.9m Gross Value Added (GVA) to the Scottish economy each year, supporting ca. 4,300 full-time equivalent jobs (PACEC, 2017).

The abundance of salmon returning to home waters has declined over the last 50 years (Chaput, 2012; ICES, 2021). Early reductions in abundance were largely offset by reductions in exploitation from coastal, estuarine and in-river fisheries (e.g. Gurney et al., 2015). However, adult numbers have continued to decline in recent years raising concerns that this will affect future salmon numbers through declining freshwater production. Between 2015 and 2021 the total reported rod catch for Atlantic salmon in Scotland (caught and released) declined from 56,006 to 35,693. Although likely affected by COVID-19 restrictions, the latter figure is the lowest recorded since records began in 1952 (Marine Scotland, 2022). Sea trout rod catches have declined since the mid-1960s and the rod catch for sea trout in 2021 was also the lowest on record (Marine Scotland, 2022).

In response to declining salmon numbers the Scottish Government published the Scottish Wild Salmon Strategy to promote healthy, self-sustaining populations of wild Atlantic salmon that achieve good conservation status. A detailed understanding of the status of juvenile Atlantic salmon populations and the pressures acting on them is thus pre-requisite to informing evidence-based management of the resource and its environment. Electrofishing data are one of the most commonly collected sources of information on the status of salmon and other freshwater and diadromous species.

Where collected to common standards and an appropriate survey design these data can provide assessments at nested spatial scales ranging from individual sites (ca. 100m^2), to sub-catchments, catchments, regions or whole countries. This spatial flexibility and potential for upscaling makes juvenile assessment particularly attractive for management decision making.

In 2018 Marine Scotland Science established the National Electrofishing Programme for Scotland (NEPS). NEPS is a collaborative programme of data collection supported by local fisheries managers (Malcolm et al., 2019b). It gathers spatially extensive data on the distribution and abundance of freshwater fish, physical habitat, water quality (to inform assessment of pressures) and levels of introgression; the levels of genetic material in wild populations resulting from wild fish breeding with farm escapees (Gilbey et al., 2021). In 2018 the programme was funded by Marine Scotland (MS), the Scottish Environment Protection Agency (SEPA) and Scottish Natural Heritage (now Nature Scot). In 2019, the programme was run for a second year with funding support from MS and Crown Estate Scotland (CES). There was no national survey in 2020 due to COVID-19. However, a survey was funded again in 2021 using a new survey design, supported by funding from MS and CES.

Previous reports (Malcolm, et al., 2019b, Malcolm, et al., 2020) have outlined the main data collection, survey design and analytical methods developed under NEPS. The current report extends this previous work with the following objectives:

1. Characterise changes in the survey design between the 2018/2019 and 2021 NEPS surveys
2. Provide environmental context for the surveys through a summary of inter-annual variability in rainfall and discharge
3. Model capture probability incorporating the latest data from NEPS 2021
4. Report the abundance of salmon and trout and status of salmon determined from NEPS 2021
5. Characterise variability in habitat, observed salmonid densities and benchmark (expected salmon numbers) between Strahler river orders
6. Harmonise data between NEPS surveys to assess spatio-temporal variability in salmonid densities and the status of salmon.

7. Identify the potential of NEPS data to assess of status of salmon in Special Areas of Conservation (SACs)
8. Characterise relationships between juvenile salmon density and rod catch as a proxy for salmon abundance
9. Characterise spatial variability in water quality to identify pressures acting on salmonid populations and provide an improved basis for understanding spatial controls on salmonid productivity.

Materials and Methods

NEPS Survey design 2021

The NEPS survey design that operated in 2018 and 2019 was intended to run for nine years (see Malcolm et al., 2019b for details). However, greater than expected demand for over samples (replacement samples for sites that could not be fished) in some regions determined that a new survey design was required for 2021. Given the ongoing challenges around COVID-19 and the need to progress a survey at short notice it was decided that the 2021 survey design would operate for a single year, with a new multi-year design to follow in future years.

Consistent with previous years, NEPS 2021 was an unequal probability Generalised Random Tessellation Stratified (GRTS) survey design where sample site selection was weighted towards areas where higher juvenile salmon densities were expected (based on the Benchmark model predictions from Malcolm et al., 2019a). The target population encompasses all rivers that are accessible to Atlantic salmon (i.e. below barriers to migration), where there are registered fisheries and where sampling by wading and electrofishing is possible. Samples were assigned to strata, which were typically regional aggregations of rivers, although in some cases additional strata were created for logistic reasons or to investigate particular issues where additional local resource allowed (Malcolm et al., 2020, see below).

Following feedback from local fisheries managers the sample frame, i.e. the approximate spatial representation of the target population, was extended from Strahler river orders (a hierarchical measure of stream size) 2-4, to include larger 5th order rivers in selected regions. This was not universally possible and depended on the regionally varying characteristics of rivers (e.g. depths and velocities) and their history of anthropogenic modification (e.g. channelisation, dredging) which can make access and sampling difficult or unsafe. In some situations local fisheries managers also identified new barriers or physical constraints to salmon access and this information was used to remove upstream river segments from the sample frame (Fig. 1).

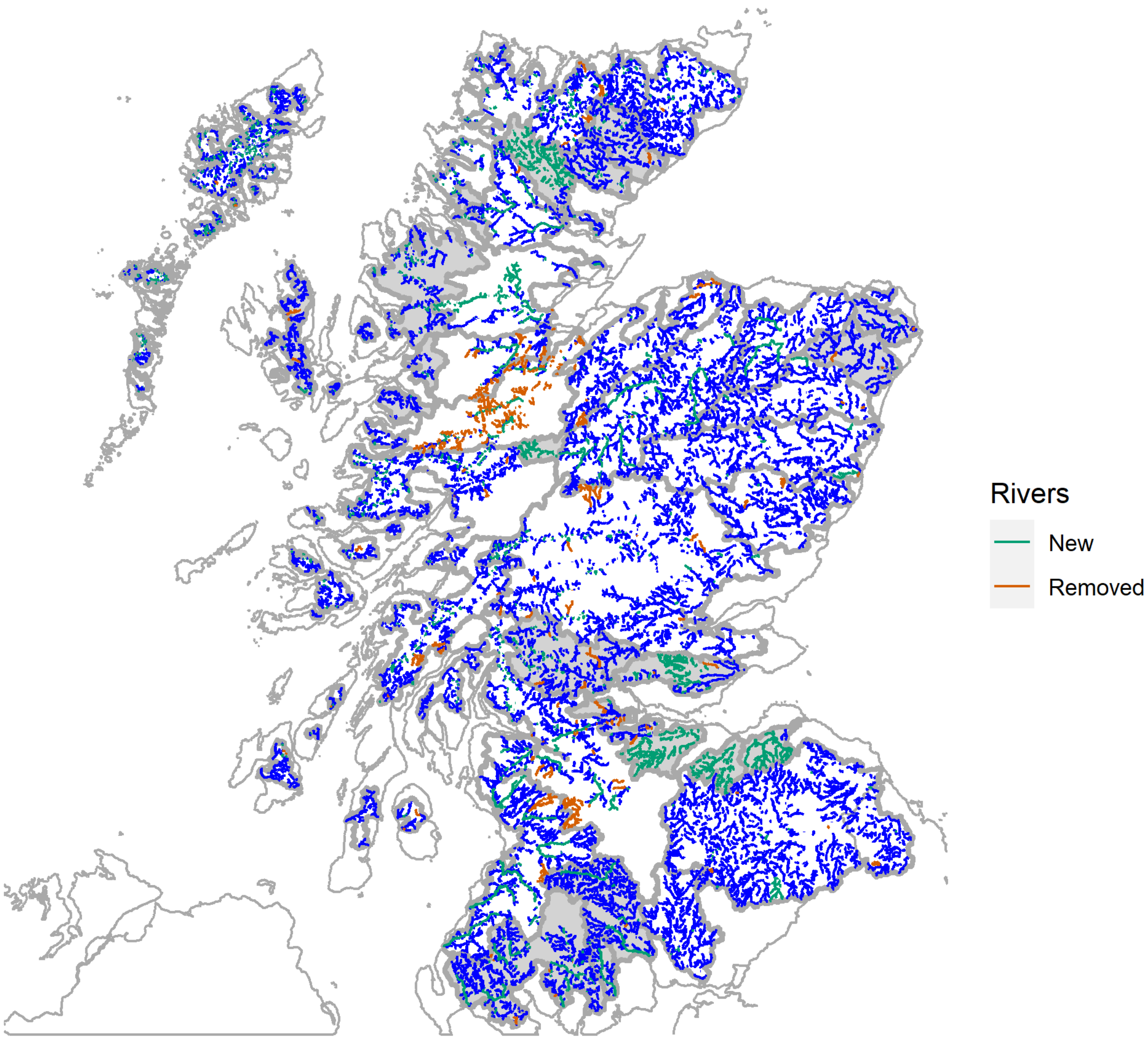


Figure 1 Map showing changes to the NEPS strata and sample frame between 2018-19 and 2021 surveys. Polygons with thick grey outlines indicate 2021 strata. Light grey shaded polygons indicate changes to NEPS strata between 2018-19 and 2021. Blue lines indicate rivers that were included in both survey designs. Blue-green lines indicate rivers that were added to the sample frame in 2021. Orange lines indicate rivers that were removed from the sample frame in 2021.

The 2021 survey design sought to maintain regional sample numbers at levels consistent with the previous surveys except where additional local resources were available to supplement core funding. In 2018-19 reporting regions and strata covered the same geographic area. However, changes were made to strata boundaries in 2021 to address local reporting requirements or to improve spatial consistency with fisheries management organisations, the latter creating challenges for the allocation and management of over samples. New strata were created for the Forth region to improve assessment in the area and to monitor the outcomes of barrier removal work. This was supported by the addition of substantial new resource from the Forth Rivers Trust which doubled the number of samples in the region (from 30 to 60 sites). New strata were also established to monitor salmon populations above Shin dam and Spey dam. Both of these sub-catchments are above barriers that are categorised as impassable by SEPA and thus did not appear in the earlier survey design, although constrained passage of salmon is possible. Monitoring above Shin dam was supported by Kyle of Sutherland Fisheries Trust. There was no monitoring above Spey dam in 2021, although such monitoring would be possible in the future. Changes to the strata were also made to allow for separate strata covering Brora and Helmsdale; Ythan and Ugie; Skye and Lochalsh, and Wester Ross. A small change was also made to the Galloway strata to include the river Urr (Fig. 1). The final survey design consisted of 36 strata and 855 samples of which 810 were funded (at least in part) centrally.

Electrofishing data

Full details of the electrofishing sampling protocols for NEPS are provided elsewhere (Malcolm et al., 2019b). However, in brief, electrofishing was undertaken by local fisheries managers following standard operating procedures developed for NEPS. All electrofishing data were area delimited (the surveyed area was measured for each site) with a target date for sampling between 01 July and 30 September. Approximately a third of sites were fished using three passes, while two thirds of sites were fished with a single pass. The effort expended on the first pass of the multi-pass electrofishing and the single pass electrofishing should be the same. Basic habitat information was recorded at each site, and water quality samples were collected for analysis at MSS-FFL (Marine Scotland Science, Freshwater Fisheries

Laboratory). Genetic samples were obtained from 30 salmon parr at all sites to assess levels of genetic introgression from farmed fish. Data were stored in the Marine Scotland Science Fish Observation (FishObs) database, making use of the FishObs Data Processing Utility (DPU) for data entry.

Generation of covariates for electrofishing sites

GIS proxies for habitat (gradient, altitude, river distance to sea, percentage conifer in riparian zone) are required as predictor variables for both the capture probability and benchmark models. Covariates were generated for every node on the Digital River Network (DRN) that represented the sample frame, and for all electrofishing sites using an in-house R package (FFL GIS) and scripts following the methods described by Jackson et al. (2017) and Malcolm et al. (2019a) where further details can be found.

Estimating capture probability

Capture probability for juvenile salmon and trout was estimated following the methods described by Millar et al. (2016) and Malcolm et al. (2019a). The capture probability model was fitted to a dataset that included previously published multi-pass electrofishing data collected across Scotland between 1997- 2015 (Malcolm et al. 2019a), ad-hoc data collected between 2016 and 2017 and new data collected under NEPS in 2018, 2019 and 2021. Capture probability was modelled as a logistic function of covariates representative of people and equipment (Organisation-Team), fish size and behaviour (Lifestage and electrofishing Pass / run), time (Year and Day of the Year, DoY), habitat (e.g. Altitude, Upstream Catchment Area, UCA; River Distance to Sea, RDS; and Gradient), land use (Conifer, Deciduous and Mixed trees, Urban area) and geographical region (Hydrometric Area, HA). The term Organisation (as an indicator of staff) was divided into broad time periods (Organisation Team) to reflect major organisational changes identified from an assessment of staff names / abbreviations identified in the SFCC database and available web-based materials.

Model selection followed a step-up-down procedure starting from a large model that included a 3-way interaction between Species, Lifestage and Pass, a multi-level factor for Year, two level factor for Urban area (essentially presence / absence) and smoothed main effects for the other continuous variables. The model scope (maximum possible model complexity) allowed for 4-way interactions between Species, Lifestage, Pass and the other covariates. The step-up-down procedure also allowed for the multi-level factor for Year to be replaced by a smooth or linear expression for Year. In some cases it was not possible to estimate capture probability for individual Organisation - Teams due to small samples sizes. In these circumstances it was necessary to group teams within a region or adjacent time period (e.g. Nairn 2019 was grouped with Nairn, Findhorn and Lossie Fisheries Trust 2018).

Estimating site-wise (observed) salmon and trout densities

Fish densities were estimated for each species, lifestage and electrofishing site following the methods described by Glover et al. (2018) and Malcolm et al. (2019a). In brief:

$$Estimated\ density = \frac{\sum count_{pass\ n}}{site\ area * Pcum}$$

where $\sum count_{pass\ n}$ is the total fish count for each species / lifestage combination across all passes and

$$Pcum = 1 - (1 - P_1) * (1 - P_2) * (1 - P_3)$$

is the cumulative capture probability across all passes (in the example above 3 passes) and P_n denotes the fitted capture probability for pass n (where n can be pass 1,2,3). To ensure consistency with the benchmark models, wetted area measured at the time of electrofishing was used to represent the site area.

Site-wise benchmark densities (salmon only)

Site-wise benchmark densities were calculated for salmon, for each electrofishing site, using GIS derived habitat proxies (see covariate generation above) and the national juvenile salmon density benchmark model reported by Malcolm et al. (2019a, Fig. 2). Benchmark densities were calculated separately for fry and parr lifestages and represent the densities that would be expected on average for a particular habitat (site location) free from anthropogenic pressures (Malcolm et al., 2019). Because the sample frame for 2021 included some larger 5th order rivers, which were not well represented in the original benchmark dataset, upstream catchment areas were capped at 250 km^2 in the prediction model to prevent unrealistically high estimates of benchmark abundance.

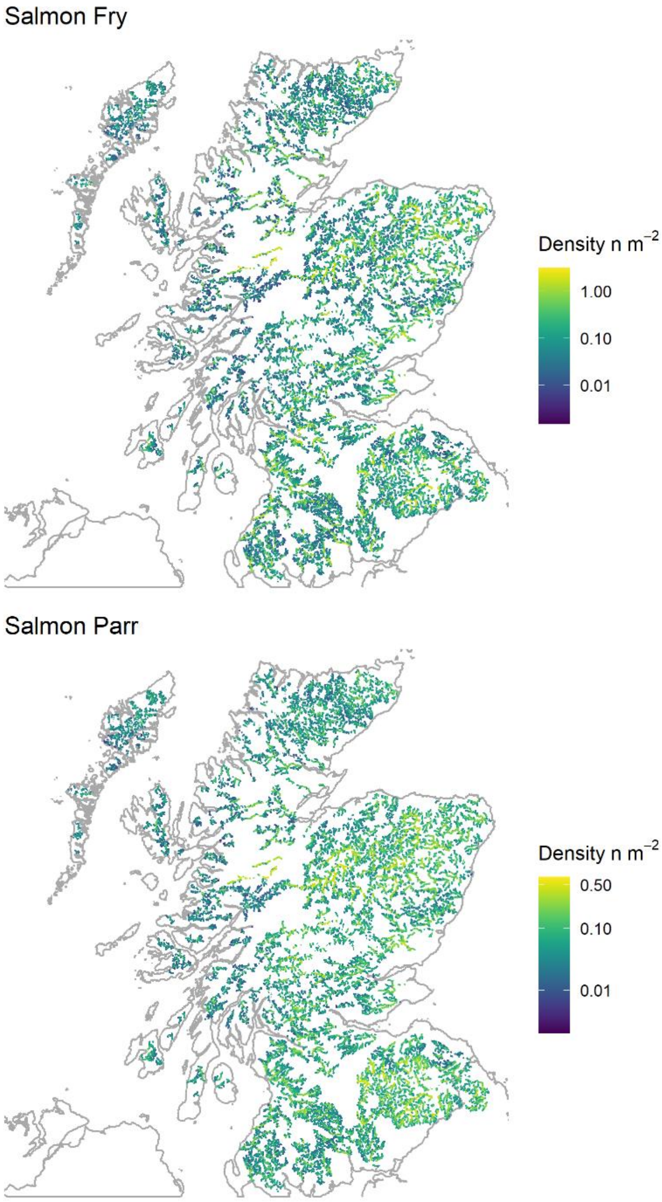


Figure 2 Map showing benchmark density predictions for salmon fry (upper panel) and parr (lower panel) for the NEPS 2021 sample frame. The effects of upstream catchment area on predicted densities have been constrained by capping upstream catchment areas at 250km^2. For further details of the benchmark model see Malcolm *et al*. (2019).

Scaling benchmark densities to region (salmon only)

The regional-scale benchmark for salmon fry and parr was calculated by obtaining a benchmark estimate of expected salmon densities and river length for each of the digitised river segments in the sample frame. Benchmark densities were predicted for upstream and downstream river nodes. In circumstances where these nodes had the same river order, the segment benchmark was the geometric mean of the two. Where the downstream node had a higher river order to the upstream node (e.g. a small tributary entering a larger river) then upstream benchmark predictions were assigned to the edge to avoid over inflating benchmark estimates for the segment.

Regional benchmark estimates were thus calculated as follows:

$$Regional\,Benchmark = \frac{\sum Edge\ \ Benchmark * Edge\,Length}{\sum Edge\ \ Length}$$

where *Edge Benchmark* is the density estimate for each river segment (edge) in the DRN and *Edge Length* is the length of each line feature (m). Consistent with site-wise estimates of the benchmark, upstream catchment area was capped at 250km^2 when making predictions.

Scaling site-wise observed densities to region

The R package “spsurvey” (Kincaid et al., 2020) was used to both design and analyse data from the NEPS monitoring programme. Sample weights were adjusted to reflect the final list of sampled locations (i.e. removing sites that were not sampled and including replacement over samples). Analysis was conducted using the “cont.analysis” function for continuous data. Separate analyses were performed for each survey year. The response variable was the site-wise observed densities (n m^{-2} wetted area). Wetted area densities were chosen as these provided greatest consistency with the benchmark. The “cont.analysis” function estimates the mean density (per unit length of sample frame) in each strata, together with associated two-sided 90% confidence intervals (i.e. one-sided 95% confidence intervals). It can also be used to combine estimates over strata e.g. for national scale or regional estimates matching with previous surveys.

Analysis of NEPS data at varying spatial scales

By combining strata or post-stratifying data it is possible to analyse the NEPS data for areas that were not individual strata in the survey design. This allowed: 1. data from NEPS 2021 to be compared to similar surveys in 2018-19 through the removal of 5^{th} order rivers and aggregation of strata where appropriate; and 2. estimates of juvenile density for different Strahler river orders.

Regional assessments of status for salmon (grades)

Since 2016, Scottish rivers have received one of three conservation grades associated with an adult assessment method (Marine Scotland, 2020c). These grades are based on the probability of meeting a spatially varying egg deposition target indicative of maximum sustainable yield (Conservation Limit). Results are averaged over a 5-year period to prevent any single poor year from bringing down the status of the river (Marine Scotland, 2020c). The grades are associated with particular management advice (below). Importantly category 3 rivers (the poorest grading) are associated with compulsory catch and release and preclude the killing of salmon.

- Category 1: Exploitation is sustainable therefore no additional management action is currently required. This recognises the effectiveness of existing non-statutory local management interventions.
- Category 2: Management action is necessary to reduce exploitation: catch and release should be promoted strongly in the first instance. The need for mandatory catch and release will be reviewed annually.
- Category 3: Exploitation is unsustainable therefore management actions required to reduce exploitation for 1 year i.e. mandatory catch and release (all methods).

It is possible to obtain status assessments for fry and parr through a similar approach by comparing the regional estimates of mean salmon density (per unit length of river), obtained from the GRTS sampling, with the benchmark regional densities (Malcolm et al., 2019a) to assess how likely it is that a particular area meets its benchmark. Small changes were made to the classification method for NEPS 2021 in comparison to previous years.

- Category 1: The mean density estimate exceeds the benchmark and the lower one-sided 95% confidence interval does not include zero
- Category 2: The mean density estimate exceeds the benchmark but the lower one-sided 95% confidence interval includes zero, or the mean density estimate exceeds 50% of the benchmark and the upper one-sided 95% confidence limit includes the benchmark.
- Category 3: The mean density estimate exceeds 50% of the benchmark but the upper 1-sided 95% confidence limit is below the benchmark, or the mean density estimate is less than 50% of the benchmark

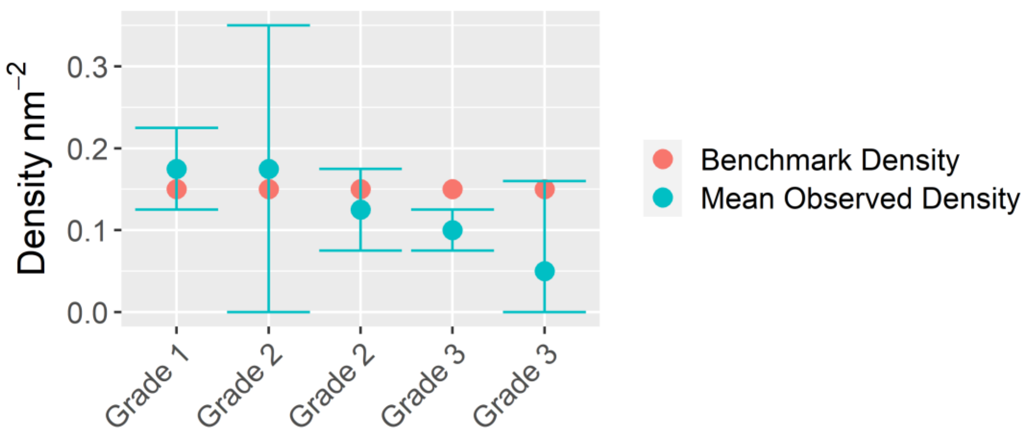


Figure 3 Theoretical scenarios under which an area would be classified as Grade 1, 2 or 3.

The grades for the two life stages are then combined to provide a single juvenile assessment grade for each year. The combined status favours the better of the two life stage assessments, reflecting the ability of populations to rebound from a single year of poor recruitment. Strong evidence is required that both life stages are failing to meet the benchmark before obtaining a grade 3 categorisation (Fig. 4)

		fry		
		1	2	3
parr	1	1	1	2
	2	1	2	2
	3	2	2	3

Figure 4 Matrix showing the rule-based system for generating an overall juvenile status assessment (grading) from individual life-stage assessments. Fry grades run horizontally, parr grades run vertically.

Assessing the status of Special Areas of Conservation

NEPS was not explicitly designed to assess the status of SACs. However, post-stratification makes assessment of status possible for some of the larger SACs that exist within the NEPS sample frame (i.e. assessable rivers under the Conservation Regulations). For the purposes of this report, status is only reported where a minimum of five samples were obtained for an SAC within each of the NEPS sampling years.

Site condition monitoring requires that SACs are assigned one of the following categories: Favourable, Unfavourable (with sub-categories Declining, Maintained or Recovering), Partially destroyed or Destroyed. For the purposes of this report it is assumed that Favourable Condition is generally consistent with NEPS Grade 1 and inconsistent with NEPS Grade 3. It is also assumed that an assessment of Destroyed would be consistent with the total absence of salmon across any survey years. These underlying principles were translated into a rules-based assessment so that SAC's characterised by an overall NEPS Grade of 3 in any survey year would be designated as "Unfavourable". In circumstances where no salmon were observed, an assessment of "Destroyed" would apply.

Because NEPS has only operated over three years and the data are broadly incompatible with previous ad-hoc and potentially biased surveys, assessment of trends in abundance are somewhat dubious using these sources of data. However, it is possible to indicate the direction of travel from the three available unbiased NEPS surveys. For the purposes of this report systematic reductions in abundance between 2018, 2019 and 2021 were considered “Declining”, while systematic increases between years were considered “Recovering”. Where density did not vary systematically across years this was assumed to indicate “No Change”. Given that NEPS estimates densities of both fry and parr, trends in either life stage were used to indicate change so long as these trends were not contradictory. In the latter circumstances a classification of “No Change” was applied.

Comparing abundance indicators: mean juvenile salmon density and rod catch

Fisheries assessment methods rely on two key components 1. A target for expectation against which to assess the performance of populations (e.g. a benchmark) and 2. Indicators of abundance. Abundance indicators can include commercial catches, rod catches, fish counters or field survey data such as that generated by NEPS. In the case of juvenile assessment methods that rely on wading and electrofishing it is not possible to sample the whole river system, but the assumption is that the surveyed areas are indicative of the wider river system. Confidence in the approach is strengthened where it can be shown that there is broad consistency with other independently collected indicators of abundance.

Rod catch data are spatially extensive for Scotland, published routinely, provide a useful proxy of adult salmon abundance (Thorley et al., 2005), and, through sophisticated modelling, underpin the adult based assessment methods used to inform Conservation Regulations in Scotland. Relationships between rod catch and mean juvenile salmon density were assessed at two spatial scales. For the national analysis rod catches were summed across Scotland and compared to national estimates of mean salmon density. For the regional comparison, reported rod catches were aggregated to NEPS region and divided by the wetted area of accessible river habitat to obtain a measure of rod catch density. These were then plotted against the regional mean density estimates of fry and parr obtained from NEPS. Data from NEPS 2021 were post-stratified to be consistent with the sample frames for 2018-19. Appropriate time lags were used for these comparisons, with parr assumed to be mostly two years old. For example rod catch data from 2016 were plotted against fry data from 2017 and parr data from 2018. For the regional data an illustrative Ricker stock-recruitment curve was fitted and data points were coloured by their NEPS grade to determine whether Grade 1 assessments were broadly consistent with maximum juvenile production.

Spatial variability in water quality: assessing pressures on salmonids

Water quality samples were obtained at the time of electrofishing and returned to MSS-FFL for analysis. A broad suite of determinands were measured including major cations (sodium: Na, potassium: K, magnesium: Mg, calcium: Ca), anions (sulphate: SO_4, Chloride: Cl, nitrate: NO_3-N), pH, alkalinity, electrical conductivity (EC), dissolved organic carbon (DOC), phosphate (PO4-P), total dissolved phosphorous (TP), total dissolved nitrogen (TN), Nitrite (NO_2-N), total ammonia (NH_4-N), Silica (Si), total monomeric aluminium (TM-Al) and labile aluminium (L-Al). The spatial variability of determinands was then mapped to help understand large scale spatial variability in water quality. L-Al data were excluded from the mapping since Al toxicity typically only arises under acidic low pH conditions (Malcolm et al., 2014). There was high correlation between some determinands e.g. alkalinity was strongly correlated with pH, Conductivity, Ca and Mg. Consequently, the list of determinands was reduced to a subset that were relatively poorly correlated (Pearson Correlation Coefficient < 0.8). Specifically: TN, NO_3-N, NO_2-N, NH_4-N, TP, PO_4-P, DOC, Si, pH, K, Cl, SO_4.

Results

Meteorological and hydrological context

There was considerable regional variability in rainfall during summer 2021 (Fig. 5). In July and to a lesser extent August, average or above average rainfall was seen in the east, while the west and north experienced unusually dry conditions. In September the west and south-east experienced lower than average rainfall, while the rest of country was characterised by near average conditions. In October much of Scotland experienced above average rainfall, with the greatest volumes falling in the south and west in particular. These patterns of spatio-temporal variability in rainfall resulted in very lows flows across the west in July, with more average conditions in August and September (Fig. 6). Flows were around or above average on most rivers in October, with particularly high flows in the south west.

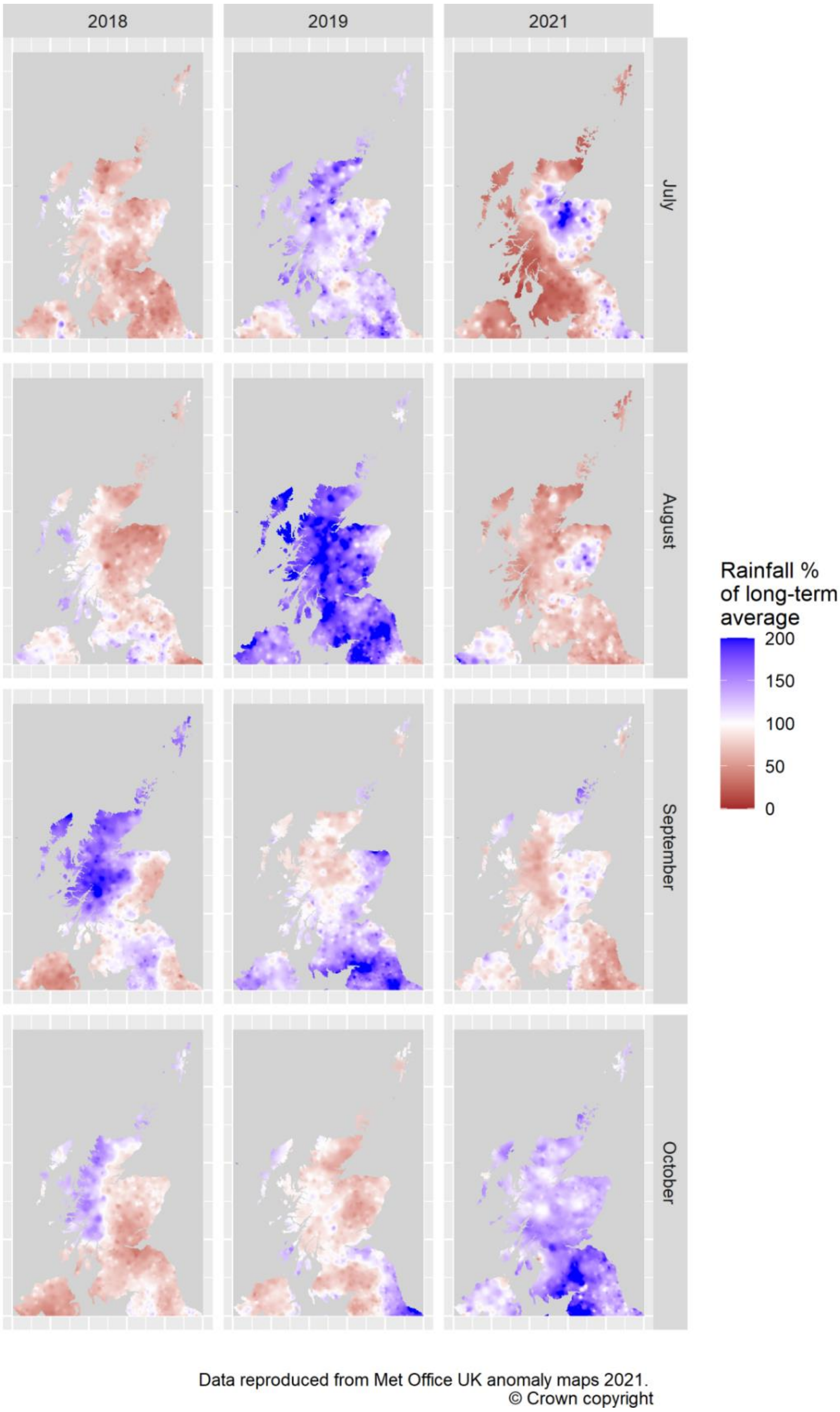


Figure 5 Percentage of long-term average rainfall for July-October when electrofishing was undertaken. Reproduced from MET Office (2021) UK actual and anomaly maps.

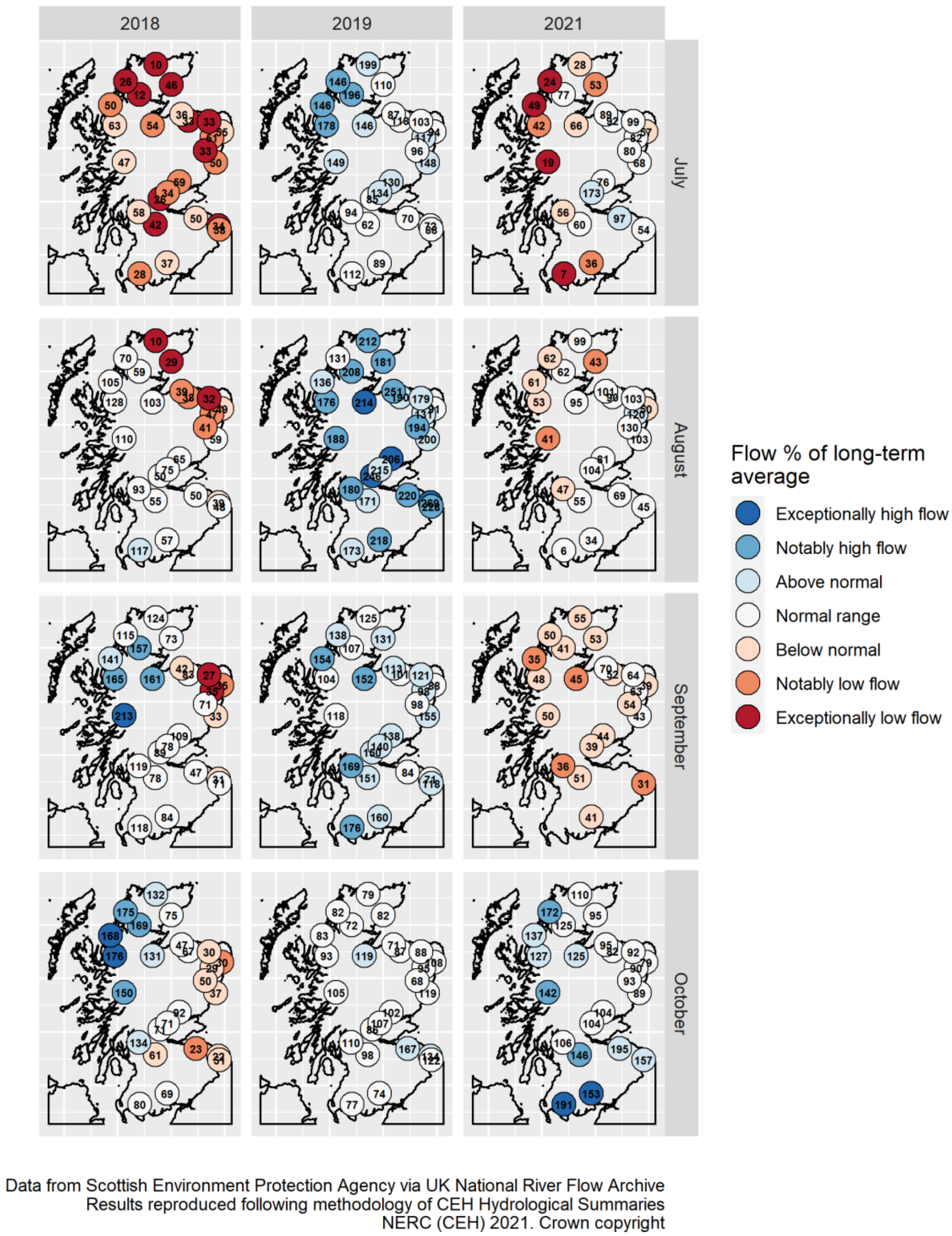


Figure 6 River flows across Scotland during the electrofishing season compared to a 20-year baseline (1981-2010). Colours indicate the 2018, 2019 and 2021 flow ranking relative to baseline years.

Capture Probability (*P*)

The final capture probability model for salmon and trout was:

logit P ~ Species + Lifestage + Pass + Lifestage:Pass + Organisation-Team + Year + Altitude + Species:Altitude + s(UCA) + s(Gradient) + s(DoY:Lifestage) + s(HA)

where s() denotes smoothed responses and : indicates an interaction term (Fig. 7).

Capture probability was higher for trout than salmon (Fig. 7A), for parr than fry and the first pass versus subsequent passes (Fig. 7B). The reduction in capture probability between the first and subsequent passes was also greater for parr than fry. Capture probability varied temporally with Year (Fig. 7C) and DoY (Fig. 7E). Year was a positive linear effect. DoY was a modal response varying by lifestage where modality was greater for fry than parr, the latter exhibiting a more linear positive response.

Capture probability varied spatially with Altitude, Gradient, UCA and HA. The response was negative with Altitude (Fig. 7F), Gradient (Fig. 7G) and UCA (Fig. 7H). The response to Altitude also varied between species, with stronger negative effects for trout than salmon. There were complex spatially correlated regional patterns in capture probability associated with HA (Fig. 7I).

Capture probability varied substantially between Organisation - Teams (Fig. 7D), although major differences were typically between Organisation, rather than between Teams within Organisation over time (not shown). Few Organisations routinely work outside their local area of responsibility. This limits contrast in the dataset and makes it challenging to separate regional (HA) and Organisation effects (Organisation - Team). To address this issue Figure 8 combines the effects of Organisation and HA for those Organisation - Teams undertaking sampling for NEPS 2021.

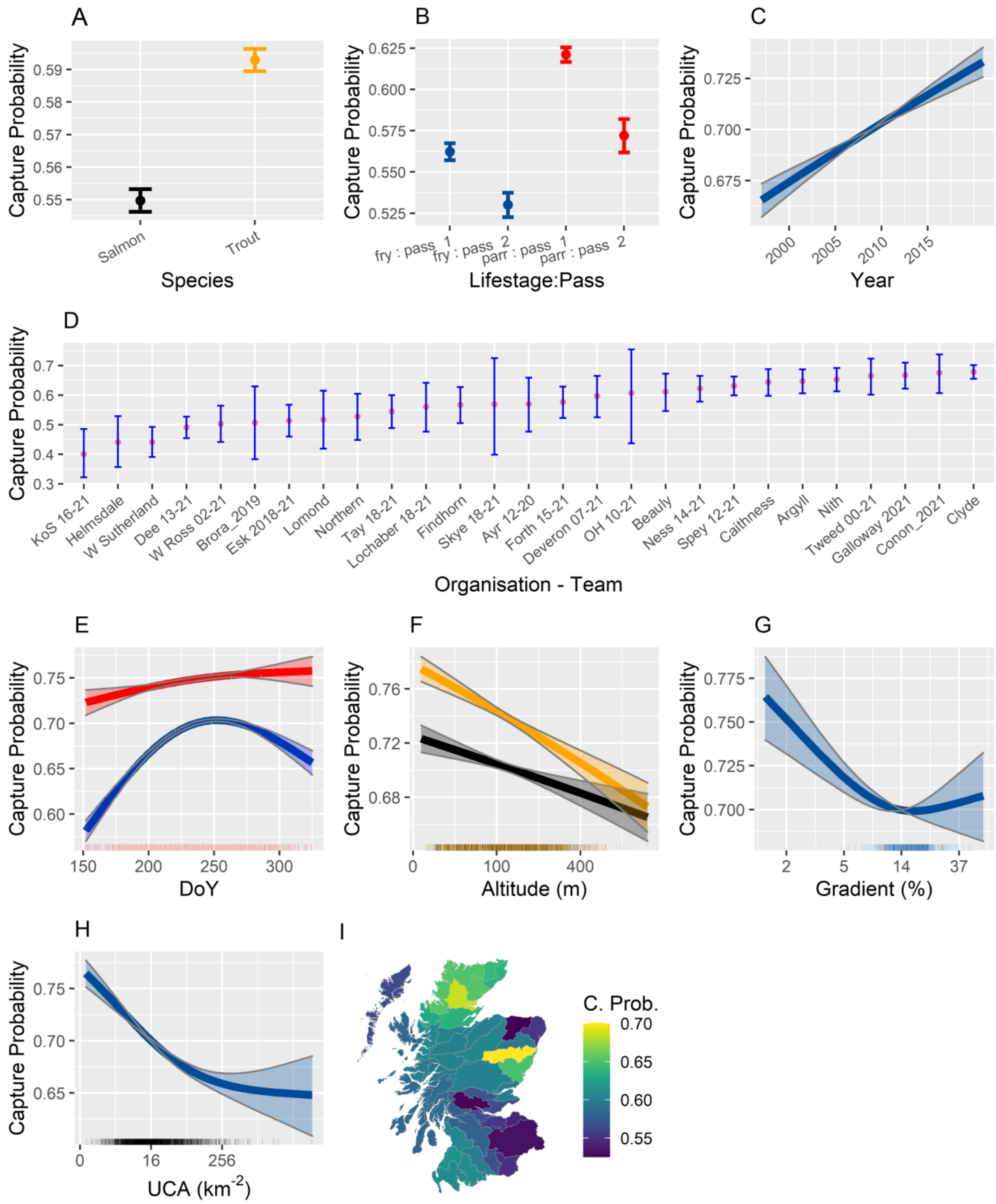


Figure 7 The effects of species (A) Lifestage : Pass (B), Year (C), Organisation - Team (D) Day of the Year : Lifestage (E), Altitude : Species (F) Gradient (G) Upstream Catchment Area (H), and Hydrometric Area (I) on capture probability. Where effects differed between Species or Lifestage they are plotted separately for salmon (black), trout (orange), fry (blue), parr (red). All effects are scaled to the mean fitted first pass capture probability. Approximate 95% pointwise confidence intervals are shown as shaded areas or vertical lines. A rug indicates the distribution of the data on the x-axis. Only Organisation Teams contributing to NEPS in 2021 are shown.

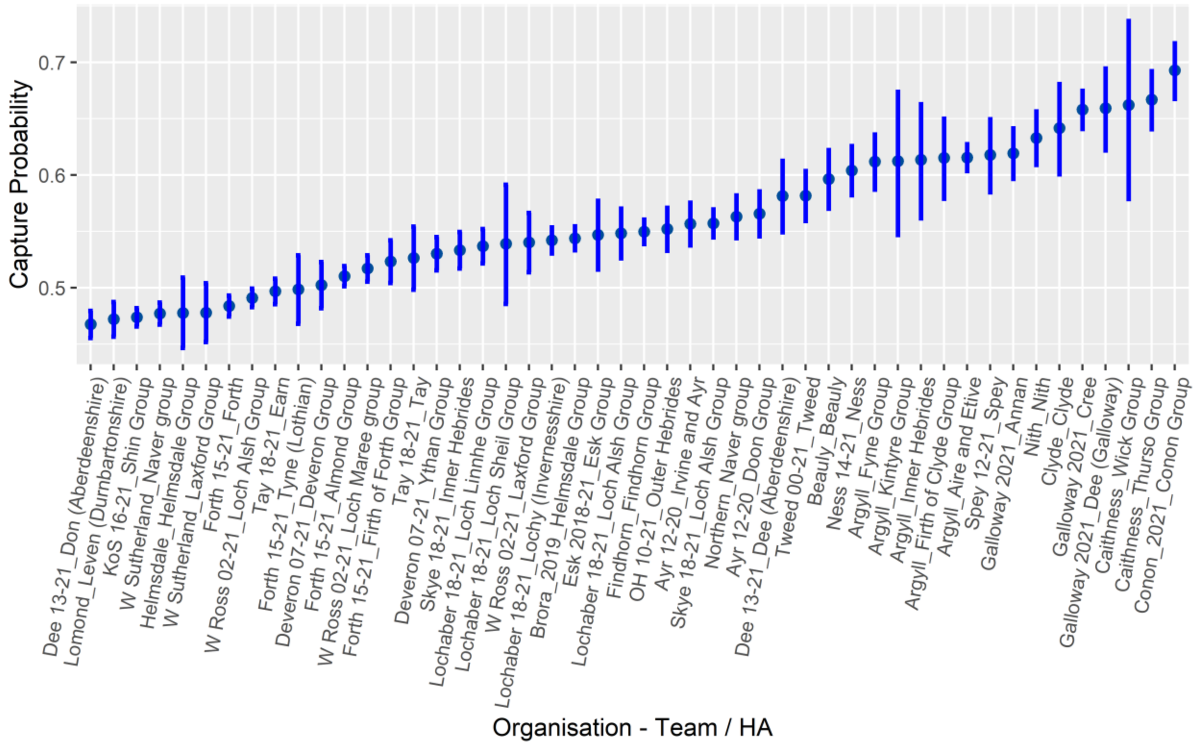


Figure 8 Combined partial effect of Organisation - Team and HA on capture probability. All effects are scaled to the mean fitted first pass capture probability. Approximate 95% pointwise confidence intervals are shown as vertical lines. Only Organisation - Teams contributing to NEPS in 2021 are shown.

Site-wise estimates of abundance (salmon and trout) and status (salmon): NEPS 2021

Estimates of the density of trout and salmon from NEPS 2021 are shown in Figures 9 and 10 respectively. Higher trout fry densities were observed at sites in the Tweed and the north-east, with generally lower densities in the north and west. Trout parr densities appeared less spatially variable with relatively high densities in the north and north-west.

Many NEPS 2021 sites contained no salmon fry (black points, Fig. 10A) and / or parr (Fig. 10B) although patterns of spatial variability were less clear than in previous years. Lower densities of fry were typically observed in the central belt, west coast mainland and the north-east corner. Salmon parr densities were generally higher in northern and eastern areas.

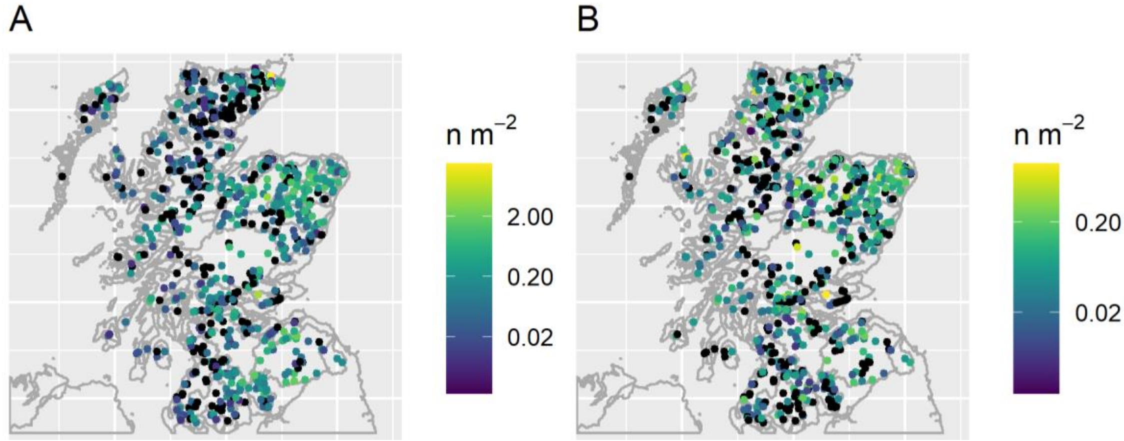


Figure 9. Maps showing spatial variability in trout densities for fry (A) and parr (B). Black points indicate sites where no fish (of the relevant life-stage) were caught.

Not all rivers are expected to produce the same number of juveniles due to spatial variability in habitat quality and thus carrying capacity. In the case of salmon, this is captured by spatial variability in the benchmark (Malcolm et al., 2018, Fig. 2). Unfortunately, a benchmark is not currently available for trout. Thus, only the performance of salmon at individual sites can be assessed through comparison with the benchmark (Fig. 10 C, D). NEPS 2021 data showed a wide range of performance against the benchmark, but sites where observed densities were below the benchmark dominated the picture. The only exceptions to this general pattern were the rivers on the east coast of Scotland, north of the Moray Firth and in the Outer Hebrides, although areas in the south-west around the Solway coast also appeared to perform well, at least in terms of fry.

While the percentage difference plots (Fig. 10 C, D) provide a useful indication of the status of sites, they do not differentiate between poorly performing unproductive sites and poorly performing productive ones. From a fisheries management perspective, the latter is arguably of more concern and is illustrated in Figure 10 (E, F). Production is often substantially below expectation across much of the country, although the effect appears less severe in the north. The underperformance of some sites in the Ness appears particularly marked, reflecting low observed densities and changes in the sample frame to include larger 5th order rivers where benchmark densities are higher (Fig. 2).

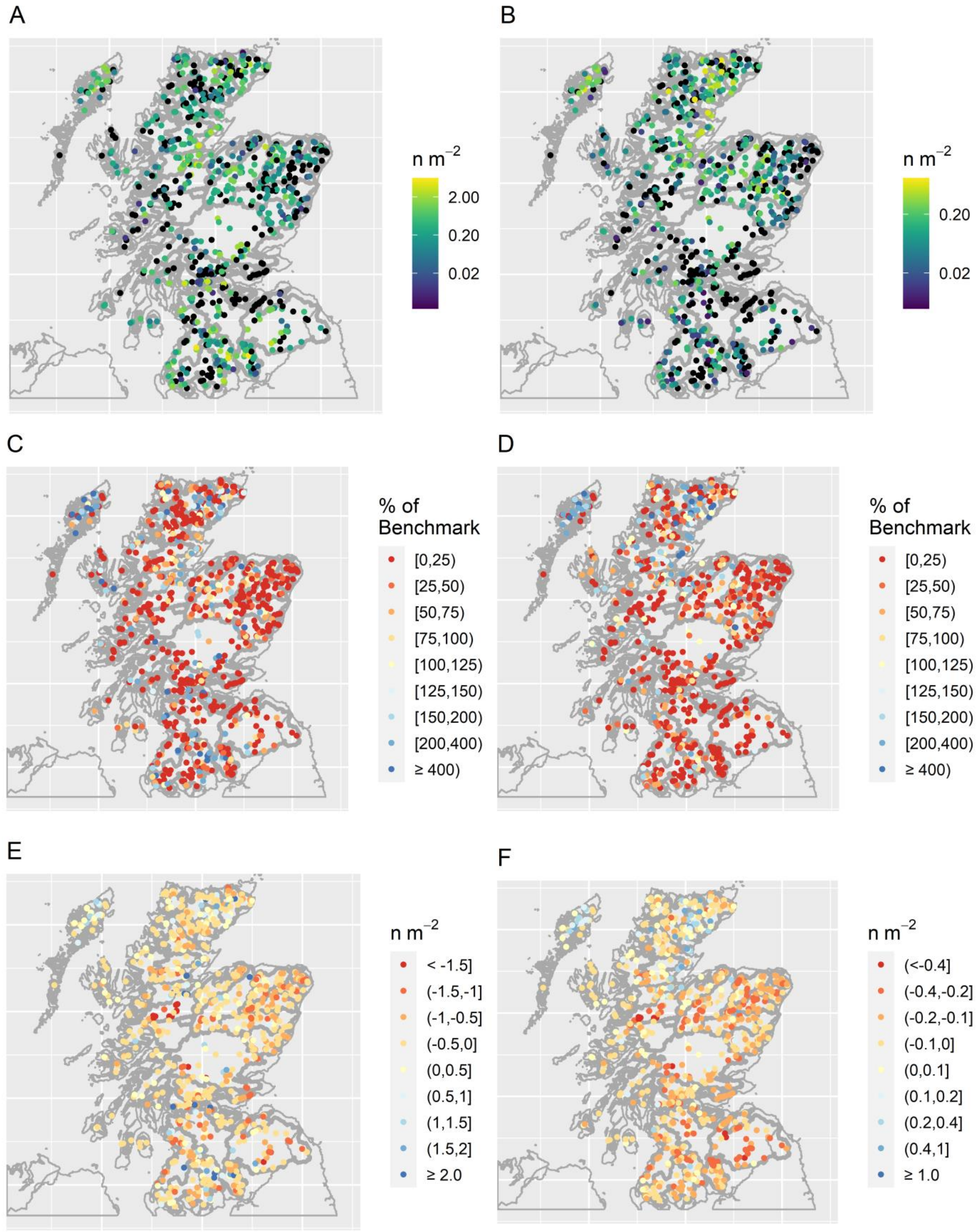


Figure 10. Maps showing spatial variability in observed salmon densities (A, B) together with their percentage (C, D), and absolute (E, F) performance against benchmark. Panels A, C and E show the results for fry. Panels B, D and F show results for parr. Black points (panels A and B) indicate sites where no fish of the relevant life-stage were caught.

National and regional assessments of abundance and status (salmon): NEPS 2021

Changes to the NEPS 2021 survey design both in terms of strata and sample frame (see Methods) made direct comparisons between years impossible without post-stratification and exclusion of some samples (see comparing estimates of abundance between years, below). Regional differences in the characteristics of the sample frames, in particular the inclusion of 5th order rivers in some regions also reduced comparability of density data between regions. However, spatial variability in the benchmark was able to account for regional variation in the sample frame thereby allowing for valid comparison of NEPS Grades between regions.

At the national scale (excluding rivers above impassable barriers in the Forth) salmon fry densities exceeded the benchmark indicating that fry densities were generally healthy and would achieve a Grade 1 classification (Fig. 11). The situation was starkly different for salmon parr where mean densities were around 60% of their benchmark. Taken together this would result in a Grade 2 classification for the country as a whole.

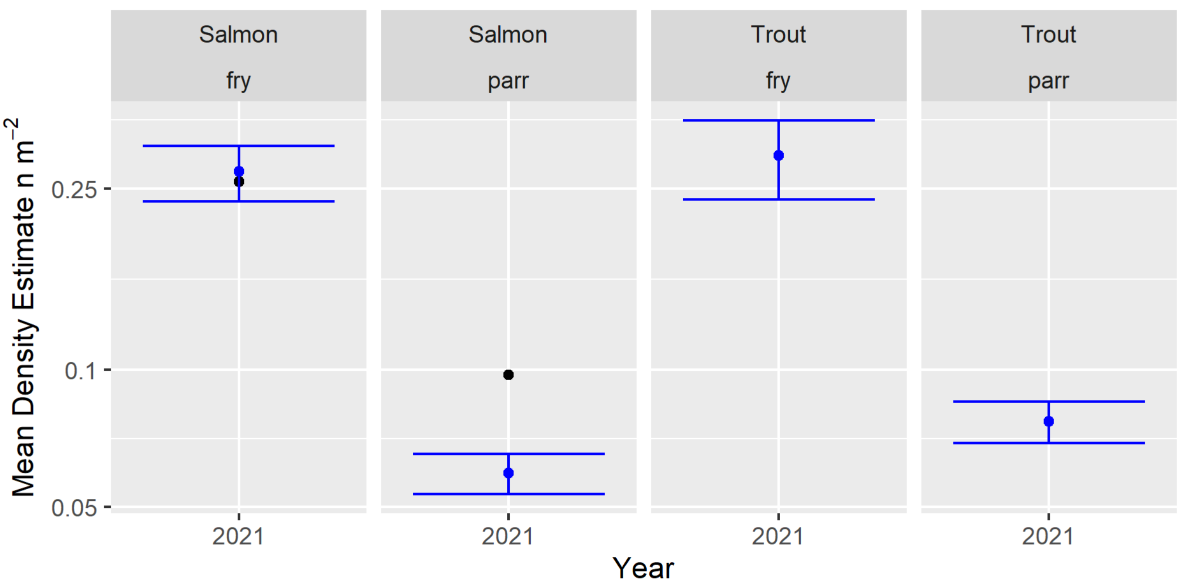


Figure 11 Mean density estimates of salmon and trout, fry and parr for the NEPS 2021 survey. Blue points and error bars indicate mean density estimates and 2-sided 90% confidence intervals. Black points indicate the target benchmark (only available

for salmon). Areas above impassable barriers in the Forth region have been removed from the national analysis, although areas above Shin dam have been retained.

Regional (strata level) differences in benchmark densities were greater in NEPS 2021 than in previous years (Figure 12). Higher benchmarks were associated with regional sample frames that were dominated by larger low altitude rivers, at intermediate to high distances to sea (e.g. Conon). In contrast, the presence of many smaller rivers resulted in lower regional benchmark densities (e.g. Lochaber). The effect of removing smaller rivers and adding larger rivers (5^{th} order rivers) to the sample frame between 2018-19 and 2021 was thus to increase the benchmark density in affected regions. This is most clearly seen in the case of the Ness, where changes to the sample frame resulted in sampling a substantially greater proportion of larger rivers.

By combining regional density estimates, their uncertainty and regional benchmark densities, it was possible to assess spatial variability in the status of salmon (Figures 12 and 13). Salmon fry, which reflected spawner numbers from 2020, were generally characterised by higher grades than salmon parr which reflected spawner numbers from 2019 and earlier years. There were pockets of Grade 1 for salmon fry in the south-west (Annan, Nith, Ayrshire), Firth of Forth, Tay and the north (Beauly, Conon, Helmsdale, Caithness, Northern, Outer Hebrides, Skye and Lochalsh). In the case of salmon parr only regions to the north attained a Grade 1 (Beauly, Conon, Brora, Helmsdale, Caithness, Northern, Outer Hebrides and Wester Ross). Overall grades were also patchy, with Grade 1 regions only observed in the north (Beauly, Conon, Brora, Helmsdale, Caithness, Northern, Outer Hebrides and Skye and Lochalsh) and south-west (Ayrshire). The river Shin (above Shin dam) was the only Grade 3 stratum in the north. This is perhaps unsurprising as Shin dam is a substantial barrier which is classified as impassable by SEPA, primarily for its impacts on downstream migration.

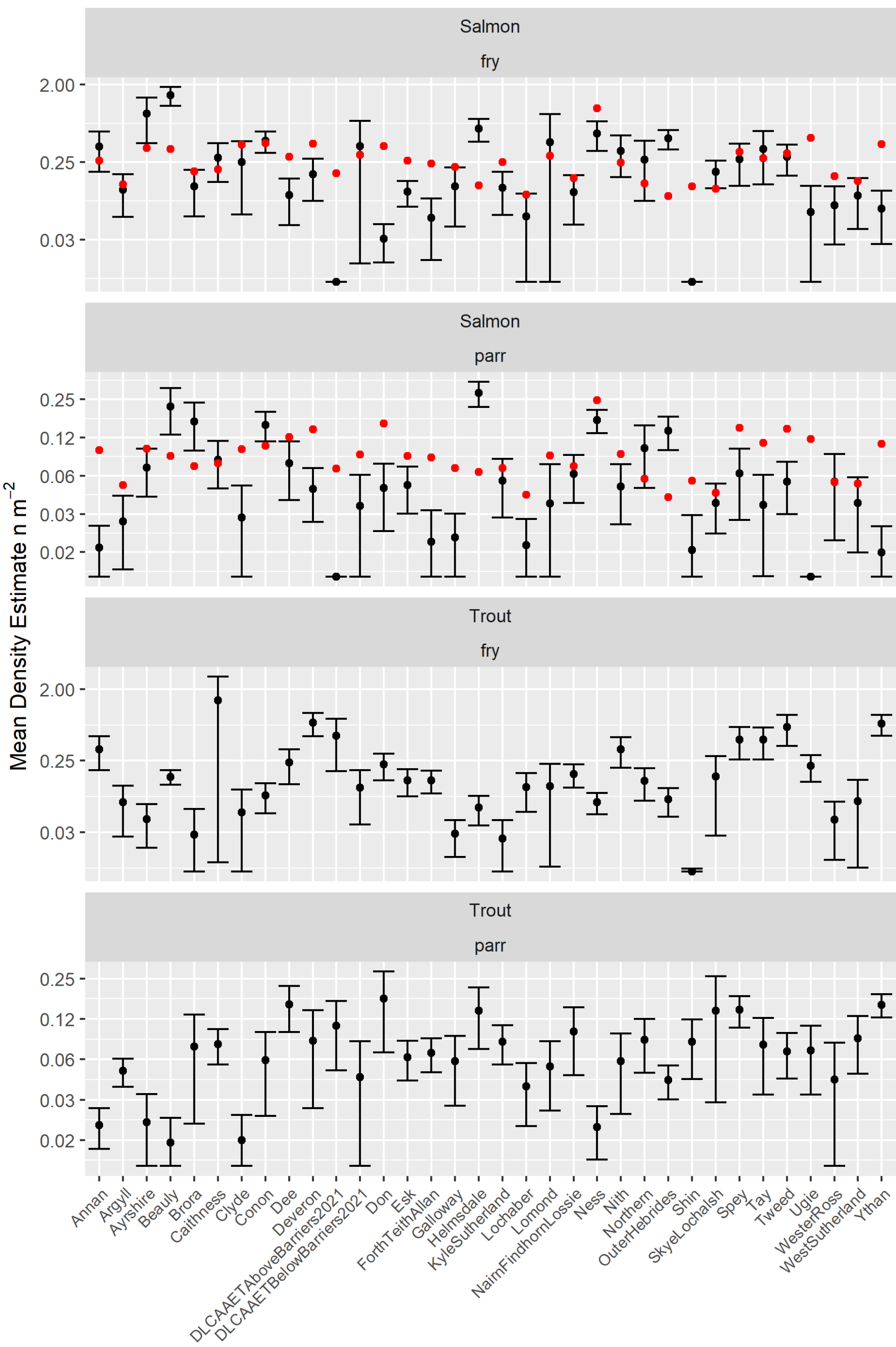


Figure 12 Plots showing density estimates (black points), with associated 2-sided 90% confidence intervals for each of the strata included in NEPS 2021, separated by species and lifestage. In the case of salmon red points indicate the benchmark (expected densities) against which estimated densities can be compared to determine performance grade.

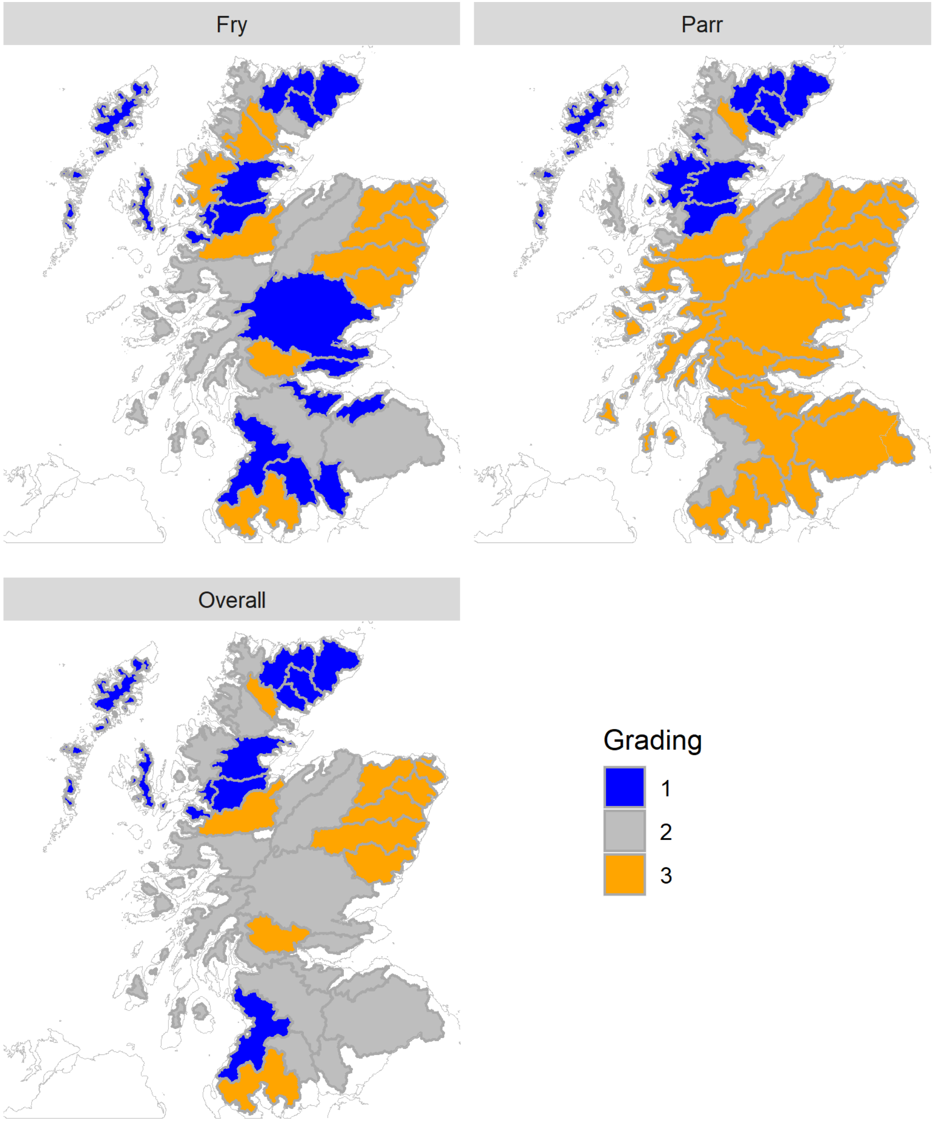


Figure 13. Maps showing NEPS grades for salmon fry, parr and overall grading (fry and parr)

Relationships between Strahler river order and the habitat characteristics of surveyed river reaches

The percentage of riffle and run habitat that was surveyed increased with Strahler river order, while the percentage of surveyed pool habitat declined (Figure 14). This could reflect genuine spatial variability in channel characteristics or increased use of micro-siting on larger rivers to avoid surveying deeper pool habitat.

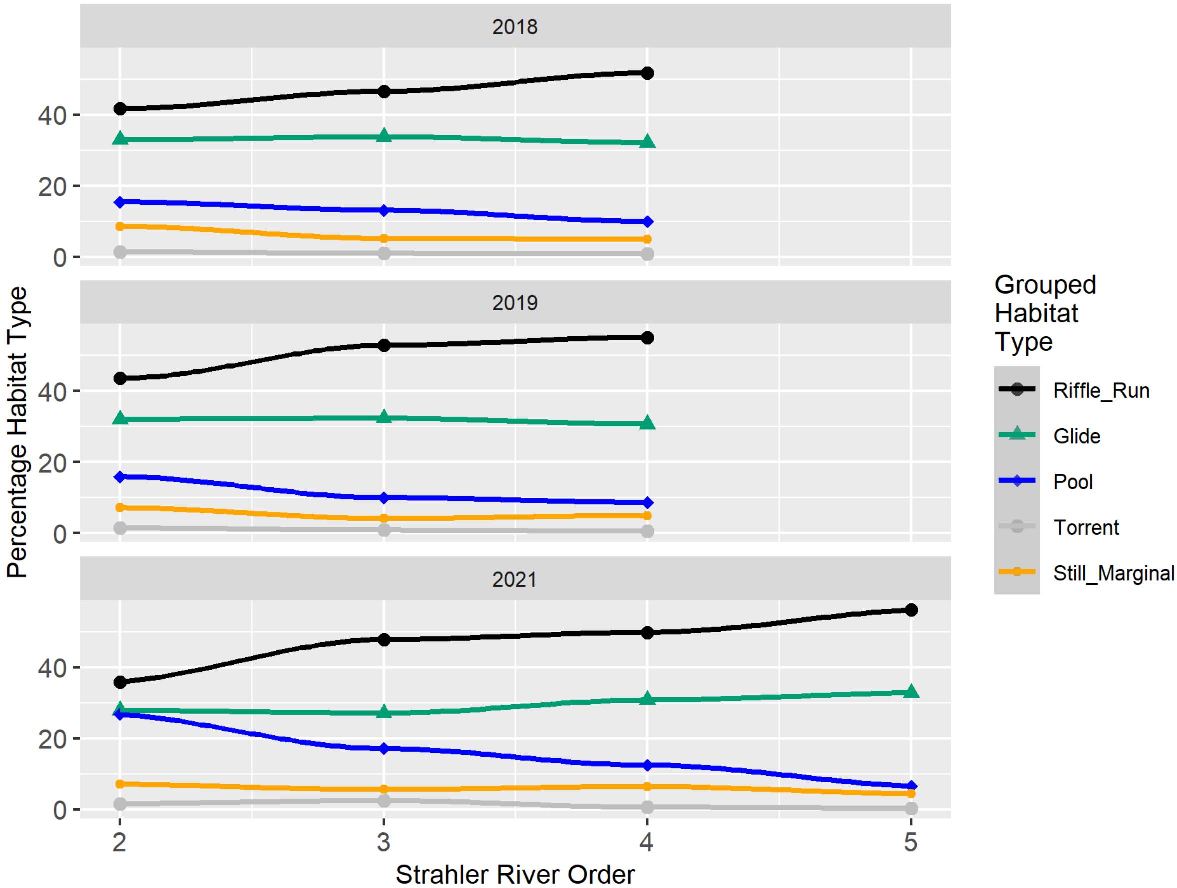


Figure 14 Relationships between Strahler river order and the percentage of different habitats that were surveyed. Rows indicate the different NEPS survey years. Fifth order rivers were only surveyed in some regions in 2021.

Relationships between Strahler river order, mean observed densities of salmonids and the NEPS benchmark

By post-stratifying the NEPS data for each survey year it was possible to investigate spatial variability in densities across Strahler river orders (Fig. 15). Densities of salmon fry and parr increased significantly across all Strahler river orders, whereas trout densities were unchanged between Strahler orders 2,3 and declined over orders 3 to 5 (Fig. 15). Variability in benchmark densities for salmon between river orders was broadly consistent with variability in mean estimated densities (Fig. 15).

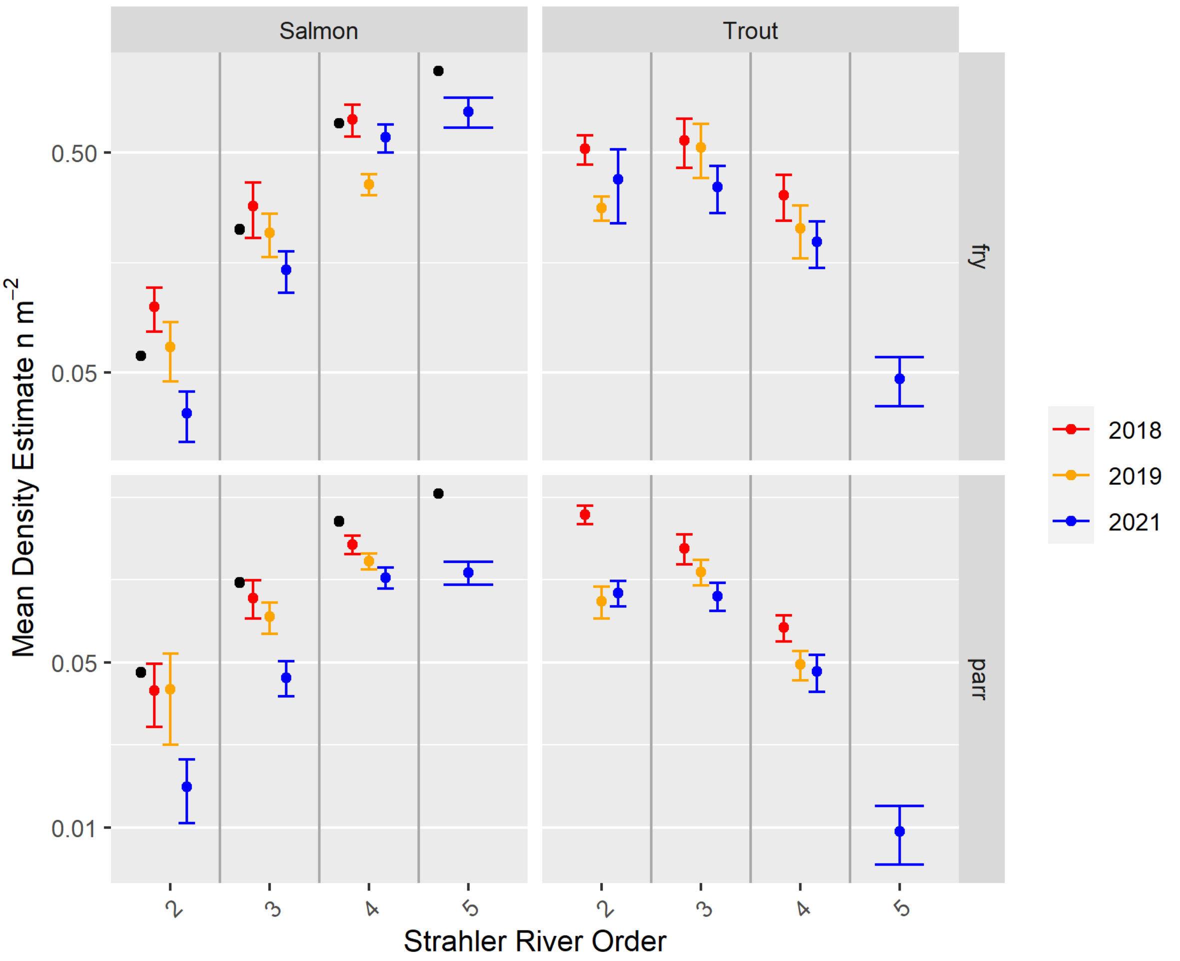


Figure 15 Relationships between Strahler river order and mean estimated densities for salmon and trout, fry and parr obtained by post-stratifying the NEPS data. Coloured points and error bars indicate different survey years. Black points (salmon only) indicate the benchmark for each river order in 2021. Note that plots contain all data collected under NEPS 2021, including strata above barriers on the Forth and Shin that will reduce mean density estimates for salmon relative to 2018 and 2019 surveys.

Inter-annual variability in salmonid densities and status

At the national scale, salmon fry densities were higher in 2021 than 2019, but lower than 2018 (Fig. 16). Parr densities in 2021 were substantially lower than previous surveys and appeared to show a downward trend. Fry densities were above the national benchmark in 2021 and classified as Grade 1. Parr densities were significantly below the benchmark and as such were classified as Grade 3. The overall 2021 classification at a national scale was therefore Grade 2. At a national scale, the densities of trout fry and parr declined across years.

There was considerable regional variability in the abundance of salmon and trout between years (Fig. 17). This spatio-temporal variability in abundance was reflected in similarly complex patterns of variability in NEPS Grades (Fig. 18). However, the consistent downward trend in parr densities observed at the national scale was evident in declining Grades for parr across much of the country, with better performing regions (Grade 1) becoming constrained to the north by 2021.

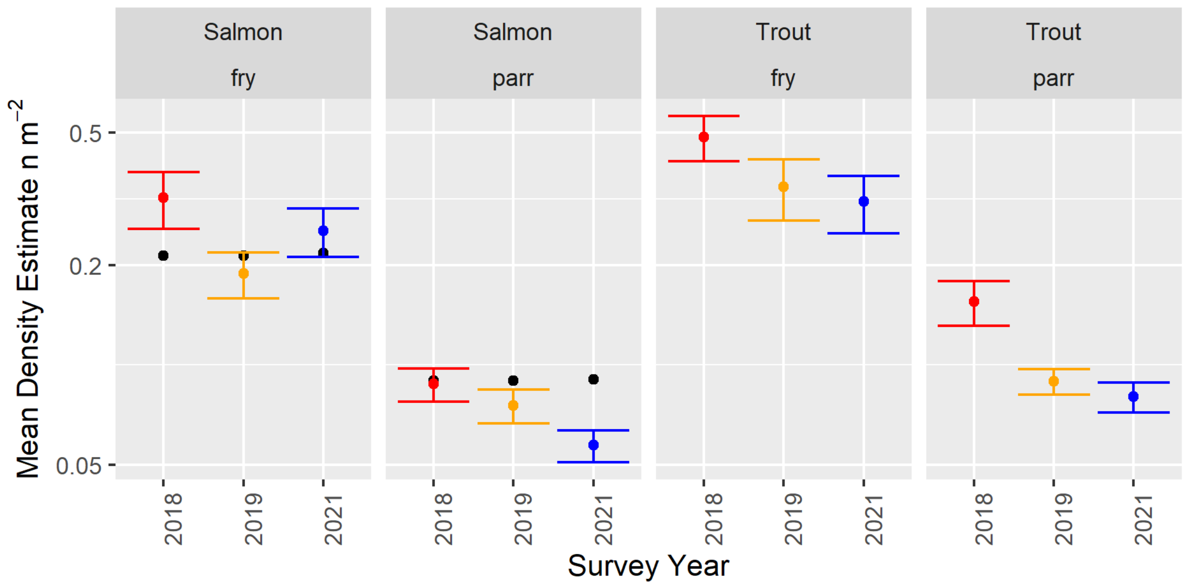


Figure 16 Comparison of juvenile trout and salmon, fry and parr densities between years. Coloured points and error bars indicate mean density estimates. Black points for salmon indicate the national benchmark. Data from NEPS 2021 was post-stratified to provide a sample frame that was broadly consistent with 2018-19 NEPS surveys. Small differences to the benchmark between years reflect changes to sample frame that were not possible to resolve

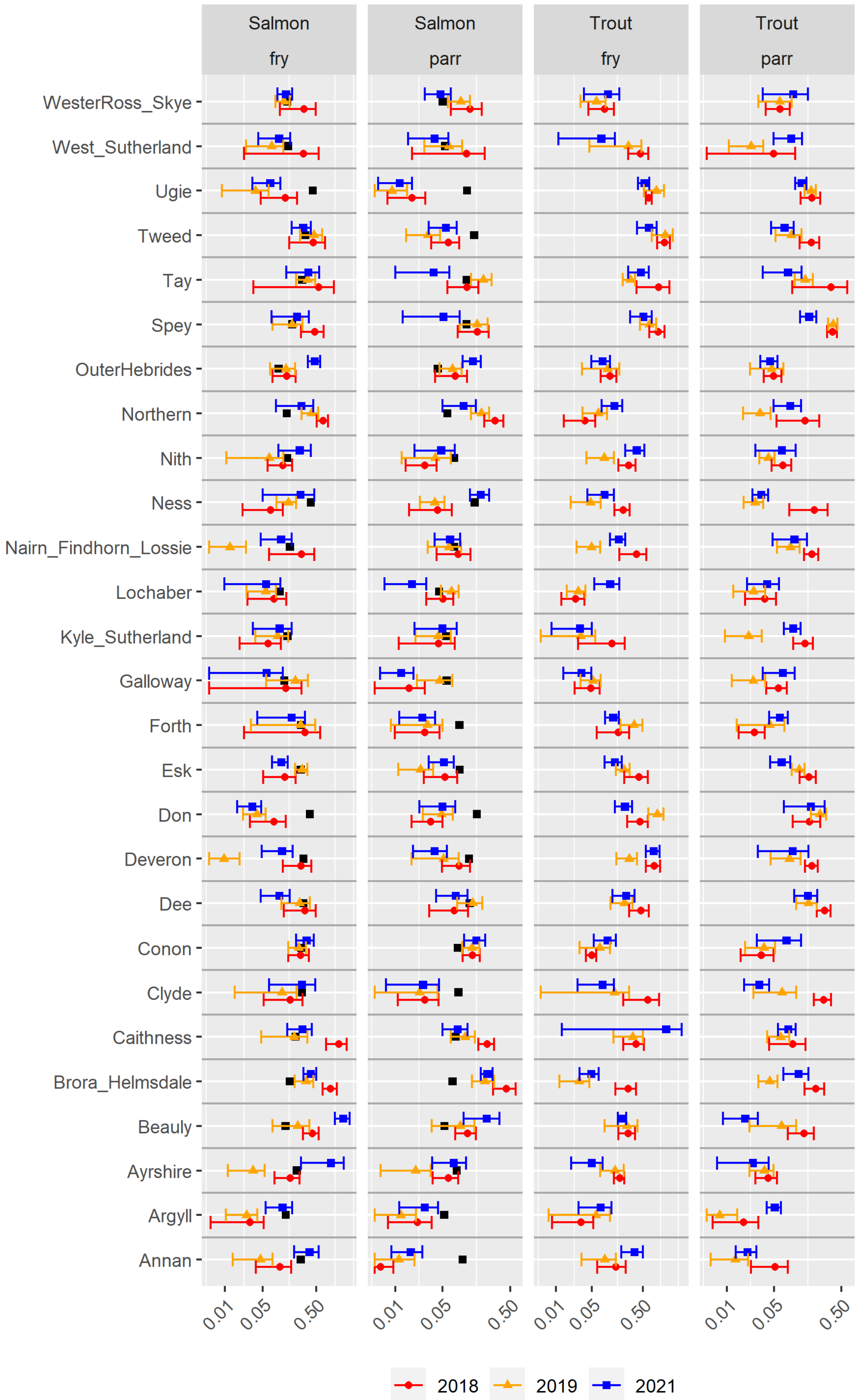


Figure 17. Comparison of observed salmon and trout, fry and parr densities across years. Black circles indicate the benchmarks for salmon. Data from NEPS 2021 were made comparable with data from previous years using post-stratification.

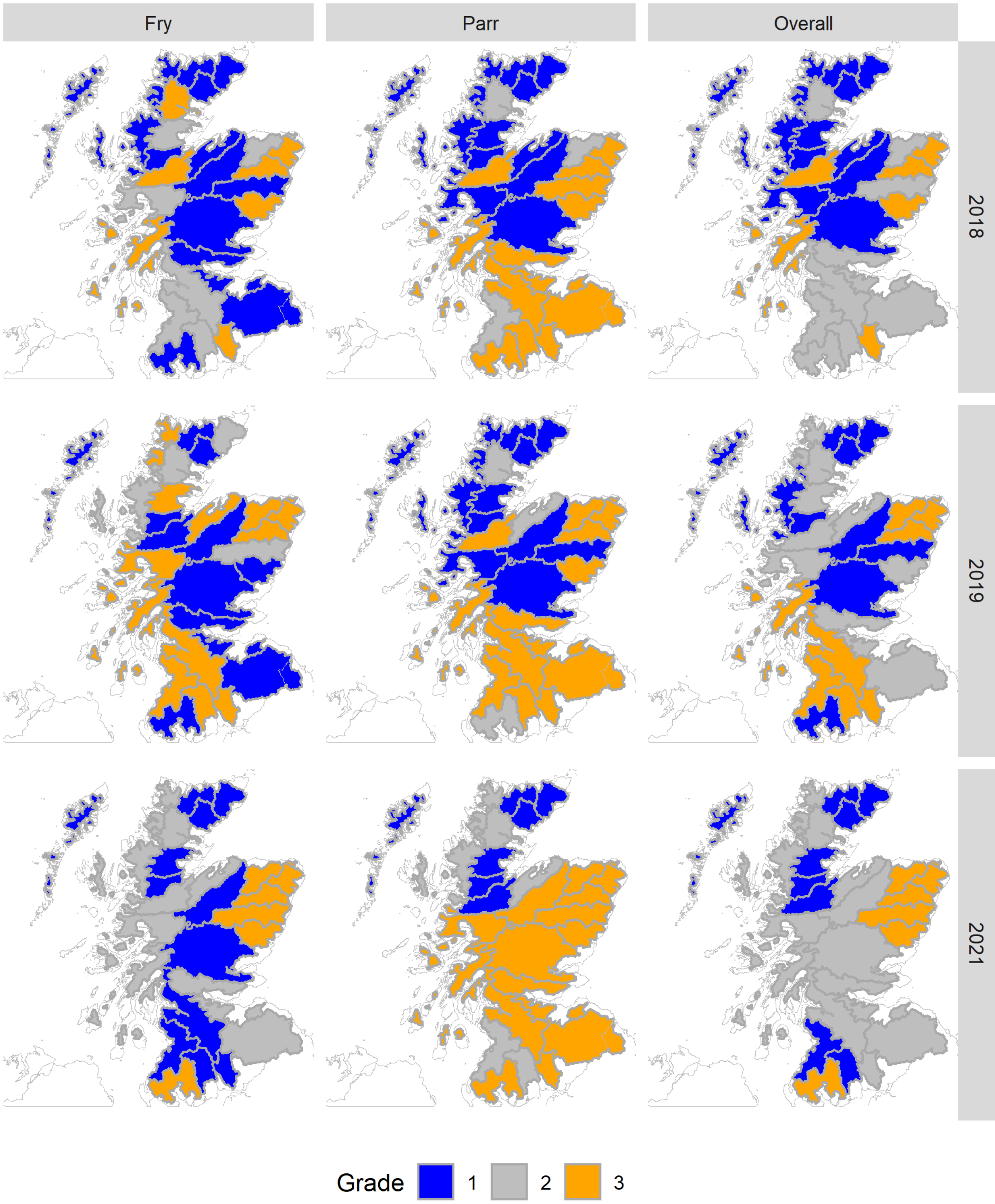


Figure 18 Inter-annual variability in the status (Grades) of salmon fry, parr and the combination of lifestages between NEPS surveys. Data from NEPS 2021 were post-stratified to harmonise between years and allow comparison for common regions and sample frames (Strahler order 2-4 rivers).

Assessing the status of Special Areas of Conservation (SACs) for salmon

There was considerable variability in the estimates of mean salmon densities, benchmark and NEPS grades between SAC rivers (Fig. 19). Only half of the SACs were considered to be in Favourable Condition. Of these, only the River Naver and Mallart Water received a NEPS Grade 1 assessment in every year, with the Spey, Tay and Dee receiving a Grade 1 assessment in two of the three years (Table 1). The River Teith received a NEPS Grade 3 assessment in all years while the River Moriston received a Grade 3 assessment in two of the three years.

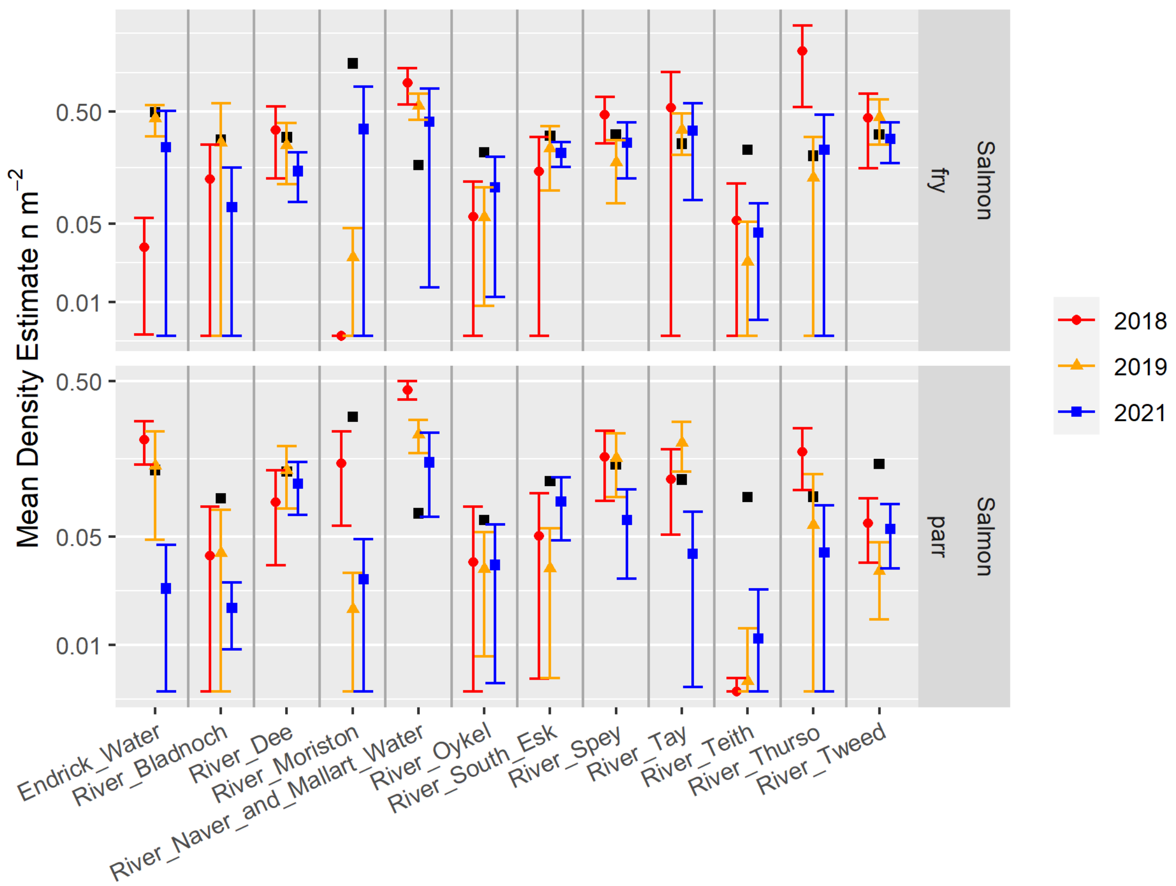


Figure 19 Estimated mean densities (with associated uncertainty) of salmon fry and parr in Special Areas of Conservation (SACs). Data are shown only for SACs with a minimum of five samples in each NEPS sampling year. Black circles indicate the benchmarks for salmon. Data from NEPS 2021 was harmonised with data from previous years by post-stratifying data where necessary.

SAC	Grade 2018	Grade 2019	Grade 2021	Condition	Fry Trend	Parr Trend	Overall Trend
Endrick	2	1	3	Unfavourable	No Change	Declining	Declining
Bladnoch	2	2	3	Unfavourable	No Change	No Change	No Change
Dee	1	1	2	Favourable	Declining	No Change	Declining
Moriston	2	3	3	Unfavourable	Recovering	No Change	Recovering
Naver & Mallart	1	1	1	Favourable	Declining	Declining	Declining
Oykel	2	2	3	Unfavourable	No Change	No Change	No Change
South Esk	3	2	2	Unfavourable	No Change	No Change	No Change
Spey	1	1	2	Favourable	No Change	Declining	Declining
Tay	1	1	2	Favourable	Declining	No Change	Declining
Teith	3	3	3	Unfavourable	No Change	Recovering	Recovering
Thurso	1	2	2	Favourable	No Change	Declining	Declining
Tweed	2	2	2	Favourable	No Change	No Change	No Change

Table 1 Proposed site condition assessments for SACs based on NEPS data.

Relationships between juvenile density, rod catch and NEPS grades

Although NEPS has only run for three years, there were strong positive relationships between rod catch (as a proxy of spawner abundance) and estimates of mean juvenile salmon density at the national scale (Fig. 20). Similar positive relationships can be seen between rod catch (scaled for wetted habitat) and juvenile density at regional scales (Fig. 21), although the greater number of observations and wider range of stock values suggests that habitat may be saturated in some areas (particularly in the north of Scotland) and years. Plotting data in this way ignores spatial variability in habitat quality and carrying capacity which is known to be an important control on abundance (Glover et al*.,* 2018; Malcolm et al., 2019). Nevertheless, accepting these limitations, there is a suggestion that NEPS Grade 1 classifications are likely to be somewhat below maximum carrying capacity.

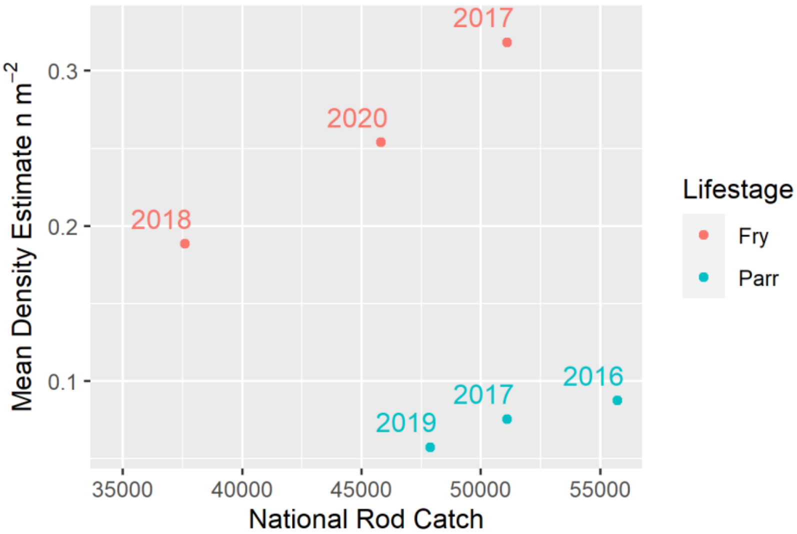


Figure 20 Relationship between salmon rod catch (retained and released) and mean estimated juvenile salmon densities in Strahler order 2-4 rivers. Coloured numbers indicate lagged spawner years (assuming parr are primarily 2 years old).

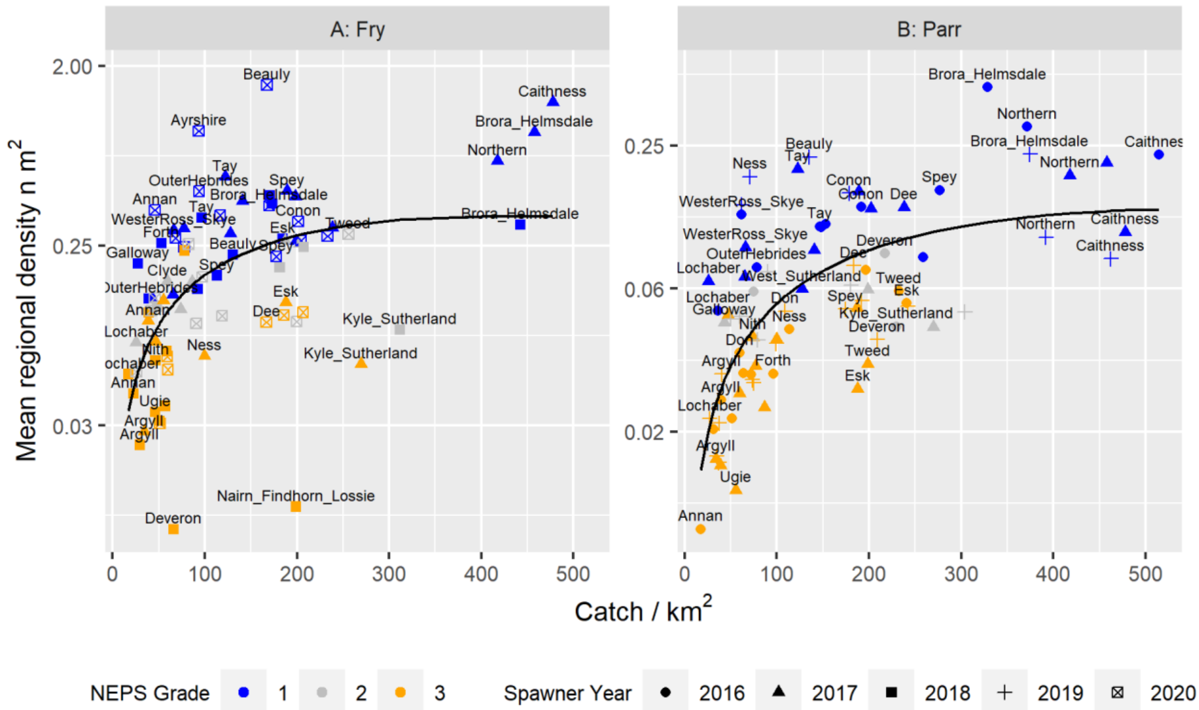


Figure 21 Relationship between salmon rod catch density (catch / km^2 of accessible river wetted area) and regional estimates of mean juvenile density from Strahler river orders 2-4. Symbols indicate lagged spawner years assuming parr are predominantly 2 years old. Colours indicate NEPS Grades. Black lines show a fitted Ricker stock recruitment relationship.

Spatial Variability in water quality: assessing potential pressures

Spatial variability in water chemistry was broadly consistent between years (Fig. 24, 25, 26). This suggests that the spatially extensive summer spot samples, collected under the low flow conditions, provide a strong basis for characterising within and between river variability in water quality necessary for identifying pressures acting on fish populations.

Total Nitrogen concentrations were highest in urban areas around the central belt, and agricultural areas of the east, north-east and south-west (Fig. 24). Nitrate was the dominant form of nitrogen, although less so in the south-west where organically bound nitrogen likely contributed more substantially than seen elsewhere. As expected, Nitrite and Total Ammonia concentrations were relatively low compared to Nitrate. Nitrite concentrations typically tracked concentrations of Total Nitrogen and Nitrate. Ammonia concentrations were often higher in 2019 than other years but were often patchy in character rather than regionally coherent reflecting potentially localised pollution sources. Nevertheless, higher ammonia concentrations were observed across some north-east and south-western rivers, particularly in 2019.

Total Phosphorous concentrations exhibited spatial patterns that were broadly consistent with Total Nitrogen (Fig. 25). Higher concentrations were observed on the East coast (particularly in the north-east), south-west and central belt. Phosphate, the inorganic form of Phosphorous, was a relatively small component of Total Phosphorous and higher concentrations were generally associated with the north-east and the central belt.

Dissolved Organic Carbon concentrations were typically highest in areas where Nitrogen and Phosphorous concentrations were low reflecting the spatial distribution of organic rich soils that are of lower agricultural value (Fig. 25). Silica concentrations were generally lower in the north-west and higher in the east, particularly the north-east, reflecting regional differences in geology, groundwater contributions and residence times.

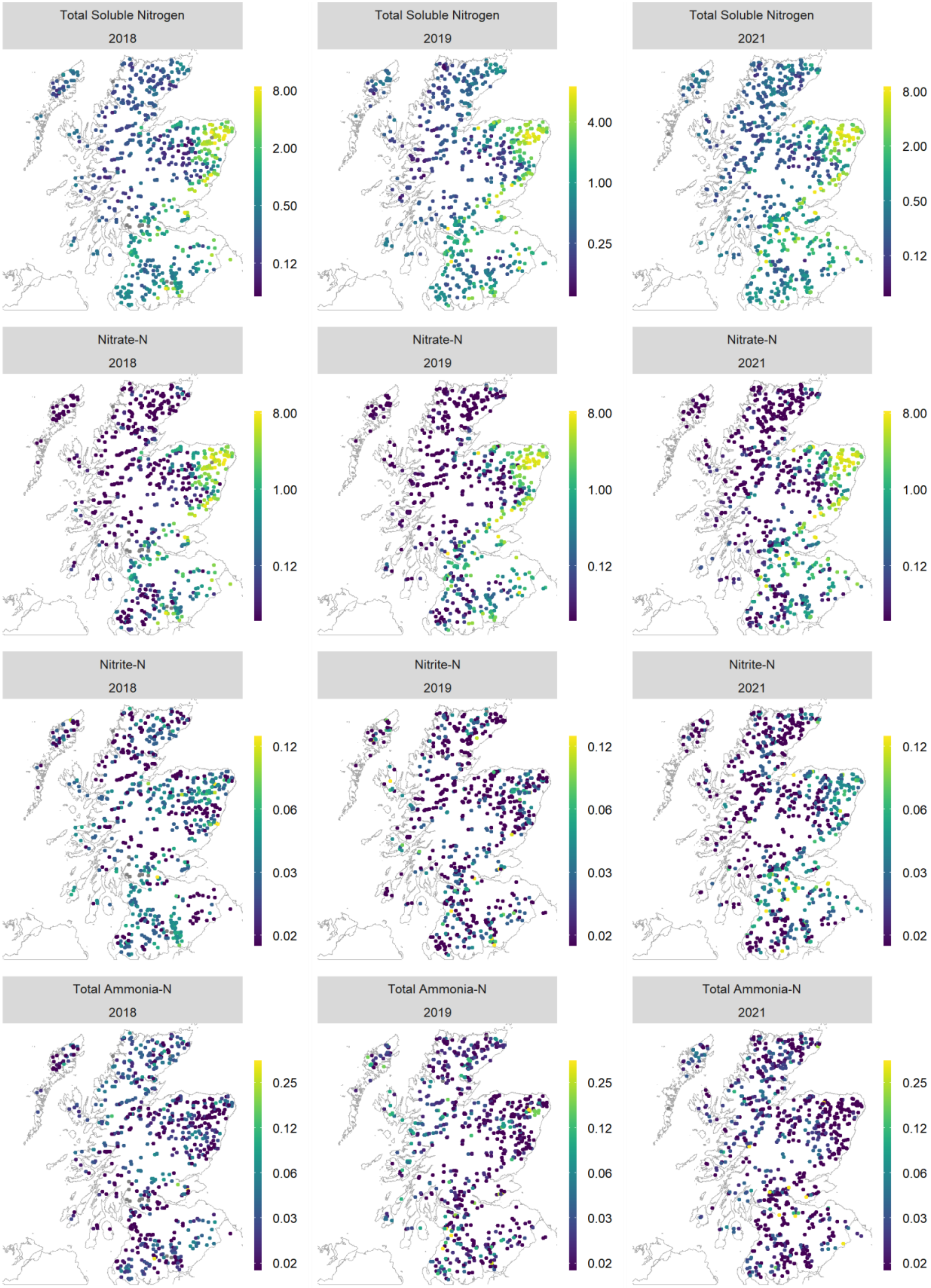


Figure 24 Spatial variability in Nitrogen and Nitrogen compounds between NEPS surveys. Columns relate to NEPS survey years (2018, 2019, 2021), rows relate to chemical determinands. All concentrations are in parts per million (ppm)

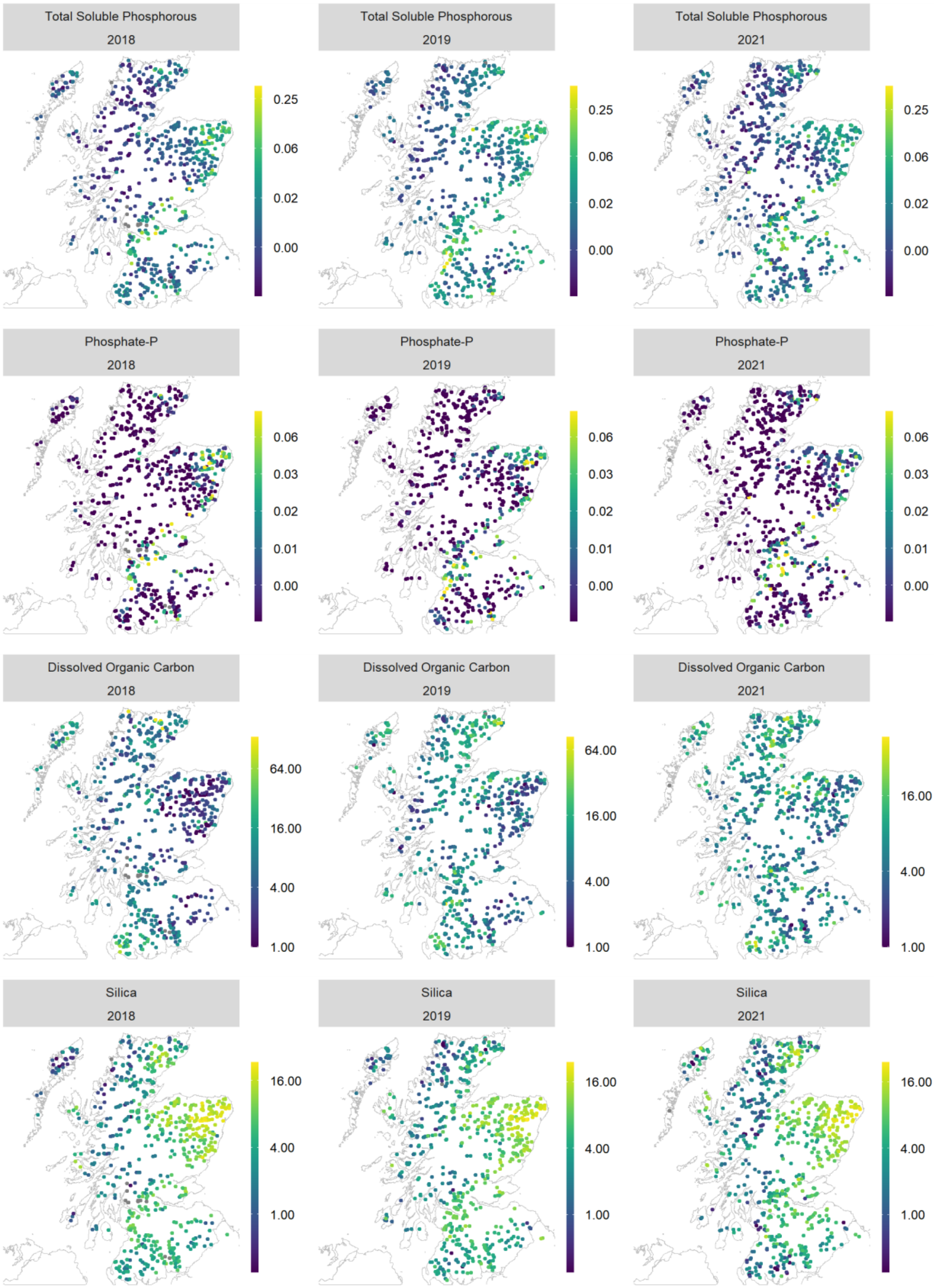


Figure 25 Spatial variability in Total Phosphorous, Phosphate, Dissolved Organic Carbon and Silica between NEPS surveys. Columns relate to NEPS survey years (2018, 2019, 2021), rows relate to chemical determinands. All concentrations are in parts per million (PPM)

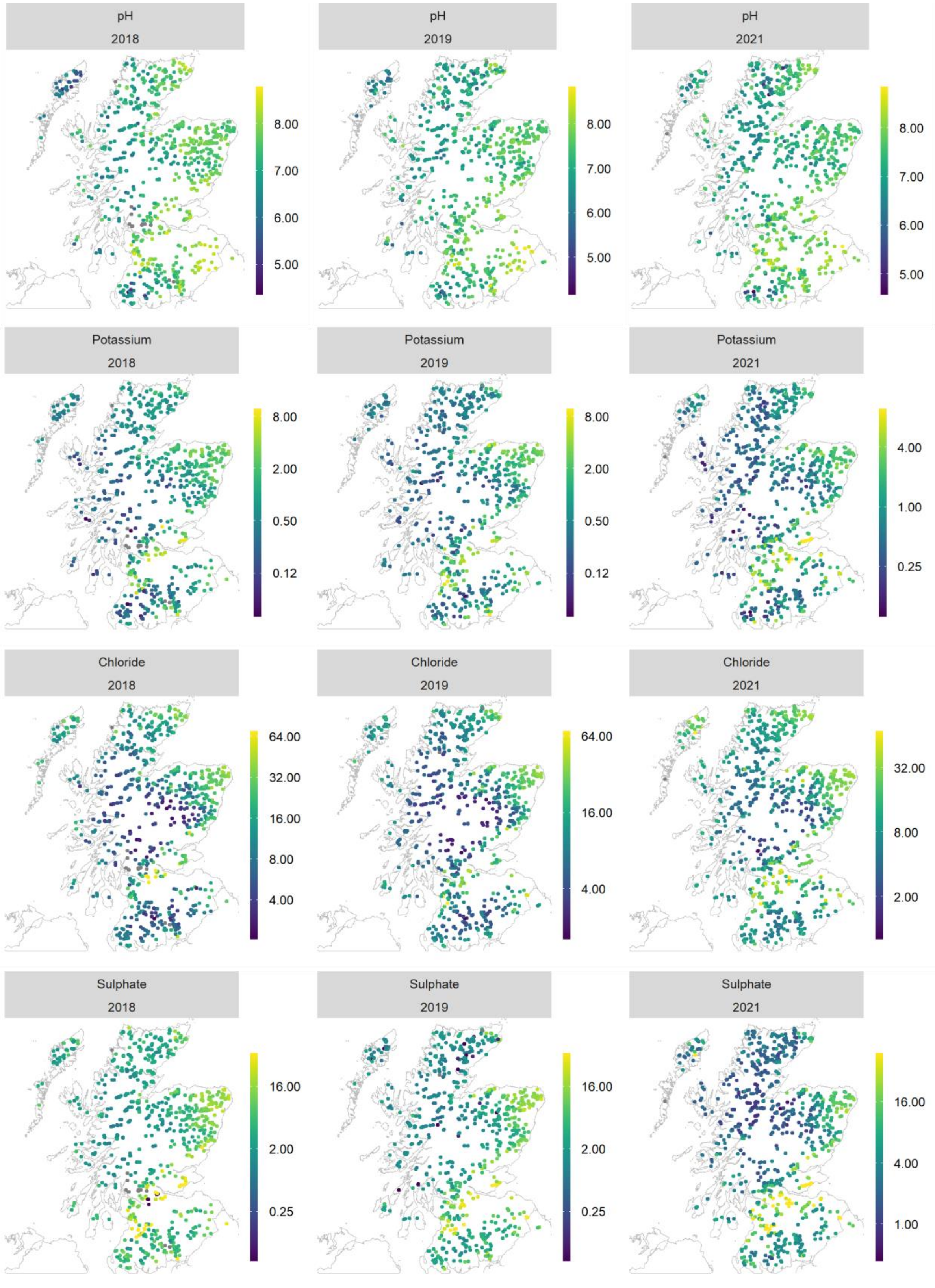


Figure 26 Spatial variability in pH, Potassium, Chloride and Sulphate between NEPS surveys. Columns relate to NEPS survey years (2018, 2019, 2021), rows relate to chemical determinands. All concentrations are in parts per million (ppm) except for pH.

Spatial variability in pH was again consistent with geology, soils and land use. Lower pH values were observed in the west, south-west and Cairngorm mountains, with higher pH on the north-east coast and around the central belt (Fig. 26). Spatial variability in Potassium concentrations largely matched that of nutrients Nitrogen and Phosphorous, potentially indicating a common source from NPK fertilisers. Chloride concentrations were generally higher in coastal areas reflecting marine derived sources. Sulphate concentrations were typically lower in the north-west and higher in the south and east reflecting the influence of both marine derived and anthropogenic sources, the latter being particularly associated with burning of fossil fuels.

Discussion

A third NEPS survey was undertaken in 2021. When combined with previous surveys these data provide a strong quantitative evidence base from which to assess spatial and temporal variability in the densities of salmon and trout, the status of salmon, and the potential influence of pressures including water quality and farm to wild genetic introgression. Such robust evidence and understanding provide an important underpinning to target management actions to ensure good quality habitat and healthy fish populations as envisaged by the Blue Economy Vision for Scotland and Wild Salmon Strategy. With additional work and / or resources, the assessment methods developed for salmon under NEPS could be extended to other species and reporting contexts. This could include Habitats Directive, Water Framework Directive and Conservation Regulations, although this is not without challenges (see below for further discussion).

NEPS 2021 employed a new single year survey design that evolved in response to feedback from local fisheries managers and logistical challenges identified in previous years. The new survey design added value by incorporating local monitoring and reporting requirements where possible. While the new design offered many advantages and increased flexibility over previous surveys it also posed substantial challenges in terms of data analysis and interpretation, particularly through the inclusion of larger 5th Strahler order rivers in some regions. Nevertheless, it was possible to overcome these challenges to present new and improved data, whilst also providing data comparable to previous years and surveys.

Post-stratification of the NEPS survey data allowed assessments of density and status for individual rivers including Special Areas of Conservation where it was also possible to suggest approaches for classification that could meet the needs of Site Condition Monitoring. A comparison between juvenile salmon density estimates and rod catch at national and regional scales provided assurance that the abundance metrics underlying the adult and juvenile assessment methods in Scotland are broadly coherent. Although water quality data were collected during surveys in previous years, this was the first year that these data have been presented as part of NEPS reporting. When considered alongside assessments of status these data provide a powerful basis for identifying environmental pressures acting on salmon, thereby informing targeted conservation and restoration activities. These issues are discussed in detail below.

Capture Probability

Capture probability models are essential for harmonising the data collected under NEPS (and from other electrofishing data sources) and for producing reliable, unbiased density estimates. Without appropriate modelling, spatio-temporal variability in apparent abundance (i.e. fish counts) can be confounded with spatio-temporal variability in capture probability (Millar et al., 2016, Dauphin et al., 2018, Glover et al., 2018, Malcolm et al., 2019a, Glover et al., 2019) leading to erroneous understanding of the status of stocks and potentially poor management decision making. The capture probability model presented in this report was similar to that from previous years (Malcolm et al., 2019b, 2020). Trout were generally more catchable than salmon, parr were more catchable than fry, and fish were more catchable on the first pass than subsequent passes, with the between pass differences in capture probability being greater for parr. It is possible that some of this variability reflects differences in habitat use among species and lifestage or the effects of different average size, with larger fish typically being more catchable.

Some new Organisation – Teams were established in 2021 due to new individuals undertaking fieldwork, or movement of individuals between organisations. It was necessary to make some pragmatic decisions to group a few small Teams within larger Organisations where there were insufficient data to derive the capture probability for individual Teams. The effects of Organisation-Team and Hydrometric Area (which could also include other effects including water quality and equipment) continued to be difficult to disentangle given the spatially constrained range of sites typically sampled by individual Organisation-Teams. Nevertheless, their combined effect was large emphasising the need for further investigation to identify the key underlying causes. Three important areas that could be examined would be the effects of electrical conductivity, equipment and fish size. These controls have been characterised under the NEPS programme and their effects would be expected to vary regionally. Unfortunately, these data were not routinely recorded in the past so modelling of historical data might not be possible.

Consistent with previous analyses there was a positive linear effect of year in the final capture probability model. This indicates that capture probability increased over time at the national scale. This has major consequences for the use of single pass and timed electrofishing for assessing population trends. Specifically, the use of uncalibrated single pass or timed data could result in biased trend assessments, potentially leading to inappropriate management decisions (Glover et al., 2019). NEPS 2021 continued to include multi-pass data in the survey that allow capture probability models to be fitted that address spatial and temporal biases to provide a reliable assessment of spatio-temporal variability that is often absent from other more ad-hoc surveys. These complex models have been made available (through an online R Shiny application) that allow NEPS collaborators to harmonise and correct data collected for other local purposes[1].

NEPS 2021: Changes to strata

Changes were made to the NEPS survey design to address challenges related to the allocation of over samples (replacement sites for those that could not be sampled), allow sampling of larger 5th order rivers in selected regions as requested by local fisheries managers, and allow locally driven sampling and reporting requirement to be incorporated into the larger NEPS programme with associated benefits for both local and national management.

[1] Electrofishing Data Analysis Tool - National Electrofishing Programme for Scotland - gov.scot (www.gov.scot)

In the NEPS 2018-19 survey design the spatial distribution of strata matched NEPS reporting regions, which in return received a standard allocation of 30 samples (Malcolm et al., 2019b). This was appropriate from a survey design perspective. However, it caused logistical problems in regions supported by more than one local delivery organisation because over samples could fall anywhere in the region and affect the relative number of sites to be sampled by the different organisations. To address this problem strata were sub-divided where multiple organisations fell within a reporting region. For reporting purposes, it remained possible to post-stratify the data and recombine strata to match reporting regions from previous years.

Additional strata were also added to assess fish populations above barriers on the Shin and in the Forth regions. These changes to the design came with additional local resource and increased the overall value of the NEPS programme both locally and nationally. Where possible this concept should be extended in future years to maximise the robustness of local fisheries monitoring while also improving efficiency given the extensive method development and overhead costs incurred in running NEPS.

NEPS 2021: Changes to the sample frame

The target population for NEPS is rivers that are accessible to salmon (below physical barriers), support salmon fisheries (are assessable under Conservation Regulations) and can be sampled by wading and electrofishing. In 2018 and 2019 the sample frame (i.e. the approximate spatial extent of the target population) included Strahler river orders 2-4. First order rivers often ran dry, were too small to sample reliably or were impossible for salmon to access. Fifth order (and larger) rivers were considered on average to be too large to reliably sample across the country. However, some local fisheries managers considered that 5th order rivers could be sampled and requested that this be considered in revisions to the NEPS survey. In response, local fisheries managers were asked to identify whether they wanted fifth order rivers to be included in the sample frame on a region-by-region basis. At the same time, some local fisheries managers took the opportunity to remove smaller rivers from the sample frame where physical access was known to be impossible. The result was substantial changes to affected regional benchmarks, increased spatial variability in benchmarks and a requirement to harmonise data between survey years to allow for appropriate comparisons of abundance between regions and years. These challenges were addressed through development of appropriate spatial data, an extended suite of analyses and careful survey design. However, the increased flexibility has come at a cost in terms of the complexity of analyses now required.

The NEPS benchmark model (Malcolm et al., 2019a) predicts that salmon densities should increase with upstream catchment area and thus river order. Given the regionally variable inclusion of fifth order rivers, it was important to explore whether patterns of spatial variability in benchmark density were at least broadly reflected in the observed juvenile density data. It was also important to establish whether inter-annual variability in densities within river orders were also broadly consistent between river orders. Salmon fry and parr densities increased with river order and inter-annual variability in densities within river order were indeed broadly comparable across river orders. This suggests that spatial variability in the benchmark was appropriate and that temporal variability in observed densities should be similar regardless of the particular sample frame used.

The observation that salmon densities increase and trout densities decrease with river order could reflect one of two potential processes. Firstly, hydraulic and sedimentary characteristics and food availability (broadly habitat quality) could vary systematically across the sampled rivers (Wyrick and Pasternack, 2014) in a way that favours salmon and constrains trout. For example, the proportion of run, riffle and glide habitat characterised by higher velocities favoured by drift feeding salmon could increase in a downstream direction, while the percentage of pools and other less favoured slow water habitats could decline. Alternatively, local delivery organisations could introduce a systematic bias into the survey by micro-siting survey locations to avoid deeper water areas in larger rivers that could not be fished by wading based electrofishing. This could have the effect of sampling areas that are on average associated with higher salmon densities in larger rivers. The available site-wise habitat data collected during electrofishing shows that the percentage of pool habitat surveyed decreased with river order, while the percentage of run and riffle increased. What is not clear is whether this reflects genuine changes in habitat availability or local survey bias. Importantly, these observations do not affect the ability of NEPS to assess the status and abundance of freshwater fish as the data supporting the benchmark model will be biased in a similar way to the NEPS survey. However, interpretation of the observed spatial variability would become important if it were used to try and scale juvenile production across whole river systems, potentially underestimating the value of smaller rivers to whole system production. The extent of any biases could be determined by asking local managers to characterise habitat at the precise location of the allocated NEPS sample and then at the location that they were able to access the river for survey (i.e. following micro-siting). However, a comprehensive assessment of the true value of rivers of different size would require development of alternative survey methods capable of sampling larger, and particularly deeper rivers.

Abundance of trout

It is not currently possible to assess the status of brown trout due the absence of a suitable density model from which to estimate benchmark densities. This remains a priority for method development in the future. In the absence of a benchmark it is still possible to assess changes in density among years. At a national scale trout fry and parr densities have declined between 2018 and 2021, although densities in 2019 and 2021 remained broadly comparable. Sea trout populations (as indicated by rod catch) have been in long-term decline and it is possible that changes in juvenile trout abundance at least partially reflect these changes, although it is not possible to readily separate individuals of resident and migratory origin.

Abundance and status of salmon

The numbers of juvenile salmon fry and parr in the NEPS 2021 survey provide a strongly contrasting picture of population health. Salmon parr densities were lower than observed in the 2018 and 2019 surveys reflecting multiple years of relatively low spawner numbers. Grade 1 regions were restricted to the north of Scotland and the national-scale density was only ca. 60% of the benchmark. In contrast, there was an increase in salmon fry densities between 2019 and 2021 to levels which exceeded the national benchmark. In some regions (e.g. Annan, Ayrshire, Nith, Clyde) this led to improvements in status. It is likely that improvements in salmon fry densities largely reflected local improvements in spawner returns. However, it is also possible that substantial reductions in older age classes of salmon (parr) reduced competition and predation (Bacon et al., 2015) allowing for compensatory improvements in the survival of fry. Although higher salmon fry densities were not observed across all regions, the overall picture was better than 2019 and was more positive than that observed for parr.

NEPS assessments in the context of statutory reporting requirements

Where possible, multiple reporting needs should be addressed through a common set of monitoring activities and methods. This maximises efficiencies, reduces costs associated with data collection and reporting, and ensures greater consistency of procedure between assessments in different statutory contexts. At face value juvenile assessment methods could meet many of the reporting requirements of the Habitats Directive, Water Framework Directive and Conservation Regulations as they relate to Atlantic salmon and other freshwater fish populations. However, the specific requirements and drivers vary between legislation so it is useful to assess where NEPS data and assessments can be used at present, or where further work and developments would be required. Specifically, there is a need to consider issues relating to the reference level (e.g. Benchmark), spatial coverage of samples (sample frame), and the frequency and density of sampling.

The benchmark for NEPS was derived from a national analysis of juvenile salmon densities (Malcolm et al., 2019a) that modelled the abundance of salmon fry and parr across Scotland from 3848 multi-pass electrofishing site visits between 1997 and 2015. The resulting density predictions were then scaled to better reflect the densities expected in a near-natural catchment, given adequate spawner returns to stock available habitat. The aim of the benchmark was thus to define a reference level that was close to saturated habitat (or Smax in stock-recruitment terms). However, direct comparisons with stock-recruitment derived references are challenging because well-defined stock-recruitment relationships only exist for very few locations in Scotland (Gurney et al., 2010), and of those, only two sites (Girnock and Baddoch Burn) also have adequate data on juvenile salmon abundance to make suitable inferences (Glover et al., 2018).

The Habitats Directive aims to maintain and restore favourable conservation status for species of interest that includes Atlantic salmon. Both the benchmark and methods deployed for NEPS would appear consistent with definitions specified under the Common Standards Monitoring Guidance for Freshwater Fauna (JNCC, 2015), with Grade 1 appearing to be consistent with Favourable Conservation Status.

The Water Framework Directive (WFD) aims to restore rivers to Good Ecological Status. This is defined as representing only slight disturbance from natural conditions. However, WFD also requires status to be reported at five different levels (High, Good, Moderate, Poor, Bad) and that the assessments consider species composition, abundance and age structure. In this context current NEPS assessments would need to be extended to include additional classification categories consistent with WFD definitions, and also additional native fish species (e.g. trout and eels). Based on WFD definitions it is likely that High and Good categories would be consistent with NEPS Grade 1 classifications. The addition of new categories to the NEPS classification scheme would not necessarily involve substantial development work in the case of salmon because classifications are typically based on ecological quality ratios between observed and expected (benchmark) abundances. However, the addition of new species is more challenging and would involve the development of new species and life-stage specific benchmarks.

Conservation Regulations assessments are based on estimates of maximum sustainable yield (MSY) derived from adult-adult stock recruitment relationships. These references are likely to be lower than the NEPS benchmark, although in reality this would be extremely challenging to assess given available stock-recruitment data. One pragmatic solution could be to compare densities at the benchmark, with those observed under MSY for the only two suitable datasets (Girnock and Baddoch) and then scale the benchmark based on the proportional difference in abundance. However, this would require substantial new analyses.

The NEPS sample frame covers wadeable rivers, below impassable barriers in catchments supporting salmon fisheries. This means that all of the catchments that need to be assessed for Conservation Regulations are included in the sample frame.

However, the sample frame does not include all of the waterbodies that need to be assessed for WFD, or all of the catchments that need to be assessed for salmon under the Habitats Directive. Specifically the NEPS sample frame does not include smaller catchments that do not support salmon fisheries, areas above physical barriers, large and deep rivers or lochs that cannot be sampled by wading and electrofishing. It would be possible to extend the sample frame to include additional rivers or to supplement the current design with complementary but consistent designs for other rivers depending on resource availability and sampling limitations. Nevertheless, this does not constrain use of the data that are already available.

The density of samples in the NEPS survey reflects the size of the regional strata, allocation of samples to strata (currently 30 samples per NEPS 2018-19 strata), availability of funding, the ability of the fisheries management sector to complete surveys over the summer and the desire to obtain adequate data to assess status and trends. Sample density is thus a pragmatic balance between what is desirable from a scientific and management perspective and what can be achieved given available financial and practical resources. WFD assessments are conducted at a waterbody scale and thus a key driver is to obtain as many site-wise assessments as possible in different waterbodies. Habitats Directive requires assessments of status and trends at the scale of each SAC, which are catchment, sub-catchment and indeed multi-catchment scales (North Harris). Conservation Regulations require assessments for each river catchment supporting a salmon fishery. In all cases the confidence of reliable assessment will improve as the number of samples within each reporting area increases (and as inter-site variability decreases). In this report we did not assess the status of any spatial extents where there were less than five samples in each year of NEPS surveys. This decision was practical based on the minimum data requirements of the spsurvey R package, but also clearly represents a lower limit on the sample numbers that would be desired. This means that there were no assessments for smaller rivers or SACs. If assessments were required for every individual SAC and catchment then an increase in sample density would be required in those areas that currently receive few samples. This would be technically feasible by varying sample numbers and / or strata numbers, but would come with resource implications.

WFD has a requirement to report on the status of waterbodies once in a five year period. Habitats Directive requires reporting every six years and Conservation Regulations assessments need to be completed annually. NEPS surveys were carried out in 2018, 2019 and 2021 with funding support variably coming from Marine Scotland (2018-2021), Crown Estate Scotland (2019, 2021), Nature Scot (2018) and SEPA (2018). Additionally, the fisheries management sector provide support in-kind since the funding available for NEPS cannot cover all incurred costs. Funding for future iterations of a nation-wide NEPS programme are not guaranteed and this has potential consequences for statutory and other reporting requirements where it is envisaged that NEPS data could contribute. It is possible that NEPS assessments could be completed on a bi-annual basis and still provide useful and near-continuous assessment data as each survey includes two cohorts (fry and parr), but less frequent sampling also limits the value of the data in terms of assessing recruitment between life stages.

Future work: Water quality as a predictor of abundance

Water quality influences capture probability and is a critical control on juvenile salmon survival and abundance through effects on fish physiology (Malcolm et al., 2014), in-stream productivity and food availability (Williams et al., 2009). Water quality is not included in the current benchmark model (Malcolm et al., 2019a), nor will it be included in the forthcoming trout benchmark model, due to the absence of historic water quality data at electrofishing sites underpinning benchmark models. However, it is a potentially important predictor that could further explain within and between catchment differences in salmonid abundance. Water quality data collected during NEPS and provisionally reported here would allow further investigation of these effects and could be incorporated into future assessments at site-wise scales. With further large-scale spatial modelling of water quality (e.g. Smart et al., 2001; Monteith et al., 2015) these data could be included in future benchmark models. This requirement was highlighted in the NEPS 2018 report and remains a priority (Malcolm et al. 2019b).

Future work: Identifying pressures acting on freshwater fish populations

In recent years there have been attempts to characterise the pressures acting on Atlantic salmon to inform management, habitat restoration and regulation of potentially detrimental activities (Forseth et al., 2017). NEPS provides a strong quantitative framework for characterising pressures at multiple spatial scales. Recently tissue samples from a sub-set of NEPS sites were used to undertake the first national scale assessment of the effects of farm to wild genetic introgression on wild salmon populations (Gilbey et al., 2021). In 2021 tissue samples were obtained from all NEPS sampling sites across the country and laboratory analysis is currently underway. This will provide an unprecedented quantitative assessment of the scale of introgression effects on wild Atlantic salmon in Scotland and allow reporting at regional scales comparable with NEPS status assessments.

For the first time this report has included a large scale characterisation of water quality across Scotland using the data collected under NEPS. While one-off spot samples do not replace the need for more frequent and long-term monitoring, such surveys are able to fulfil two of the major goals of water quality monitoring, namely identifying pollutant sources and informing locations for conservation and restoration (Dupas et al., 2019). Mapping of NEPS data revealed strong spatial patterns in water quality reflecting both natural (e.g. geology, soils, climate) and anthropogenic (e.g. nutrient pollution, sulphur deposition) influences that can directly or indirectly affect survival and productivity of salmon and other freshwater fish species (Malcolm et al., 2014; Forseth et al., 2017). There have been strong concerns in recent years over the impacts of excess nutrients on ecological systems (Jarvie et al., 2018). Anthropogenic sources of nutrients can include atmospheric deposition, agriculture, leaking septic tanks and sewage (Edwards and Withers, 2008). High nutrient concentrations can cause eutrophication (Rankinen et al., 2019), damaging algal blooms and reductions in dissolved oxygen. Some forms of nitrogen e.g. ammonia and nitrite can also be directly toxic. In the case of ammonia the relative contributions of the dominant non-toxic form (ammonium, NH_4^+) and toxic free ammonia (NH_3) is controlled by temperature and pH, with greater risks associated with high pH and temperature. There are thus clear risks associated with water quality that could be exacerbated by climate change that threatens to both increase temperature and reduce flows with consequent effects on chemical concentrations (Charlton et al., 2018).

Future Work: Development of benchmarks for brown trout and European eel

There is a desire to improve assessment of both brown trout and European eel. This has been highlighted by WGTRUTTA and WGEEL ICES working groups. The addition of new benchmarks would add value to the NEPS programme and increase the potential utility of the work in the context of WFD. The development of an assessment method for trout is also a commitment in the Scottish Government's response to the Salmon Interactions Working Group (SIWG) to support the sustainable development of aquaculture in Scotland.

Future Work: NEPS survey designs

During 2022 there have been substantial efforts to develop a new multi-year design that could be used to support future NEPS surveys. This has involved the development of new spatial datasets and consultation with local fisheries managers to further refine the spatial extent of the sample frame to identify rivers that can be sampled by wading and electrofishing. Where local resources have allowed (and where there is a local desire), new strata have been created to improve the spatial scale of NEPS assessments within larger regions. For the remainder of the 2022/23 financial year MS will focus on the delivery of a new survey design, the development of necessary R code, spatial data and methods required to support future NEPS programmes should these be prioritised for future funding.

Conclusion

NEPS provides large scale, strategically designed, quantitative data on the distribution, abundance and status of freshwater fish in Scotland. These data can be combined or post-stratified to provide assessments across a wide range of spatial scales. With careful thought, scientific development and partnership working across Government, its agencies, the wild fisheries sector and other stakeholders, NEPS could potentially contribute to meeting the varying reporting needs of current and future legislation (e.g. Habitats Directive, Water Framework Directive, Conservation Regulations) and policy imperatives (e.g. Blue Economy Vision for Scotland, Wild Salmon Strategy). When combined with information on the distribution of pressures including water quality, genetic introgression (through the associated National

Introgression Programme for Scotland: NIPS) and climate change (through links to the Scotland River Temperature Monitoring Network) NEPS provides the evidence base necessary to plan conservation, restoration and management of Atlantic salmon and other freshwater fish species including brown trout and European eel.

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