Chapter 1: Assessing salmonid freshwater production and habitat quality in the flowing waters of the Lomond catchment.

Compiled by Megan MacDonald, Hannele Honkanen and Colin Adams

June 2022

Non-technical Summary

- Populations of Atlantic salmon across the eastern Atlantic are declining. Sea trout populations are declining in some parts of Europe but not in others.
- There is strong evidence that both sea trout and salmon populations from the Loch Lomond catchment have declined since the 1960’s and 1970’s.
- A major tool enabling us to audit change in salmon and trout populations is through electrofishing for juveniles to determine change sin density
- There are juvenile electrofishing data from the Lomond catchment extending over a wide geographic area and over two decades.
- These data however are held by multiple organisations, they have been collected and recorded in different ways and are stored in a range of formats, much of this data was in very poor condition.
- In this study we collected, collated and formatted all the electrofishing data generously supplied by the Loch Lomond Fisheries Trust (LLFT); the Loch Lomond Angling Improvement Association (LLAIA); the Scottish Environment Protection Agency (SEPA); the Scottish Centre for Ecology and the Natural Environment at the University of Glasgow (SCENE).
- We collated data from 666 electrofishing surveys of the Lomond catchment from across 20 years.
- Data from additional surveys of 52 sites were added to this in 2020 as part of this project
- This dataset will be available to all key stakeholder organisations under a data sharing agreement and in multiple formats (excel, csv, GIS file formats).
- This will allow future survey work to build upon, and remain compatible, with that of the past.
- Salmon were supported in 117 km of stream length in the catchment.
- Trout were supported in over 180.6 km of stream length in the catchment.
- Trout juveniles occupy more of the catchment than do salmon.
- Although commonly found together, trout and salmon juveniles do not always occupy the same habitats; this will affect the spatial focus of management if action is focused on one species.
- There are still large parts of the catchment which have never been surveyed for the presence of salmon or trout. This is a major impediment to the management of the catchment; it is impossible to assess the importance of these sites to salmon and trout populations in the catchment and to provide evidence-based objections to catchment development or habitat change without this information.
- In this study we also compiled a database on all known natural and man-made impediments to fish passage and sites of significant point source habitat damage.

- A substantive amount of these data were provided by the LLFT but additional data were provided by SEPA and SCENE and additional contemporary data were collected from riverine surveys in 2020 (7 detailed river habitat surveys and additional barrier surveys in conjunction with electrofishing work).
- All habitat damage data were also assessed for the ease and economic viability of management action, as well as importance.
- This information was then compiled on to a site-specific habitat damage database and also converted to a spatially explicit GIS format.
- A spatial overlay of habitat impairment data and salmonid presence is presented in Figures 2 and 3.
- Across the whole catchment and all years there were 139 sites where there were estimates of juvenile salmonid density.
- Comparing these data with data from more broadly across Scotland (*sensu* Godfrey 2005):
    - Trout fry density was on average 0.14 fish/m^2. This is within the 60th percentile for densities of trout fry from sites from the Clyde area.
    - Salmon fry density was on average 0.16 fish/m^2. This is within the 40th percentile for salmon fry from sites from the Clyde area.
    - Trout parr density was on average 0.09 fish/m^2. This is within the 80th percentile for trout parr from sites from the Clyde area.
    - Salmon parr density was on average 0.05 fish.m^2. This is within the 40th percentile for salmon parr from sites from the Clyde area.
- Across all sites there was statistical evidence for declining salmon fry and parr density over the nearly 20 years for which there are data.
- There was statistical evidence for a complex pattern of declines and increases in trout fry and parr density across the catchment for the 20 years over which there are data.
- The pattern of change in salmonid density was not equal everywhere.
- In the Endrick Water salmon density decline was similar to that of the whole catchment – trout density statistically increased over the period of this study.
- In the Luss Water there was evidence of salmon fry (but not parr) increasing in density over the period of the study.
- In the Fruin Water the pattern of change closely matched that of the wider catchment.

Project Outputs:

1. Creating guidelines for accurate and consistent electrofishing data collection and storage to ensure that high quality data is collected. Meeting with LLFT LLAIA and others to discuss the quality issues to ensure the best data management for the future.

2. Creating a data sharing agreement between LLAIA, LLFT and SCENE which will significantly improve what can be achieved with the data collected.

3. Creating a standardised database comprising all known historical electrofishing data forming a repository of this highly valuable dataset.

4. A very significant output of this project is an updatable GIS file comprising all presence/absence data for salmon and trout juveniles in the catchment.

5. A very significant output of this project is both the database and updatable GIS files comprising all currently known habitat damage or natural impediments to salmonid passage and an assessment of the relative cost of management action. This is a major tool for the identification of on-the-ground management action that is available to management stakeholders.

6. This project contributed to the LLFT's 'Loch Lomond watercourse surveys' online app, which allows quick recording of salmonid habitat assessment and river barrier data. All data collected through this app contributes to the wider database. The app can be found here: https://arcg.is/49uT4

7. A graded list of the ten most important (in terms of potential benefit to salmonid production) habitat issues in the catchment is provided, including recommendations for restoration work and an assessment of feasibility. Additionally, a list of all of the other habitat issues will be produced as well.

8. A set of suggested core electrofishing sites was created; it is suggested that these sites are fished yearly using the fully quantitative three pass electrofishing method.

Key Recommendations:

1. All future electrofishing data should be curated into this dynamic evolving dataset.

2. Major gaps in the knowledge of juvenile salmonid distribution in the catchment should be filled through surveys and these data should be curated into the newly developed but evolving GIS spatial database. Based on this work, a list of these sites will be produced; this list will be finalised and shared.

3. The newly developed salmonid habitat impairment database is an evolving resource, it should be added to, as new information on habitat damage is collected and efforts to collect these data should continue.

4. The habitat impairment database should be used as a resource to create habitat restoration targets for management.

5. The habitat impairment database can, and should, be used as an evidence base for seeking grant funding to improve habitat quality for impacted habitat that requires significant resources to improve (funding sources for such exist).

6. One element of identifying habitat restoration priorities should be to identify locations where salmonid presence may be impacted by instream habitat degradation.

7. There is evidence that in some parts of the catchment, change is occurring more quickly than others – these are the sites where habitat restoration and surveillance priorities should be focussed.

8. Electrofishing data has the potential to act as an early warning of rapid change - one of the major impediments to identifying on which part of the catchment to focus management action, is the absence of a reference site for which there is a measure of salmonid density each year. We strongly recommend that at least one reference site is established for each of the major salmonid tributaries and that these are surveyed annually.

1. Introduction

Atlantic salmon (*Salmo salar*) and sea trout, the anadromous form of brown trout (*Salmo trutta*), are two iconic migratory species that have a significant cultural and economic value, both globally and in Scotland. Both are characterised by their complex anadromous life histories, with significant time spent both in freshwater and marine environments. Wild fisheries in Scotland contribute nearly £80m Gross Value Added to Scottish economy yearly, highlighting the huge importance of these two species (PACEC, 2017).

There is currently a conservation concern for both species, as the stocks have been in decline for decades (see Figure x; ICES, 2021; de Eyto *et al*., 2016; Parrish *et al.,* 1998). Using data from the ICES Working Group on North Atlantic Salmon, it can be seen that in the southern north-east Atlantic coast region (which includes UK, Ireland, France and south/west of Iceland), salmon numbers (pre-fishery abundance, PFA) have decreased significantly; 66% for the one sea winter fish (1SW) and 81% for the multi-sea winter (MSW) fish (Chaput, 2012). Focusing on Scotland, investigating salmon catch records held by Marine Scotland reveals a decline of around 72% between 1971 and 2016 (Adams et al., *2022*). The status of brown trout, both the resident and anadromous forms, are less well recorded but what is reported suggests a more complex pattern of change. For example the Rivers Dee and Fowey (in Wales and England) saw increases in returning sea trout between the 1990s and 2010s (Davidson et al. 2017), as did six north-eastern English rivers over a similar period (Evans and Harris, 2017). However, there are also examples of decline; this was seen in 14 rivers in north-western England (Evans and Harris, 2017). Estimating historical change in resident brown trout numbers is challenging as there is no nationally or internationally collected data on these catches. However, some river-specific studies suggest fairly consistent temporal stability over several decades (Lobon-Cervia 2007, Palm et al. 2003, Elliot 1987).

There are numerous drivers of decline, with marine mortality largely being blamed. Historically commercial fisheries had an impact but this is no longer a significant issue. There are also impacts in the freshwater environment, examples include pollution, habitat loss and habitat degradation. One of the main threats to salmonid populations in fresh water is habitat barriers that either completely or partly disrupt migration up- or downstream (Buddendorf et al. 2019). This is a significant issue for anadromous fish such as Atlantic salmon and sea trout that undertake long-distance migrations, but is also an issue for fish that are fully freshwater resident (for example, resident brown trout can make considerable in-river movements). A recent review found that there are at least 1.2 million rivers barriers in 36 European countries (Belletti et al. 2020).

However, monitoring these fish in the marine environment is very difficult. It is much easier to monitor the species in fresh water and to manage the impacts of factors affecting their numbers there. Additionally, it has been suggested that while mortality during the juvenile freshwater stages is density-dependent, it is density-independent in the marine environment – therefore maximising smolt output should lead to increases in returning adults. It is also in the freshwater habitats where management actions can be implemented. Efficient assessing and monitoring of fish stocks relies on accurate and complete data-sets (including juvenile surveys, smolt trap data and adult catch records), which can make assessing long term changes difficult because often good-quality data sets are rare. Careful monitoring of the freshwater life stages will also allow us to track the effectiveness of any mitigation measures. One frequently used method to gather information on freshwater populations is electrofishing.

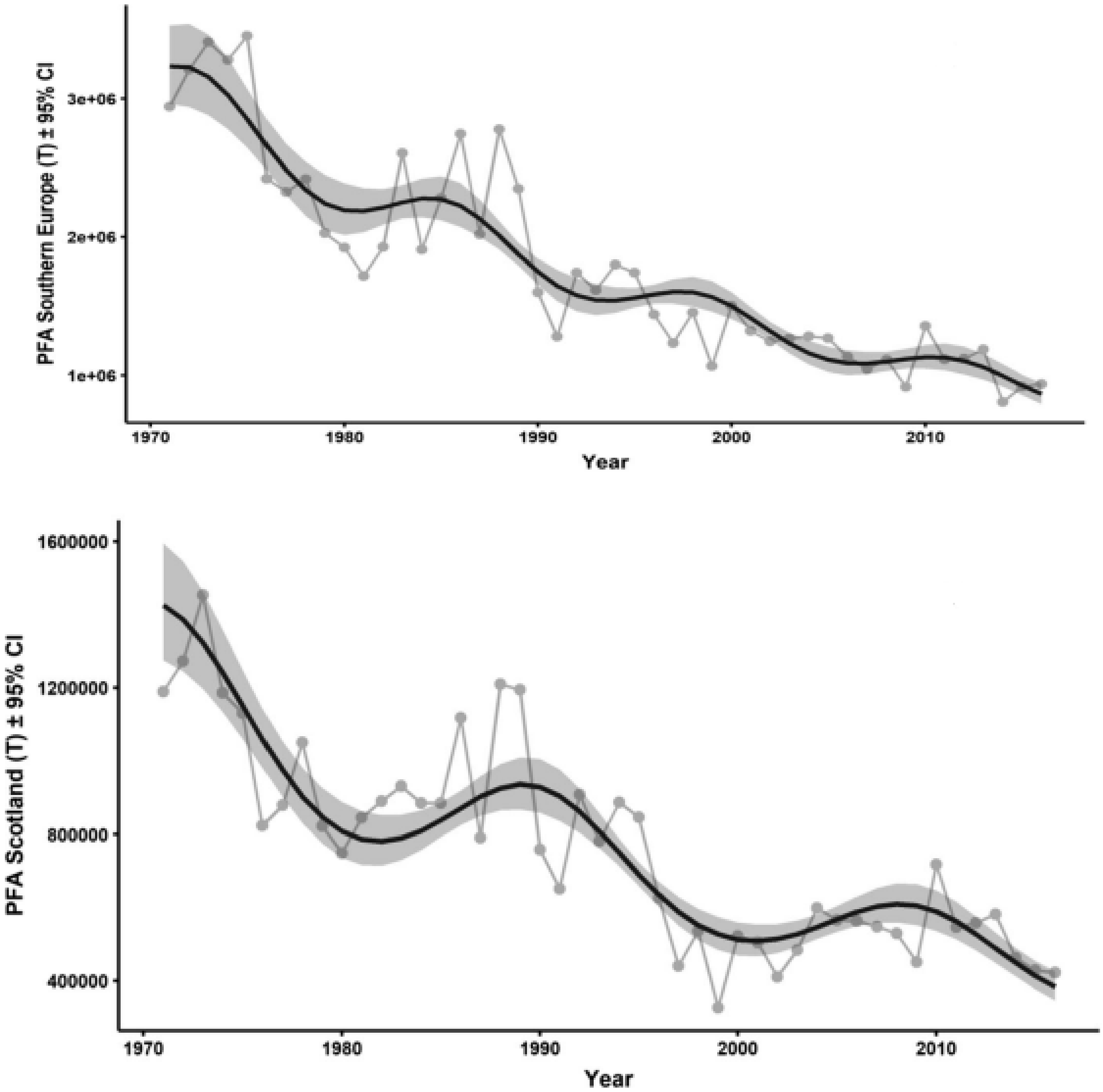


Figure x: Pre-fishery abundance (PFA) estimates (fish number), upper panel: across ICES WGNAS reporting countries for southern Europe (Scotland, Northern Ireland, England & Wales (combined), Ireland, France and south and west Iceland) between 1972 and 2016; lower panel: in Scotland between 1960 and 2016. Figure adapted from Adams et al. 2022.

Electrofishing is a commonly used method for sampling fish populations for the purpose of providing information on fish abundance and assemblage. It is an effective way to capture fish by using either an AC or DC current to briefly immobilise individuals. Although it can be used from a boat, it is generally used in wadeable rivers and streams and considered less stressful to fish and more effective than netting in shallow water. Survey data can be used to monitor species or areas of interest, assess impacts from human activity and show spatial-temporal diversity.

For electrofishing to work, it requires the water to carry an electrical charge. Electrofishing equipment, whether it be backpack, bankside or boat-mounted, generally consists of three major pieces of equipment: a power source, a transformer and electrodes. Electrofishing efficiency is affected by a number of ecological or resource-limiting factors, including skill of staff, but perhaps the most important being water conductivity. This factor determines the voltage required, with much higher voltage required in low conductivity streams. However, an increase in voltage increases the risk of injury and mortality especially in larger fish so care should always be taken to minimise the voltage.

There are three generally used forms of electrofishing surveys. Quantitative, or depletion, sampling is often referred to as a 3-pass minimum survey whereby one site is fished three or more times with each subsequent pass resulting in a reduction in the number of fish caught. This method provides a reasonably accurate estimate of a population at that site as well as being self-calibrating as it is possible to work out the probability of capture, calculated as the rate at which the catches on successive electrofishing sampling runs decline and the total number of fish caught (e.g. Zippin, 1958; Carle and Strub, 1978). After each run the fish are held in buckets, separated by run, and stop nets at the start and end of the site prevent fish surrounding the site migrating in, and fish in the site, migrating out. Fishing should be carried out in an upstream direction with a time delay between each pass. This time can be used to process the fish caught between each run.

Other types of electrofishing survey include semi-quantitative, 1-pass, surveys which can be used to give a minimum estimate of a population at a given site, and timed surveys. With both methods, measuring the study site wetted (or wet) area will give an estimate of fish density. The latter is generally used to provide information on the fish diversity of a site or an index of salmonid fry abundance. More information on quantitative electrofishing and other forms can be found in the SFCC electrofishing team leader manual (SFCC, 2014).

As with any surveying method, there are constraints to electrofishing which have to be considered if undertaking an electrofishing study. Electrofishing at times selects for certain species, sizes, behaviours and morphologies of fish (Honkanen et al. 2018, Glover et al. 2019). Bias can also be introduced to data by selecting sites that only support a certain age class of fishes or species (Marine Scotland Science 2019). Capture can be influenced by a number of factors such as increase in body size with salmonids thus overestimating the capture probability causing an underestimate of population size. Water temperature has also been attributed to influencing capture probability.

It is often difficult to compare electrofishing data over large spatial and temporal scales, as data is often collected for any number of reasons and thus does not follow a set sample design. So, while Hanks *et al*. (2018) demonstrates that you can detect a declining trend between quantitative and semi quantitative methods, *Glover et al*. (2019) argue that this only works because the data set is short having only 6 years of data and that with a long time series you must calibrate for capture probability as has been done in Malcolm *et al*. (2019b). Semi-quantitative data can be useful if collected alongside quantitative due to being able to infer capture probability.

For these reasons, Marine Scotland (MS), designed the National Electrofishing Programme for Scotland (NEPS), which is a collaborative project funded by MS, the Scottish Environment Protection Agency (SEPA) and NatureScot (previously SNH) and is achieved by working together with local fisheries trusts (Malcolm et al. 2019). Started in 2018, the aim is to collect electrofishing data and compare it to published benchmark juvenile salmon densities at site, catchment, regional and national geographic scales to determine the status of salmon and trout populations in Scotland. This scheme was designed to provide well-defined, representative sampling, which allows for unbiased estimation of salmon density at nested spatial scales using a Generalised Random Tessellation Stratified (GRTS) survey design. This design provides a spatial balance with an unsystematic component, meaning it covers the region of interest but incorporates randomness in site selection thus removing bias in fishing preferred habitat. The full methodology for this programme is explained in Malcolm *et al. (2019a)*.

To manage the stocks of Atlantic salmon and sea trout in Scotland, since 2016, Marine Scotland have created a 3-level grading system for Scottish rivers based on an adult assessment method (Malcolm et al. 2019a). Each grade is associated with management advice; ranging from ‘no management action required’ for grade 1 rivers to ‘mandatory catch and release’ for grade 3 rivers. The Lomond catchment is currently grade 2. A similar 3-level grading system can also be created for juvenile numbers, by comparing the regional density estimates to benchmark regional densities (Malcolm et al. 2019a); category 1 areas have a mean observed density exceeding the benchmark, category 2 areas have a mean observed density within the 95% confidence limits of the benchmark, and category 3 areas are below the benchmark. Based on the juvenile grading system, the Lomond catchment which is within the Clyde region, is assessed as category 3 (Figure 1c). The Endrick Water in the Lomond catchment has been designated as a Special Area of Conservation (SAC) for salmon (covering an area of 2.4 km^2), it is one of the 11 salmon SACs in Scotland (Godfrey, 2005).

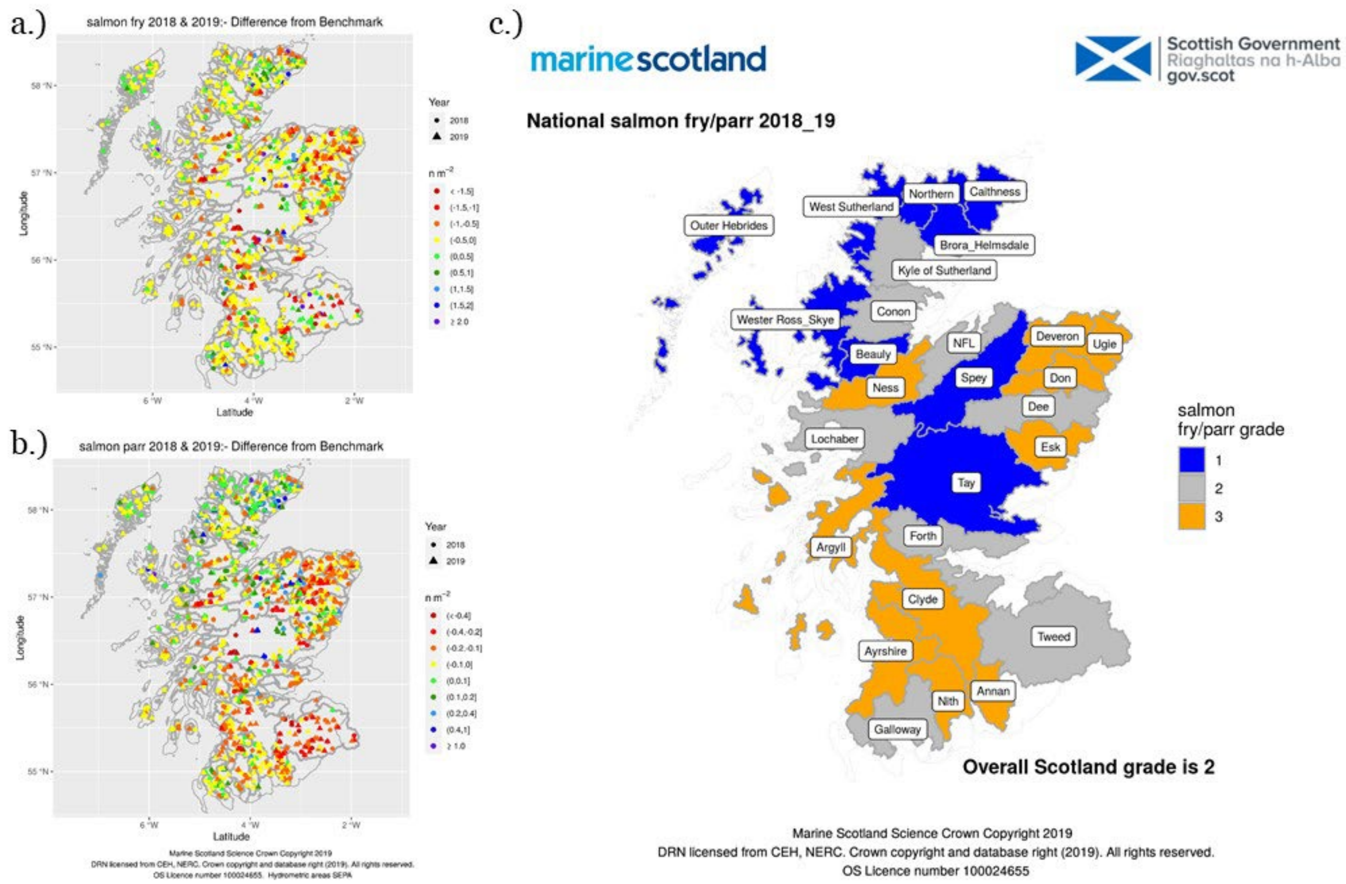


Figure 1: a.) Salmon fry density difference from the estimated benchmark value, b.) Salmon parr density difference from the estimated benchmark value, c.) MS juvenile salmon grades for Scotland. All figures from Malcolm et al. (2019a).

In this project we aim to use a relatively long-term data set (19 years) to access changes in abundance and distribution of two salmonid species, Atlantic salmon (*Salmo* salar) and brown trout (*Salmo trutta*) across the Loch Lomond catchment, Scotland. Additionally, we identified areas of the catchment that may have features impeding salmonid production.

2. Material and methods

2.1 Study site and data collection

The Loch Lomond catchment in southwestern Scotland is 272km^2 , has five main contributing waterbodies varying in length. The longest being the Endrick Water at 48km and the shortest being the Douglas Water at 8km. The loch is linked by the River Leven to the Clyde Estuary. There are also many smaller burns that feed directly into the loch.

2.1.1 Historical data collection

Historical data for this project was available from 2002 to 2019. This data was collated by the Loch Lomond Fisheries Trust (LLFT) as well as the Scottish Environment Protection Agency (SEPA) and the Scottish Fisheries and Coordination Centre (SFCC). Some of this data was collected by the LLFT for the purposes of the National Electrofishing Programme for Scotland (NEPS) which is being run by Marine Scotland. Data was collected in the form of both paper and electronic formats and included all three electrofishing types. The amount of data per year varied but is summarised in Table 1. As the data was coming from a multitude of sources, it needed to be compiled into one database, in the form of an Excel sheet.

Of the 666 electrofishing surveys only 226 had site area data, allowing calculation of densities, many of which were heavily focused on the most productive river in the catchment, the Endrick Water

2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
49	43	29	70	84	42	81	17	50	44
2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	
40	0	10	5	8	14	14	14	52	

Table 1: Number of electrofishing surveys per year.

2.1.2 Contemporary data collection

Using the collected historical data described in the previous section, we were able to identify areas within the Lomond catchment that were i.) devoid of data (had never been surveyed), ii.) extensively surveyed in the past but had not been surveyed for >10 years and iii.) sites of continuing interest, were we have consistent good quality data over several years (>4 years). It was this information that helped us to decide where to survey in 2020. A total of 52 electrofishing sites across the Lomond catchment were fished between July and October 2020; the historical data determined whether surveys were fully quantitative (3-pass) or semi-quantitative (1-pass). In the absence of data on whether species were present or absent, and to maximise the number of sites that could be surveyed, one-pass sampling was used. These electrofishing sites were completed by a team from the Scottish Centre for Ecology and the Natural Environment (SCENE - University of Glasgow) and the LLFT.

Electrofishing was conducted using a backpack electrofisher, manufactured by Efish Solutions UK, with a DC pulsed 24V battery. The water conductivity of each site determined the voltage which ranged from 200-500v. Once the site had been completely fished, all fish caught were anaesthetised with Tricaine mesylate. This is also referred to as TMS or MS-222. Species were then identified, measured to the nearest millimetre (fork length) and placed in a bucket of fresh water to recover. Each electrofishing site was measured for length and wet width at several intervals. Once sites were measured, the fish were safely released. If large numbers of fish were caught, they were released in batches at different points along the site to prevent territorialism especially amongst brown trout.

2.2 Presence and absence of Atlantic salmon and brown trout across the Lomond catchment

As mentioned in section 2.1.1, the data firstly needed to be sorted in to one central database; this was completed using Microsoft Excel. As the data was collected by a variety of sources, data such as the location information was in different formats, i.e. northings and eastings; Ordnance Survey grid references and latitude/longitude, which needed to be converted. For our work, we selected latitude and longitude. Data were excluded if there were descriptions of locations rather than coordinates and also in case where grid coordinates were inaccurate (e.g. where coordinates placed the location in a field rather than a portion of a river course). Of the 659 entries to the data base, only 524 sites were used, this is including the 52 new electrofishing sites described in section *2.1.2*. An example of the spreadsheet can be seen in the appendix. Information included, but was not limited to: electrofishing type, river, salmon fry totals, trout fry totals, density for each.

Once all the data was cleaned and organised, it was imported into QGIS 3.16 (QGIS.org, 2021). Data layers for these maps were acquired from data.gov.uk for the national park boundary and the outline of Scotland and Ordnance Survey for the water course and for the surface water layers.

The database was then uploaded as a text file to QGIS to allow each species and each juvenile life stage (fry and parr) to be separately plotted. A separate marker was placed on each individual map to show a site that was fished but no life stage or species found at that site. Then the habitat available to each life stage was highlighted.

It was important to include full barriers to migration onto the map, to better explain certain absences for a species (see section 2.4 for details).

2.2.1 Up to date species assessment

All the new data collected during the 2020 field season was mapped in the same way as the data stated above in section 2.2. Based on the density of each species life stage observed at the site, the points for each data were shaded using a colour gradient based on Marine Scotland NEPS survey colours.

2.3 Historical change in salmonid numbers across the Lomond catchment

To investigate historical change in salmonid numbers in the Lomond catchment a 3 step approach was used. These steps determined:

1. Change across the Lomond catchment as a whole.
2. Change among individual rivers (if enough data was available).
3. Change in 'core' sites (sites with 4+ years' worth of data).

This approach was chosen to investigate if the potential changes are similar across the catchment and at different spatial scales. Additionally, much of this data is heavily focused into one area of the catchment, the Endrick Water, and therefore this was a potential source of bias. This approach also accounted for the limited size of the data set. The salmon and trout data sets differ in number as they do differ in some habitat preference and there are a number of barriers to migration within the catchment which would exclude salmon but do contain populations of brown trout which are monitored. Any sites that have never had evidence of a salmon population (as determined by the full dataset) were removed. The two species were analysed separately as the focus was on species-specific patterns. Additionally, as the two species have different life history strategies it is likely that they may respond to changes in different ways.

From the work completed in section 2.2, it was clear that there were some locations that had been surveyed multiple times over the years but while very close, were not always fished on the exactly the same coordinates. Subsetting those sites that had density values, it was possible to create clusters that were comprised of sites that were very close to one another. The purpose of this clustering of the data was to create core sites formed of survey locations that could be considered to be one site; these sites were used for aim 3. Sites were clustered using the QGIS function 'select by radius'. The radius for clustering was set at 200m regardless of year. On occasion this meant that we had a couple of sites very close together fished within one year. The reason distance was set at 200m was because it has been shown that one Atlantic salmon family can dominate river reaches of about this length (Hansen et al. 1997). The clusters were then checked by eye as the package did not cluster along a river but by the actual direct distance meaning that it did not factor in bends or discriminate from the main river body channel and a burn.

To analyse the data to investigate potential change in density, we modelled the data using the following model:

$$\text{Count} \sim \text{Year} + [\text{Site}] + \text{Offset (Area)}$$

This generalised liner mixed model allowed us to test whether we are seeing an increase or a decrease in the number of salmon and trout being caught over time. With year being centred and using the raw count data with an offset for area allowing for Poisson distribution. Total counts of fry and parr for each species were combined across multiple sampling passes at single sites where necessary. Site was entered in this model as a random factor. These generalised linear mixed models were built in R studio (R Core Team 2019) using the R package 'lme4' (Bates et al. 2015). The residuals for these models where check using the diagnostic package DHARMa function 'stimulating residuals' (Hartig 2021).

2.4 Assessment of the stream habitat for salmonids in the Loch Lomond catchment

Together with the analysis of the salmonid distribution and density, in 2020 we conducted surveys to identify freshwater habitat degradation that may impact salmonid production. This sub-project had three aims: i.) create a classification system for habitat issues, ii.) data collection (habitat surveys) and iii.) create a map-based database of the issues.

For the first aim, the classification system was designed in a way that it would include the most commonly found issues in the Lomond catchment. Habitat surveys (second aim) were done by SCENE staff either as detailed surveys of river habitat and in conjunction with electrofishing surveys. For the third aim, the data came from three sources: the habitat surveys described earlier, SEPA's 'Obstacles to migration' map, and most of the habitat information came from surveys conducted by LLFT.

3. Results

3.1 Presence and Absence of Atlantic salmon and brown trout across the Lomond catchment

3.1.1 Atlantic salmon

Within the Lomond catchment, Atlantic salmon have a restricted distribution see Figure 2. Salmon are mostly confined to the southern part of the catchment that flows into the southern basin of Loch Lomond. They are seen in the three major tributaries in that basin; the Fruin Water, Luss Water and the Endrick Water (which includes the Blane Water). As the River Leven links the whole catchment to the Clyde estuary, salmon are present there, although to what extent is not fully known due to the lack of data resulting from sampling difficulties in electrofishing in a relatively large river. However there are several sections of the Leven that have very good salmonid nursery habitat and previous electrofishing surveys have found salmon and trout in the Leven and in several of the smaller side burns flowing into the Leven.

Aside from the main tributaries, salmon are only found in a few small burns draining directly into the loch, all of which are in the southern basin. The only northern populations of salmon are in a couple of tributaries of the River Falloch. The main channel of the lower River Falloch, the river at the northern end of the loch, has no known electrofishing surveys and so it is impossible to determine whether this area holds any populations of their own.

There is also a distribution difference between life stages, with salmon parr being seen in more burns leading into the loch than the earlier fry stage. This is especially true with the results of the most recent surveys. Looking at the presence/absence of salmon, historically 40.5% of sites that have been sampled had no fry and 38.8% of sites with no parr. When looking at 2020 sites only, the numbers were 57.7% and 48.1%, respectively.

Table 2: A summary table showing the total number electrofishing sites and the number of sites where the different life stages of Atlantic salmon has been found.

	Number of sites	Life stage found (%)	Life stage not found (%)
Fry	524	277 (52.9%)	247 (47.1%)
Parr	524	280 (53.4%)	244 (46.6%)

In total, in the Lomond catchment, the length of the river habitat in which Atlantic salmon fry has been detected extends to 103.6 km (Figure 2). This is calculated by the furthest upstream point that salmon have been found at along a river or a burn and thus they are deemed to have access to that amount of river habitat. The total length of water course channel below impassable falls which has been surveyed comprises 137.7km. Including their respective burns, this is approximately 48.9 km of habitat that is available for salmon on the Endrick Water and 13.1 km on the Blane Water, 19.4 km is available on the Fruin, 8.4 km is available on the Luss Water and 12.4km on the River Leven (although exactly how much of this is suitable fry habitat is unknown). Only around 593m is available on the Falloch, and this is restricted to just three small burns.

Salmon parr have been recorded over 116.9km of river habitat length, of which 2.9km is made up from the small burns flowing directly into Loch Lomond. In contrast, salmon fry has been found to only utilise 0.7 km of Lomond burns. Also, on the Falloch salmon parr were only recorded on 1.1km of the 3.6km of river channel habitat surveyed on this tributary before a set of impassable falls.

3.1.2 Brown trout

Brown trout have a much wider distribution than Atlantic salmon in the Lomond catchment, being present in all major tributaries and burns (see Figure 3). Trout fry however are recorded less in the main channels than trout parr and overall less frequent in the main channels than Atlantic salmon, especially within the River Leven. Brown trout are present above a number of natural falls within the catchment. In total trout fry were recorded over a total of 172.7km of river habitat length but this includes areas above barriers to migration for anadromous fish (Figure 3). Trout located above these barriers are most likely to be resident trout populations. Trout fry are much more frequently found in the very small burns that run directly into the loch; these burns cover a total habitat length of 6.6 km. In contrast trout parr are found in a total of 180.6km of rive habitat across the catchment. Looking at the presence/absence of trout, across all historical survey data 31.3% of sites had no trout fry and 18.8% of sites had no trout parr. When looking at 2020 sites only, the fry and parr numbers were 25% and 13.5%, respectively.

Table 3 A summary table showing the total number of electrofishing sites that have been surveyed historically and the number of sites where the different life stages of brown trout were found.

	Number of sites	Life stage found (%)	Life stage not found (%)
Fry	524	345 (65.8%)	179 (34.8)
Parr	524	396 (75%)	128 (25%)

3.2 Contemporary electrofishing data 2020

Figure 4 illustrates that in 2020 overall across the Lomond catchment, there were lower densities of both salmon life stages than for trout. This is especially true for parr in some tributaries. The density (number of individuals / m^2), estimated from sites where trout or salmon were recorded and a single pass electrofishing survey (or the first pass of a three pass survey) was conducted, overall Atlantic salmon had a mean fry density of $0.136/m^2$, and for parr it was $0.052/m^2$. For brown trout, the mean overall fry density was $0.166/m^2$ and for parr at $0.151/m^2$ (see Table 4).

The Endrick catchment (main stem and tributaries) had the highest salmon densities in the catchment. In the main stem Endrick Water, the average density of Atlantic salmon fry was $0.462/m^2$ and for parr it was $0.167/m^2$. For trout, the average fry density for main stem sites fished was $0.222/m^2$ and for trout parr it was $0.580/m^2$.

The highest densities of trout were found in the Finlas with $0.281/m^2$ for fry and $0.475/m^2$ for parr. However these numbers were based on data from only one site. High trout densities were also found in the small Lomond burns; average of $0.250/m^2$ for fry and $0.172/m^2$ for parr.

The density values from the 2020 surveys were similar to the density values from the full historical data set. From the latter, the densities for the Lomond catchment were $0.14/m^2$ for salmon fry, $0.05/m^2$ for salmon parr, $0.17/m^2$ for trout fry and $0.15/m^2$ for trout parr.

Table 4: Densities (individuals/m^2) of salmonid juveniles across the catchment in 2020. 'Lomond burns' refers to a number of small burns flowing directly into Loch Lomond. 'n/a' means that there were no individuals of that life stage found in the surveys in that specific area. Columns highlighted in green are in the 60th percentile of sites in the Clyde Coast region (sensu Godfrey 2005).

Catchment (number of sites)	Salmon fry	Salmon parr	Trout fry	Trout parr
All sites (50)	0.136	0.052	0.166	0.151
Endrick (16)	0.225	0.075	0.109	0.211
Falloch (3)	0.018	n/a	0.084	0.012
Finlas (1)	n/a	n/a	0.281	0.475
Fruin (6)	0.125	0.031	0.183	0.049
Invergulas (2)	n/a	n/a	0.024	0.081
Luss (3)	0.011	0.007	0.067	0.034
Lomond burns (19)	0.017	0.050	0.250	0.172

Figure 2: Atlantic Salmon Presence within the Loch Lomond Catchment

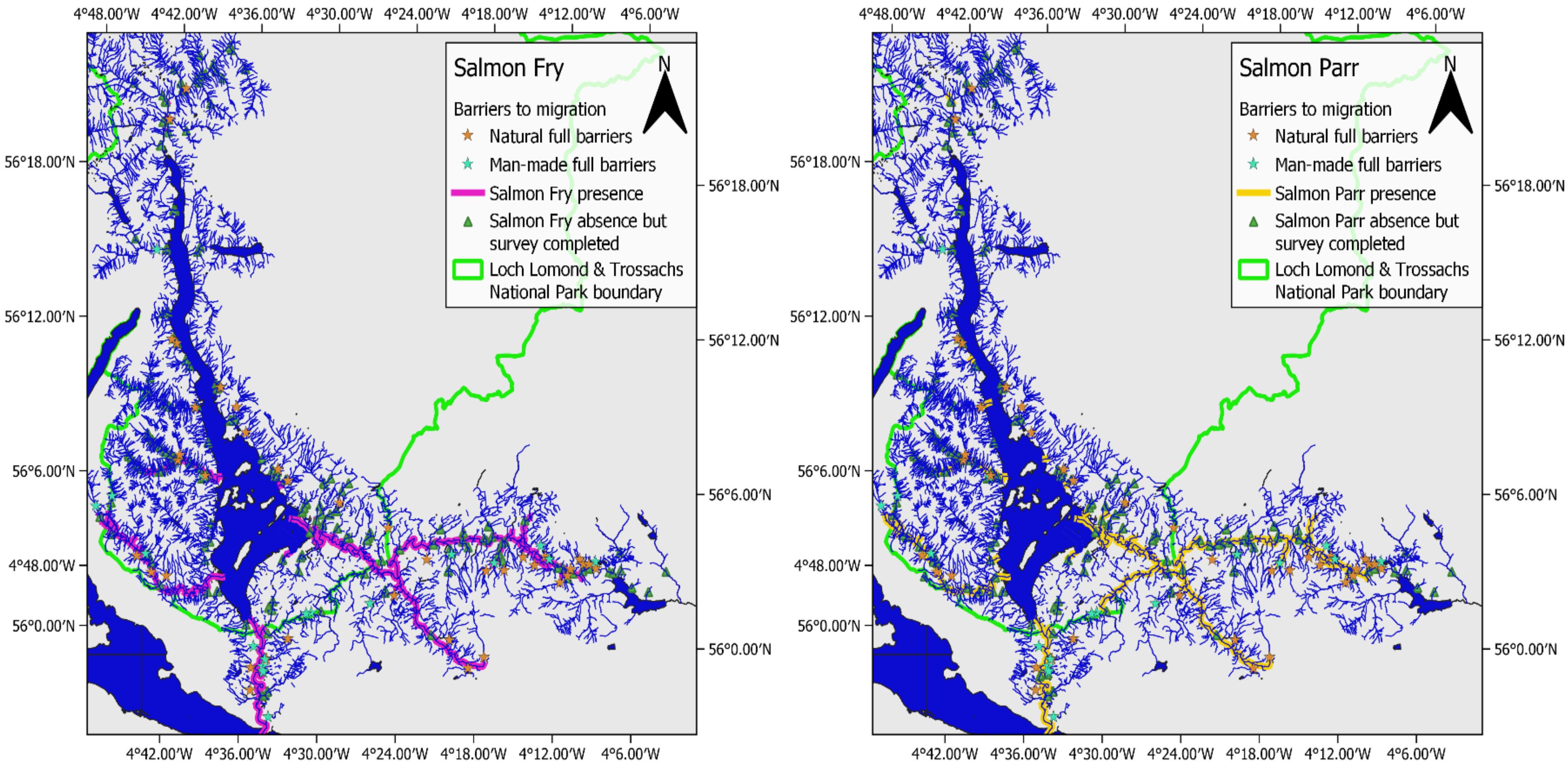
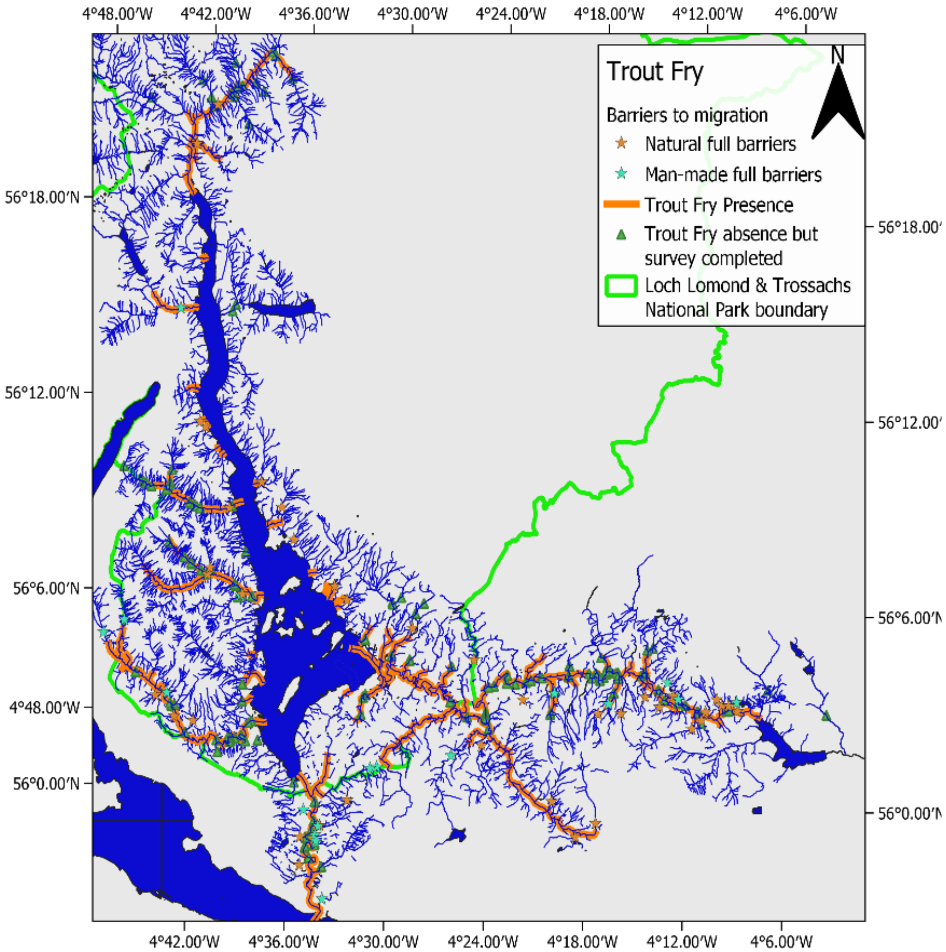


Figure 3: Brown trout Presence within the Loch Lomond Catchment



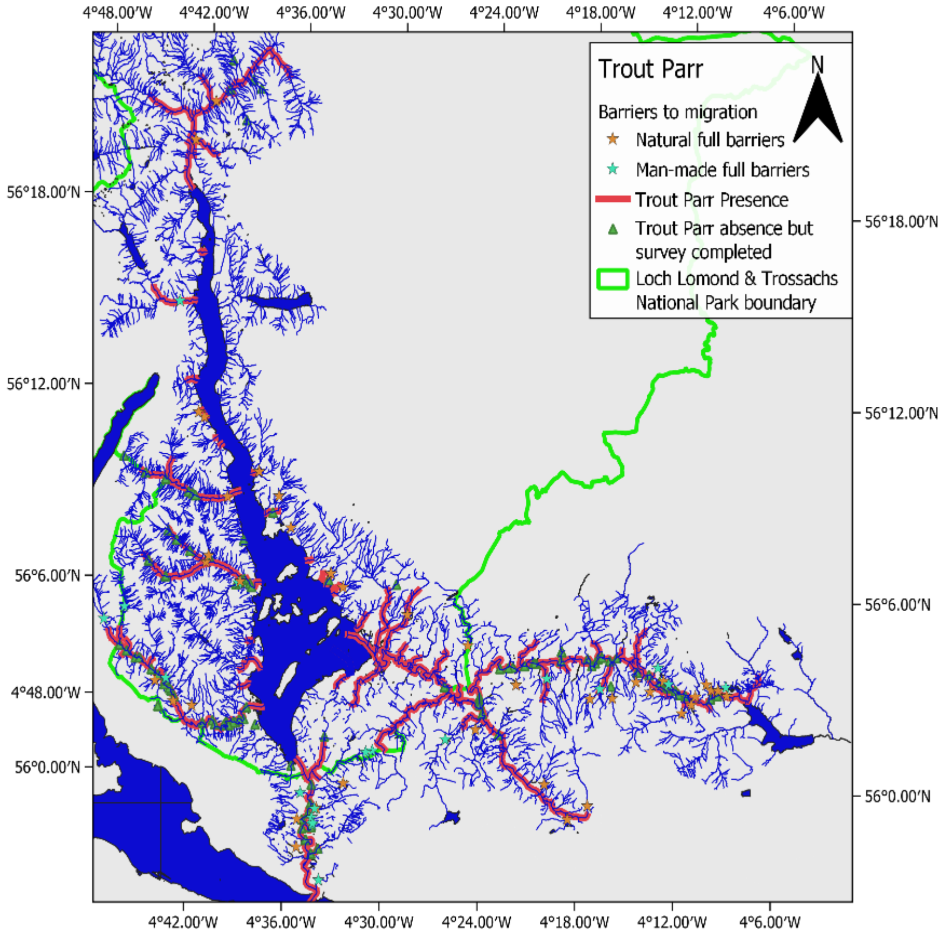
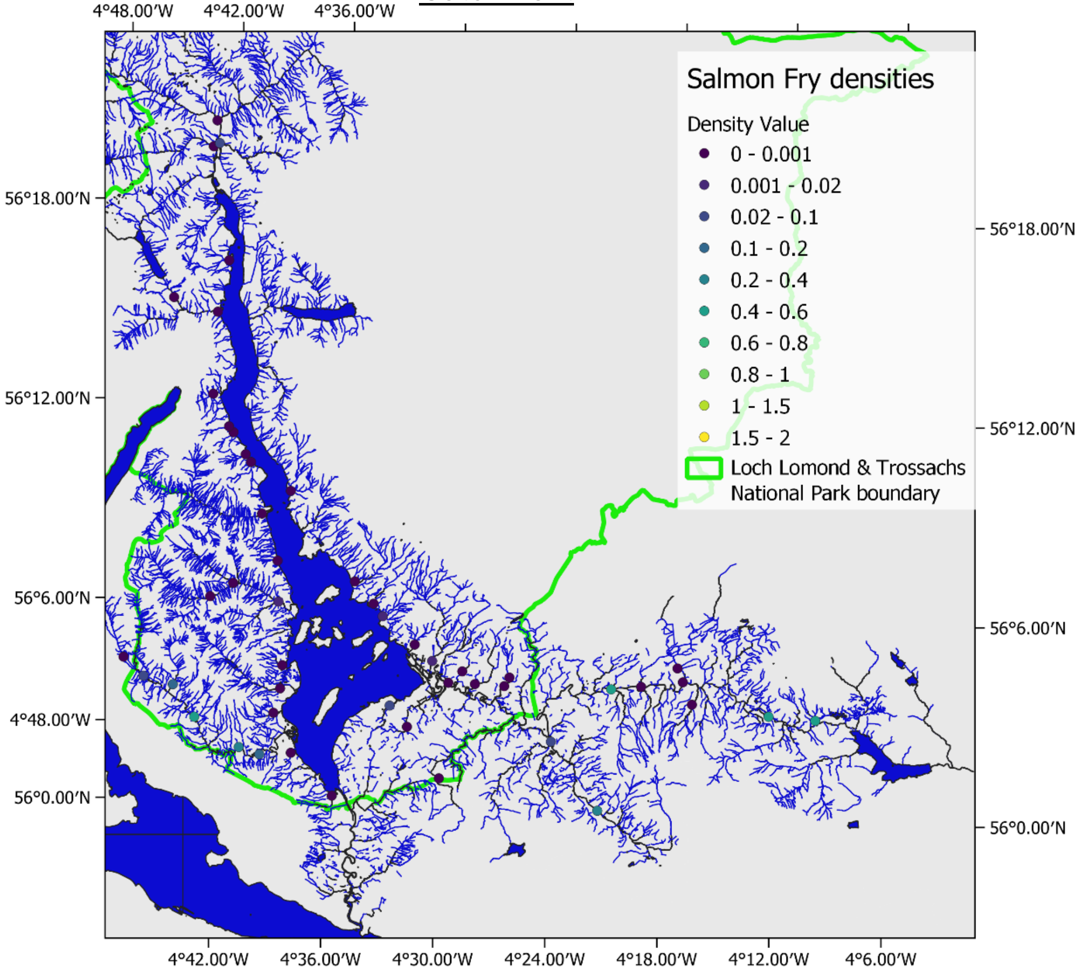


Figure 4: Atlantic Salmon density during 2020 electrofishing season within the Loch Lomond Catchment



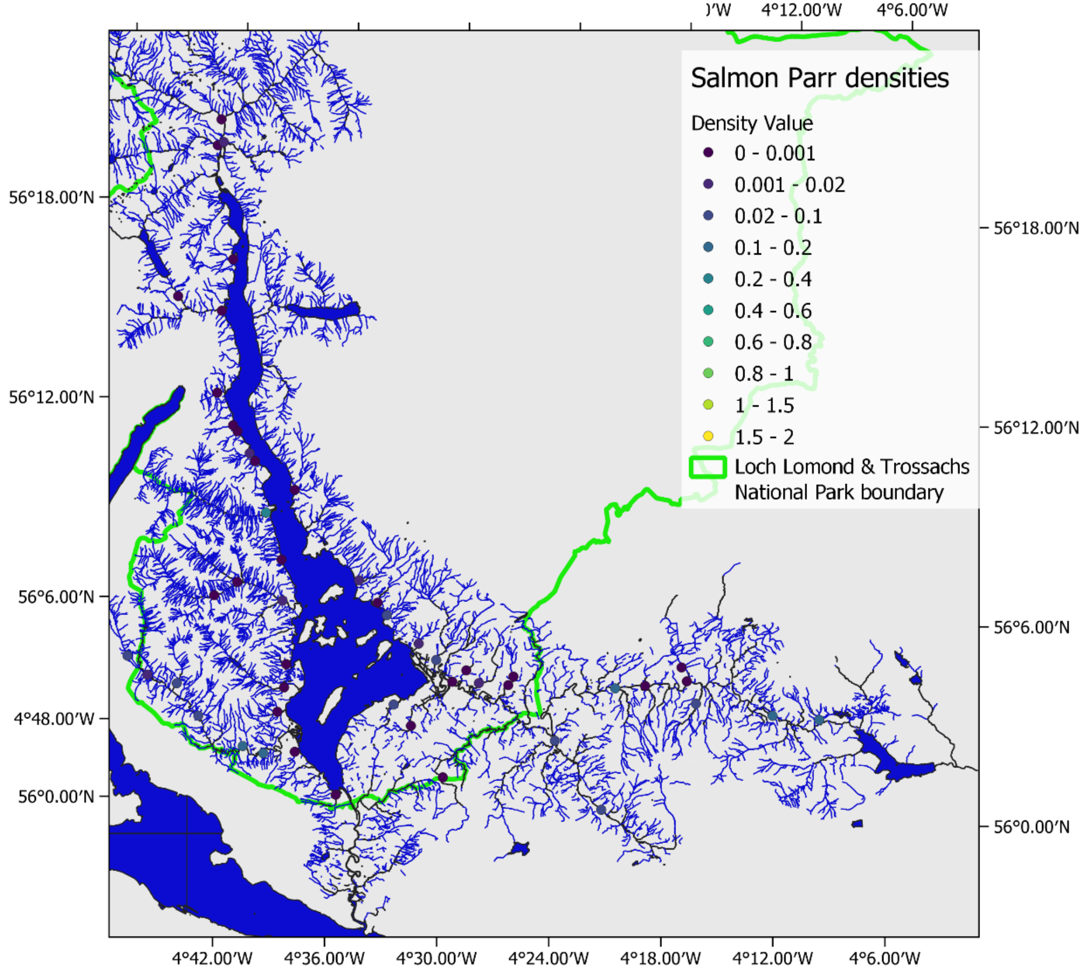
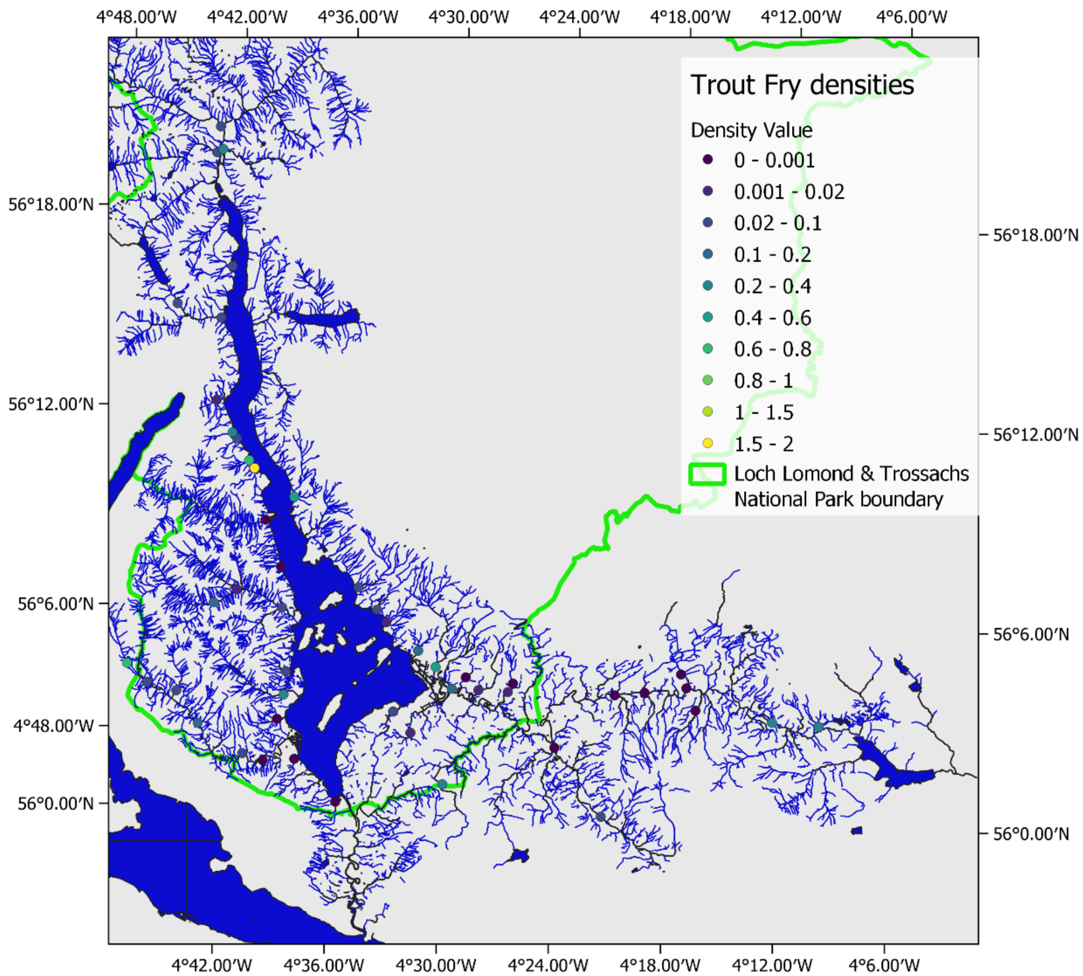
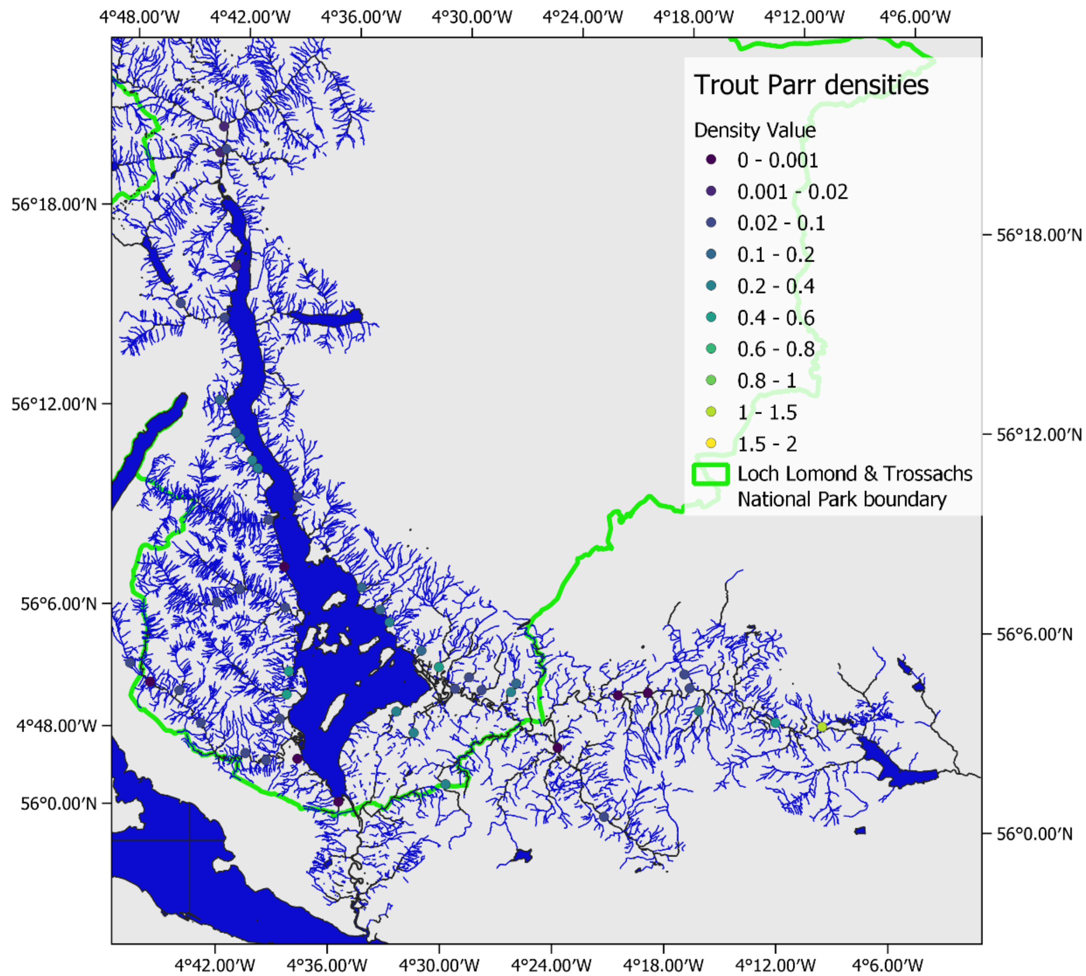


Figure 5: Brown trout density during 2020 electrofishing season within the Loch Lomond Catchment





3.3 Historical change across the Lomond catchment

3.3.1 Change across the whole Lomond catchment

For both species and life stages, statistical modelling showed that year had a significant effect on the density of fish caught by across the whole of the Lomond catchment (meaning there has been a significant change over time), but the direction of the effect was not identical for all species and site combinations. For salmon fry, salmon parr and trout fry, there was a strong, clear and statistically very robust negative effect of year; indicating that density of these groups declined over time (Table 5). This means that each year the density decreased. However trout parr density had a positive relationship with year, meaning that overall there was a slight increase in trout density over time across the historical data.

*Table 5: Summary of the output of a GLMM model testing for change in the number of fish of two species and two life stages over time (year) across the whole of the Loch Lomond catchment. * Indicates a statistically significant result.*

Species and life stage	No. of observations	Estimates	*Std.Error*	Z-value	Pr(>|z|)
Salmon Fry	139	-0.034045	0.004569	-7.452	<0.001*
Salmon Parr	139	-0.047715	0.001026	-46.52	<0.001*
Trout Fry	226	-0.010742	0.003737	-2.875	0.004*
Trout Parr	226	0.017625	0.004354	4.048	<0.001*

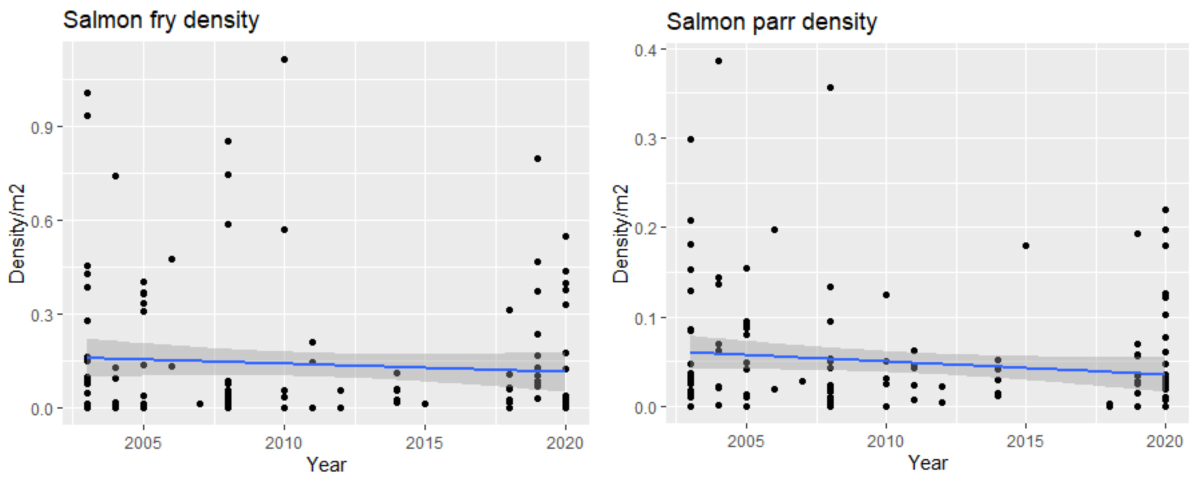


Figure 6: Salmon fry and parr densities declined significantly with time over the historical electrofishing data set. Individual data points show the very considerable between site and inter-annual variation in the density values and number of sites surveyed.

3.3.2 *Change among individual rivers*

3.3.2.1 Endrick Water

For data from surveys on the Endrick Water, there were strong statistical support for the effect of year for both species and life stage. However, the direction change of the relationship is different between the two species. For brown trout (parr and fry) there was a positive relationship between trout density with time whereas the converse is true for salmon, thus indicating that trout densities have increased with year whereas Atlantic salmon numbers have decreased.

*Table 6: Summary of the output of a GLMM model testing for change in the number of fish of two species and two life stages over time (year) at the Endrick Water. * Indicates a statistically significant result.*

Species and life stage	No. of observations	Estimates	*Std.Error*	Z-value	Pr(>|z|)
Salmon Fry	69	-0.03551	0.00568	-6.252	<0.001*
Salmon Parr	69	-0.028519	0.008847	-3.223	0.001*
Trout Fry	95	0.019118	0.005292	3.612	<0.001*
Trout Parr	95	0.056435	0.006016	9.38	<0.001*

3.3.2.2 Fruin Water

For the Fruin Water model outputs showed strong evidence of a decline over time for both Atlantic salmon fry and for trout parr (Table 7), meaning that numbers caught there of these two groups have been decreasing with year. In contrast the numbers of trout fry have been increasing. However, for salmon parr, there was no evidence of an effect of time on numbers in electrofishing surveys suggesting that there has been no change in salmon parr numbers in the Fruin over time.

*Table 7: Summary of the output of a GLMM model testing for change in the number of fish of two species and two life stages over time (year) at the Fruin Water. * Indicates a statistically significant result.*

Species and life stage	No. of observations	Estimates	*Std.Error*	Z-value	Pr(>|z|)
Salmon Fry	18	-0.030249	0.008509	-3.555	<0.001*
Salmon Parr	18	-0.003472	0.022276	-0.156	0.876
Trout Fry	21	0.10612	0.03201	3.315	<0.001*
Trout Parr	21	-0.01189	0.00254	-4.68	<0.001*

3.3.2.3 Luss Water

For the Luss Water modelling showed robust statistical significance for a decline in salmon fry numbers over time (Table 8). However there was no evidence of a decline in salmon parr or trout fry or parr numbers over time at this site.

*Table 8: Summary of the output of a GLMM model testing for change in the number of fish of two species and two life stages over time (year) at the Luss Water. * Indicates a statistically significant result.*

Species and life stage	No. of observations	Estimates	*Std.Error*	Z-value	Pr(>|z|)
Salmon Fry	15	0.11530	0.03496	3.298	0.001*
Salmon Parr	15	-0.02312	0.03064	-0.755	0.450
Trout Fry	27	0.005358	0.010416	0.514	0.607
Trout Parr	27	-0.002827	0.015470	-0.183	0.855

3.3.3 Change in core sites

Change in the abundance of fish at core sites (sites with consistent data of at least four years) was also examined statistically. For trout, there were nine such core sites located across the catchment: three are on the Endrick Water – including one Blane Water site; one on the River Falloch; two on the

Luss Water and the final three were in burns draining directly into the loch. Across these core sites, there was a significant positive effect of year on trout for both life stages (Table 9), meaning that at these sites the trout numbers were increasing over time. For Atlantic salmon, there were only seven core sites; one on the River Falloch and three on the Endrick Water, one on the Luss Water and two from burns that flow directly into Loch Lomond. Modelling showed that year did not have a significant effect on salmon numbers of either life stage (Table 9) indicating that there is no evidence of change at the core sites for salmon. In contrast model output (Table 9) showed a significant positive effect of year on both trout parr and fry. Indicating that both of these life stages increased in number at these core sites over time.

*Table 9: Summary of the output of a GLMM model testing for change in the number of fish of two species and two life stages over time (year) at the core sampling sites. * Indicates a statistically significant result.*

Species and life stage	No. of observations	Estimates	*Std.Error*	Z-value	Pr(>|z|)
Salmon Fry	34	-0.01156	0.00668	-1.731	0.083
Salmon Parr	34	-0.01466	0.01093	-1.341	0.180
Trout Fry	42	0.013706	0.004631	2.960	0.003*
Trout Parr	42	0.071338	0.007064	10.099	<0.001*

3.4 Assessment of the stream habitat for salmonids in the Loch Lomond catchment

The first aim for this part of the project was to create a classification system to quantify habitat issues that are relevant to the management of salmon in the Lomond catchment.

To achieve this, a pilot survey was undertaken to gather a range of potential salmonid habitat degradation types. These were then grouped into four impact types: impediments to migration, pollution, riparian zone impacts and channel modification or damage. Each of these were then sub-categorised to reflect varying degrees of impact and the end result allocated to 13 “categories” comprising both impact type and impact severity. These categories are shown in table 10.

Table 10: Habitat degradation categories for the Lomond catchment and the frequency of each category of impact identified in surveys of the catchment to date.

Category #	Category description	Number of issues found
1	Full barrier to upstream salmonid migration (natural)	36
2	Full barrier to upstream salmonid migration (anthropogenic)	19
3	Partial barrier to upstream salmonid migration (natural)	11
4	Partial barrier to upstream salmonid migration (anthropogenic)- weirs and road culverts for example	29

5	Sewage discharge point (septic tank)	0
6	Sewage discharge point (sewage works)	6
7	Stream bed sedimentation	0
8	Riparian zone denuded of vegetation	24
9	Bank collapse (significant enough to affect stream habitat quality)	7
10	Bank erosion (significant enough to affect stream habitat quality)	3
11	Instream structure (significant enough to affect stream habitat quality)	0
12	Stream channel modification	6
13	Partial barrier to migration – temporary obstruction for example fallen cattle grids	1

A total of 159 habitat impact issues were identified from historical surveys derived from SEPA, LLFT and SCENE data. These were then allocated to each of the 13 impact categories. In the habitat surveys conducted prior to June 2021, 159 issues were identified. Only three categories – Sewage discharge point (septic tank), stream bed sedimentation, and instream structure – were not found in the historical habitat surveys. Three categories stood out as the most numeric:

#1 Full barrier to upstream salmonid migration (natural) was detected at 36 sites,

#4 Partial barrier to upstream salmonid migration (anthropogenic) was detected at 29 sites and

#8 Riparian zone denuded of vegetation at 24 sites in the Loch Lomond catchment.

Of the total of 159 habitat issues found in the catchment; 65 were located in the Endrick sub-catchment and its tributaries; 25 on the Blane; 24 on the Leven and tributaries; 25 of the Fruin; 2 on the Falloch; 7 on the Luss and the other 11 from other tributaries and smaller burns flowing into Lomond. The high number of issues on the Endrick is likely in part because of the length of the Endrick (it is longer than any other tributary of the catchment) but also partly because it has had more survey attention due to its importance for juvenile salmon in the catchment.

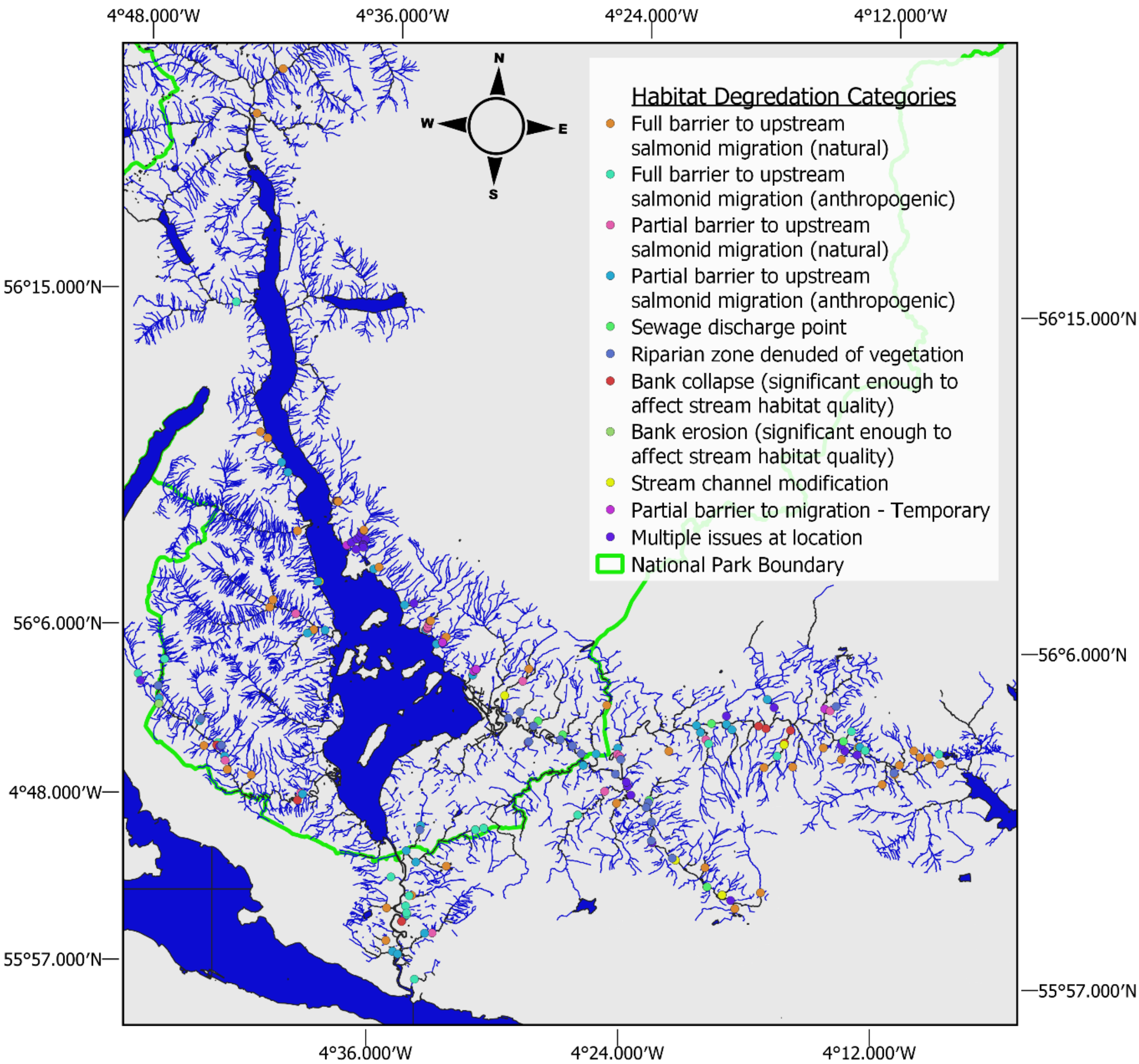


Figure 7: Map of all currently surveyed river migration barriers in the catchment.

4. Discussion

4.1 Presence and absence of Atlantic salmon and brown trout across the Lomond catchment

One of the main aims of this project was to establish the current and historic distribution of Atlantic salmon and brown trout in the Lomond catchment, in order to build a comprehensive picture of the available and used spawning and juvenile habitat. While the presence of salmonids in certain parts of the catchment is very well known, there are substantive parts of the catchment where there has been no collection of information on use by salmonids. Thus there is no knowledge of the full extent of the habitat use in the catchment. This makes it difficult to evaluate emerging threats, comment on planning proposals or identify the scope of the management need for the sites where we have no knowledge.

From what data we do have the distribution of Atlantic salmon within the catchment there is evidence of a pattern. Salmon are much more common in the southern part of the catchment. Juvenile salmon are found throughout most of the Endrick Water, River Blane, River Leven and River Fruin. Northwards of the Luss Water, salmon are found only sporadically but they have also been recorded in the northernmost river, the River Falloch. There could be multiple reasons for this pattern. One reason could simply be that the southern rivers that are closer to River Leven are easier to access for returning adults, due to the shorter distance. Additionally, the rivers in the northern part of the catchment are much shorter and have a smaller drainage area than the rivers to the south; it is therefore natural that the available habitat and thus the size of the population is limited in size. Some of the smaller streams may be populated by only a handful of spawners and therefore it is possible that in some years no fish may spawn there. This could explain the pattern seen in some of the small Lomond burns where parr were found but no fry suggesting that there are missing year classes of salmon at these sites. In addition to this, the habitat available for spawning and for juveniles downstream of a barrier to migration for salmon in many streams is quite limited in area and in the more northern rivers the main channel substrate more commonly comprises bedrock which is unsuitable for spawning and provides poor nursery area. This means that the limited available habitat is further reduced by being not suitable for spawning and nursery areas for salmonid juveniles. The percentage of sites with no salmon fry or parr recoded was higher in 2020 when compared to the historical data, however since the location of sites varied across the years and 2020 included several sites that had never been fished before (and thus might not have been suitable salmon habitat), these numbers alone cannot be used to infer a decline in salmon numbers.

Brown trout (which includes freshwater resident trout and sea migrating sea trout) juveniles are found much more widely throughout the catchment, from the River Leven all the way to the River Falloch. This is most likely due to the more complex life history strategy and different habitat requirements of brown trout. Given that juvenile brown trout can either choose a migratory or a resident life history trajectory, it is possible for populations to exist above a number of natural barriers in the catchment. Additionally, brown trout have a broader spectrum of habitat preferences and are frequently found in microhabitats where salmon are not, such as sections of river with lower flow and smaller substrate.

This means that the amount of available habitat for brown trout is much greater than for salmon. This extends to spawning habitat; while salmon tend to spawn in larger tributaries and river mainstems, trout prefer smaller streams (Louhi, Mäki-Petäys and Erkinaro, 2008). The percentage of sites with no trout fry or parr recorded was lower in 2020 than in the full historical data set, as mentioned above with regards to salmon, these numbers are not easily directly comparable and this does not necessarily imply a change in site occupancy by trout.

In the Lomond catchment, all sites with Atlantic salmon, regardless of life stage, also supported brown trout. This is a common pattern throughout the European distribution of the species (Heggenes and Saltveit, 1990). It is known that the two species compete for habitat to some extent, with brown trout being more dominant in pools and Atlantic salmon more dominant in faster flowing riffle sections (Heggenes et al. 1999), The results of this study (section 3.3) show that trout numbers have increased over the last two decades in the catchment in general. It is clear that in many of the southern Lomond rivers (Endrick Water, Luss Water, River Leven) salmon out-compete trout in the mainstem river sites where they dominate numerically, this is also something that is reported throughout the scientific literature . Salmon tend to spawn in larger tributaries and the mainstem of rivers, this is potentially due to the fact that the water velocity is faster in these water bodies and thus the substrate is larger requiring larger fish to move them to create redds at spawning time (Armstrong *et al.,*2003). Generally speaking, salmon are much larger than trout, especially multi-sea winter fish. In general and in contrast trout prefer smaller streams with smaller substrate size which is more easily moved whilst creating a redd and this general pattern is clear in pattern of the two species found in the Lomond catchment.

Very little is known about the role of lake/loch habitat as a nursery habitat for juvenile salmonids. Lochs are undoubtedly commonly used by juvenile trout and possibly to a lesser extent by salmon. For the smaller stream in the catchment, especially those short streams that discharge directly into the loch the very low densities of trout strongly point to at the end of their first summer into the loch to overwinter many of which will also feed the following summer there. Although this is also known for salmon, the full extent of this behaviour in salmon is very poorly understood. With a catchment dominated by a large standing water body, our current lack of understanding of the importance the loch itself as a nursery area for juvenile salmon and trout in the Loch Lomond catchment is a major gap in our collective knowledge needed for adequate management.

The historical data on presence of salmonids and the relative dominance of the two species may have been influenced by stocking of Atlantic salmon eggs and fry in the past. The exact locations and details of stocking are not known, but at least the Fruin Water and Endrick Water were stocked in the early 2000s. A comparison of the historical data with contemporary data for the Luss Water, seems to show a reduction in habitat use, even although there appears to be no habitat impediment to the fish migration into the upper reaches. In surveys prior to 2014 salmon were present in a 8.4km reach of the Luss Water, however post-2014 salmon were present in only 6.2km. We are not able to precisely identify why the distribution range for salmon in the Luss has declined however there are a number of possibilities. A weir with a fish pass was installed sometime between 2012 to 2014 and depending on water levels at the time adults reach the barrier, this may impact an adult's ability to migrate over this barrier. Similarly, although passable the additional effort required to migrate over a barrier may exhaust adult migrants forcing them to spawn in the lower reaches. This is a concerning change in habitat use in an important spawning and nursery area for salmon and we recommend further investigation.

The dominance of the two species at sites can change quite quickly. The Auchengaich burn, a tributary of the Fruin, was fished for the first time in 2014 and salmon were dominant at that time but in 2015 that had changed. In 2014, 82 salmon fry were caught but out of this year calls only 4 parr were caught the following year in 2015. Although it should be noted that high density-dependent mortality is a normal phenomenon during the first year of the salmon lifecycle. In 2017 it was quite clear that trout had maintained their dominant status.

Although there are around 20 years of electrofishing data available, an important finding of the work presented in this report is the extent to which many areas of the catchment have never been surveyed for trout are salmon juveniles and therefore we know nothing about the extent of their use of these sites or their densities as a result we cannot know the importance of these areas. This is especially true for north-eastern burns and streams of the loch and the main stem of the lower River Falloch (section 3.1). Through this project, we started the process of surveying some of these areas in 2020 and this work will be continued by the LLFT.

4.2 Contemporary trout and salmon population assessment

Through a coordinated effort with the LLFT in 2020, 52 sites were surveyed by electrofishing to provide up-to-date information on salmonid populations from additional sites in the Lomond catchment. Together with the historical data, these data provide more evidence to guide management approaches. The survey methodology was designed to extend the spatial coverage of the catchment, including sites that had never been surveyed before.

The aim of this aspect of the project was to build a picture of the current salmonid stocks in the catchment and to compare these with expected salmonid densities for this area. The upper limit for salmonid production in any river is the carrying capacity of that river (the maximum number of individuals that can be supported with the space and resources available), however very few population catchment combinations operate at that limit. Density of juvenile salmonids in freshwater varies markedly and consistently across Scotland. Thus comparing density values between catchments is inappropriate and provides no useful insights. Therefore comparing data from the Lomond catchment with expectations for that catchment derived from a combination of historical data and that from a catchment with similar characteristics in Scotland does provide a mechanism to allow for a meaningful assessment of salmonid density. To do this a valuable approach is to compare densities at one or more sites against a frequency distribution of densities that might be expected based on other sites and times. This allows for a judgement on densities to be put into a broader context whilst taking into account the specific features of the catchment.

As described earlier, Marine Scotland have formulated mean juvenile salmonid density values and frequency distributions around that mean for all salmonid rivers in Scotland. These values are used as a component part of the National Electrofishing Programme for Scotland (NEPS). From the two years that NEPS surveys have been conducted in the Lomond catchment (2018 and 2019) it is possible to get the average expected values for the Fruin and the Endrick. The mean expected density of salmon fry in the Fruin is 0.62 per m^2 and for parr it is 0.14 per m^2 but for reasons unknown the averages that are observed in the Fruin are 0.4 m^2 and 0.08 m^2 lower. A similar situation is found on the Endrick Water with the expected density of fry being 1.44 m^2 and parr 0.25 m^2 but the observed values for 2020 are nearly 1 per m^2 less and for salmon parr was 0.09 m^2. The observed values for the years the sites were fished were also lower than expected. Another piece of work that provides reference values for our study is the data set compiled and analysed by Godfrey (2005) for the Scottish Fisheries Co-ordination Centre (SFCC). This is an older dataset (ending on 2002) including electrofishing data collected by SFCC members. Godfrey (2005) assessed juvenile salmonid densities for different fisheries regions across Scotland and created quintile ranges.

This trend is not unique to the Lomond catchment, NEPS survey sites across Scotland in 2018 and 2019 showed the majority of sites returned densities well below the expected average (see national data in Fig 1.a and b). Reasons for this pattern are unknown but it does suggest that the lower than expected numbers of salmon in Lomond are the result of factors affecting the whole of Scotland. While the low numbers found in 2020 could be due to recent environmental conditions (across western Scotland October to December of 2019 was markedly much drier than average for rainfall which could have affected access to spawning sites). A more likely reason is that it is the outcome of a long term decrease, as can be seen in section 3.3. Furthermore, there is strong evidence that both salmon and sea trout adult catches in the Lomond catchment have declined since the 1960s and 1970s (Adams et al., 2022). Due to Covid-19, Marine Scotland did not fund NEPS in 2020 so thus it is not possible to make direct comparisons to nearby fisheries regions to see if the patterns found in the Lomond catchment in 2020 are part of a larger trend.

4.3 Historical change across the Lomond catchment

The data and analysis presented here clearly show that juvenile trout numbers have increased over the last two decades across the Lomond catchment. There is some evidence that catches of adult trout in the recreational fishery in the LLAIA catch record data of anadromous (sea) trout does show a similar pattern (see supplementary data fig 2)(Adams *et al* 2022).

In contrast over the same time period, there is some evidence that juvenile salmon numbers in streams around the catchment may have declined. Data from the core survey sites where the same site has been surveyed in successive years did not show a decline in salmon, however there was a significant decline detected when a bigger sample including all sites were modelled. Thus there is relatively strong evidence that juvenile salmon numbers have been, and are likely still, in decline. Catches of adult salmon do not show the same pattern, where numbers in the last two decades, although historically low, do not seem to be declining in the same way that juveniles are.

In what is arguably the Lomond catchment’s most important tributary, the Endrick Water, juvenile salmon numbers are showing clear and robust evidence of decline. The Endrick Water is a Special Area of Conservation (SAC), and one of the features of interest is the Atlantic salmon population there. Modelling data for two of the other most important rivers in the catchment, the Fruin Water and Luss Water, fry density was also decreasing whereas parr density had not declined.

It could be argued that the data examined for salmon fry densities is probably more robust than it is for parr (because many of the sites selected for survey were chosen because they are good fry habitat). However the randomised survey design, as used in the NEPS surveys, will give a far better understanding of the overall distribution and abundance of parr in future.

4.4Habitat degradation

The aim of this sub-project was to set up a system to enable cataloguing of habitat degradation issues in the Lomond catchment that may ultimately impact salmonid production. This included compiling a list of barriers, either full or partial, that would interfere with migration of adult salmon and sea trout, in-stream channel and bankside degradation and pollution issues. To do this data kindly provided by SEPA and the LLFT were compiled.

159 habitat issues were identified, with full natural barriers, partial anthropogenic barriers and lack of riparian zone vegetations being the three most numerous issues. Natural barriers are just that, natural, and the arguments to modify them are difficult to make. However, anthropogenic issues are the result of human activity and thus there is an imperative to modify, mitigate or remove the impediment to good ecological function. Removing complete and partial barriers has very considerable capacity to enable access to previously inaccessible spawning and juvenile habitat and for salmonids and thus should therefore be prioritised.

Riparian cover was found to be an issue in some places. Lack of tree cover can have multiple effects on juvenile salmonids; lack of trees and other overhanging vegetation could lead to reduced feeding opportunities by foraging supplementation from terrestrial invertebrates (an important source of food especially for trout). Most importantly however, lack of vegetation in the riparian zone will lead to temperature fluctuations. Salmonids are a cold water species and therefore require cool water during all life stages, however in rivers (especially smaller ones) there is a risk of water temperature rising too high during summers. Trees and other vegetation can help shade the water and therefore have a significant effect in providing suitable habitat for juvenile salmonids. In 2018 (the warmest summer on record for Scotland), ca. 70% of Scottish rivers experienced temperatures high enough (23 ºC) to cause thermal stress in juvenile salmon (Jackson et al. 2020). With climate change, it is reasonable to expect this to become more common over the next few decades. It is estimated that Scotland has 108,000 km of rivers but only ca. 35% of that has substantial tree cover (Jackson et al. 2021). Therefore, the potential benefits of tree planting are clear. However, as noted by Jackson et al. (2021): “prioritisation could consider the river reaches where temperatures are already high, susceptible to change or associated with valuable or vulnerable aquatic resources” and “prioritisation must also consider where riparian shading can be most effective in reducing river temperature”. Others have made more specific recommendations; Garner et al. (2019) suggested that tree planting should take place on the southerly banks of slow flowing rivers reaches with an E-W orientation.

A spatial examination of the identified habitat, the Endrick Water has the highest frequency of issues.. As discussed before, this may be due to sampling bias. However, with the Endrick having the highest densities of juvenile salmonids (as shown in previous sections), there is a strong case for addressing environmental degradation there first for maximum effect on salmonids. There are still several areas of the catchment that have not been surveyed, especially on the west side of the loch, and this should be one of the priority action points. Motivated by this project, in June 2021 SCENE organised a group of 13 University of Glasgow undergraduate students to help the LLFT with habitat surveys in the areas that have not been surveyed before. During these surveys, the students used app that was created by the LLFT to record the findings.

4.5 Concluding remarks

When assessing the findings presented here, it is important to consider potential weaknesses in the study that may affect the results. It is very clear that interannual variation in salmonid density estimates is large, especially for fry (see eg Fig 6). This is a pattern that can also be seen in many other juvenile salmon datasets. This variation is in part created by sampling error but by far the greatest effect is the natural year on year variation in population size. This means that to detect a change, long term data is required. The 19 year dataset that is available for the Lomond catchment is thus very valuable and it should be maintained and expanded to ensure the best chance of detecting future change in salmonids.

This study was negatively affected by the poor quality of much of the historical electrofishing data. Data collection had not been standardised and methods changed over the years and it had also been stored in different formats, however most importantly some very important information (especially on the area sampled and the location of that sample was simply not recorded). As a result two thirds of the collected data could not be used for any analysis. In addition to this there is collective memory of electrofishing surveys having been conducted for which there remains no record of any kind. As a result there has been enormous sampling effort aimed at providing information on salmonids in the Lomond catchment which has been in effect completely wasted. It is imperative that measures are put in place to prevent this occurring in future.

A more detailed and technical comment on data is that having only a few three pass sampling sites each year (the highest quality of survey design for electrofishing) meant that capture probability could not be calculated; previous work by Malcolm *et al.* (2019) and Millar *et al*. (2016) has shown that this is important in order to have a better accuracy of the density estimates.

Effective management of the salmonid stocks in the catchment requires co-operation by all the relevant organisations – mainly the LLAIA and LLFT but also SEPA, NatureScot and the Lomond and the Trossachs National Park. One of the main advantages of working partnership between LLAIA and LLFT would be joint data collection and sharing. Throughout this project, several databases have been created and these should be continuously built upon by both partners.

One of the main recommendations of this work is creating a suite of core sites that should be surveyed every year (Table 11). Such a scheme would provide the strongest study design for measuring change in salmonid numbers. We have suggested sites that are spread around the catchment for high spatial coverage. It is recommended that these sites should be surveyed with the fully quantitative three pass method to get highly accurate abundance estimates. This will allow for the quick identification of site-specific declines. Another benefit of collecting consistent data on core sites, is the ability to estimate fry to parr survival.

Table 11: Suggested core sites for annual electrofishing surveys.

River	Location description	Coordinates
Endrick	Bogside Farm	56.052267 -4.2067792
Endrick	Walton Burn	56.050665, -4.1648223
Enrick	Balfron Bridge	56.06336 -4.348154
Blane	Downstream Duntreath Castle	56.00380 -4.360082
Fruin	Black Bridge	56.042001 -4.720425
Fruin	Lumsden	56.027682 -4.679547
Luss	Upstream Eden Taggeart farm	56.10262 -4.710138
Falloch	Bein glas campsite	56.32978 -4.717680
Leven	Bonhill bridge	55.985888, -4.573440

<u>References</u>

Adams, C.E., Honkanen, H., Bryson, E. & MacCormick, M. (In review) Change in the population size and life history features of two salmonid species in the Loch Lomond catchment west central Scotland: a 115-year time series.

Douglas Bates, Martin Maechler, Ben Bolker, Steve Walker (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1-48.

Belletti, B., Garcia de Leaniz, C., Jones, J. et al. More than one million barriers fragment Europe's rivers. *Nature* 588, 436–441 (2020). https://doi.org/10.1038/s41586-020-3005-2

Buddendorf, W.B., Jackson, F.L., Malcolm, I.A., Millidine, K.J., Geris, J., Wilkinson, M.E. and Soulsby, C., 2019. Integration of juvenile habitat quality and river connectivity models to understand and prioritise the management of barriers for Atlantic salmon populations across spatial scales. Science of the Total Environment, 655, pp.557-566.

Gérald Chaput, Overview of the status of Atlantic salmon (*Salmo salar*) in the North Atlantic and trends in marine mortality, *ICES Journal of Marine Science*, Volume 69, Issue 9, November 2012, Pages 1538–1548.

Coulson, M.W., Laughton, R., Shaw, B., Armstrong, A. & Verspoor, E. (2013). The use of genetic parentage analysis to assess hatchery contribution of Atlantic salmon on the River Spey.

Davidson, I., R. Cove, R. Hillman, P. Elsmere, N. Cook, & A. Croft, 2017. Observtions on sea trout performance in the Rivers Dee, Tamar, Lune & Tyne (1991-2014) In Harris, G. (ed), Sea Trout, Science and Management. Matador, Beauchamp: 470–426.

de Eyto, E., Dalton, C., Dillane, M., Jennings, E., McGinnity, P., O'Dwyer, B., Poole, R., Rogan, G. and Taylor, D., 2016. The response of North Atlantic diadromous fish to multiple stressors, including land use change: a multidecadal study. *Canadian Journal of Fisheries and Aquatic Sciences*, *73*(12), pp.1759-1769.

Dodds, W. and Whiles, M.R., 2017. *Freshwater ecology: concepts and environmental applications*. 3rd ed. Elsevier Science, pp. 699-722.

Elliot, J., 1987. Population regulation in contrasting populations of trout Salmo trutta in two Lake District streams. *Journal of Animal Ecology* 56: 83–98.

Evans, R., & G. Harris, 2017. The collection of sea trout and salmon statistics from the recreational rod fishery in England and Wales In Harris, G. (ed), Sea Trout, Science and Management. Matador, Beauchamp: 487–506.

Glover, R.S., Fryer, R.J., Soulsby, C. and Malcolm, I.A., 2019. These are not the trends you are looking for: poorly calibrated single-pass electrofishing data can bias estimates of trends in fish abundance. *Journal of fish biology*, **95(5)**, pp.1223-1235.

Hanks, R. D., Kanno, Y., & Rash, J. M. (2018). Can single-pass electrofishing replace three-pass depletion for population trend detection? *Transactions of the American Fisheries Society*, **147**, 729–739

Florian Hartig (2021). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.3.

Hansen, M.M., Nielsen, E.E. and Mensberg, K.L., 1997. The problem of sampling families rather than populations: relatedness among individuals in samples of juvenile brown trout *Salmo trutta* L. *Molecular Ecology*, 6(5), pp.469-474.

Hedger, R.D., Diserud, O.H., Sandlund, O.T., Saksgård, L., Ugedal, O. and Bremset, G., 2018. Bias in estimates of electrofishing capture probability of juvenile Atlantic salmon. *Fisheries Research*, **208**, pp.286-295.

Heggenes, J. & Salveit, S. J. (1990). Seasonal and spatial microhabitat selection and segregation in young Atlantic salmon (*Salmo salar* L.) and brown trout (*S. trutta* L.) in a Norwegian river. *Journal of Fish Biology* 36, 707–720.

Heggenes, J., Baglinière, J. L. & Cunjak, R. A. (1999). Spatial niche variability for young Atlantic salmon (*Salmo salar*) and brown trout (*S. trutta*) in heterogeneous streams. *Ecology of Freshwater Fish* 8, 1–21.

Honkanen, H. M., Dodd, J. A., Fordyce, J. R., Boylan, P., & Adams, C. E. (2018). Density-and species-dependent errors in single-pass timed electrofishing assessment of riverine salmonids. Ecology of Freshwater Fish, 27(1), 98-102.ICES. 2021. Working Group on North Atlantic Salmon (WGNAS). ICES Scientific Reports. 3:29. 407 pp.

Jackson F, Fryer R, Hannah D, Malcolm I. 2020. Predictions of national-scale river temperatures: A visualisation of complex space–time dynamics. Hydrological Processes 34 (12): 2823–2825

Jolley, T., 2000. The hydrology and water management of Loch Lomond, Scotland. *Scottish Geographical Journal*, **116(3)**, pp.197-212.

King, R.A., Miller, A.L. & Stevens, J.R. (2021) Has stocking contributed to an increase in the rod catch of anadromous trout (Salmo trutta L.) in the Shetland Islands, UK? *Journal of Fish Biology*.

Lobón-Cerviá, J., 2007. Numerical changes in stream-resident brown trout (*Salmo trutta*): Uncovering the roles of density-dependent and density-independent factors across space and time. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1429–1447.

Louhi, P., Mäki-Petäys, A. and Erkinaro, J., 2008. Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. *River research and applications*, *24*(3), pp.330-339.

Malcolm, I. A., Millidine, K. J., Jackson, F. L., Glover, R. S., & Fryer, R. J. (2020). The National Electrofishing Programme for Scotland (NEPS) 2019. *Scottish Marine and Freshwater Science*.

Malcolm, I. A., Millidine, K. J., Jackson, F. L., Glover, R. S. & Fryer, R. J. (2019a). *Assessing the Status of Atlantic Salmon (Salmo Salar) from Juvenile Electrofishing Data Collected under the National Electrofishing Programme for Scotland (NEPS)*. Vol. 10.

Malcolm, I. A., Millidine, K. J., Glover, R. S., Jackson, F. L., Millar, C. P. & Fryer, R. J. (2019b). Development of a Large-Scale Juvenile Density Model to Inform the Assessment and Management of Atlantic Salmon (Salmo Salar) Populations in Scotland. *Ecological Indicators*, **96**, 303–316.

Millar, C.P., Fryer, R.J., Millidine, K.J. and Malcolm, I.A., 2016. Modelling capture probability of Atlantic salmon (Salmo salar) from a diverse national electrofishing dataset: Implications for the estimation of abundance. *Fisheries Research*, **177**, pp.1-12.

Palm, S., L. Laikre, P. E. Jorde, & N. Ryman, 2003. Effective populatoin size and temporal genetic change in stream resident brown trout (*Salmo trutta*). *Conservation Genetics* 4: 249–264.

Pottier, G., Beaumont, W.R., Marchand, F., Le Bail, P.Y., Azam, D., Rives, J., Vigouroux, R. and Roussel, J.M., 2020. Electrofishing in streams of low water conductivity but high biodiversity value: Challenges, limits and perspectives. *Fisheries Management and Ecology*, **27(1)**, pp.52-63.

QGIS.org, 2021. QGIS Geographic Information System. QGIS Association. http://www.qgis.org

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reid, S.M. and Haxton, T.J., 2017. Backpack electrofishing effort and imperfect detection: Influence on riverine fish inventories and monitoring. *Journal of Applied Ichthyology*, **33(6)**, pp.1083-1091.

Thompson, W.L., White, G.C. and Gowan, C., 1998. *Monitoring vertebrate populations*. Elsevier.

Thorstad, E.B., Bliss, D., Breau, C., Damon-Randall, K., Sundt-Hansen, L.E., Hatfield, E.M., Horsburgh, G., Hansen, H., Maoiléidigh, N.Ó., Sheehan, T. and Sutton, S.G., 2021. Atlantic salmon in a rapidly changing environment—Facing the challenges of reduced marine survival and climate change. *Aquatic Conservation: Marine and Freshwater Ecosystems.*