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RESEARCH ARTICLE

The spatial ecology of brown trout (*Salmo trutta*) and dace (*Leuciscus leuciscus*) in an artificially impounded riverine habitat: results from an acoustic telemetry study

J. Barry[1] · P. McLoone[1] · C. J. Fitzgerald[1] · J. J. King[1]

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Abstract

Determining where fish are distributed across days and seasons is valuable for understanding their ecology, evolution and conservation. The results presented here provide insight into the spatial and temporal distribution of brown trout (native salmonid species) and dace (invasive cyprinid species) in an artificially impounded section of lowland river, demonstrating that both species remain relatively local to their release point and do not exhibit wide-ranging movements from late summer into winter. Commonalities in the movement patterns were observed between the species despite their contrasting life histories, but there were also important differences observed both in their home range and activity patterns over the duration of the study. In general dace were much more active than trout. Both trout and dace exhibited clear crepuscular peaks in movement with higher displacement rates being observed during dawn and dusk periods which remained consistent over the duration of the study. Both species exhibited a high residency which may be a direct result of the artificial barrier present, promoting residency. Trout showed a significant increase in displacement rates and a drop in residency in November which may represent putative spawning behaviour. In general home range sizes remained stable over the tracking period for both species. Home range size was affected by fish length for both species, with larger individuals being more localised then smaller individuals. We propose that the diel patterns observed are primarily driven by foraging activity and opportunity which changes with seasonal influences and onset of potential spawning period and/or overwintering behaviour. This study demonstrates how data derived from telemetry studies can reveal movement behaviours of fish species associated with undertaking basic ecological requirements (feeding, shelter etc.) which are regulated by variation in the environment. Understanding the interplay between the environment and an animal's behaviour is important from a conservation management perspective with increasing environmental pressures and predicted regime changes. From a fishery management viewpoint these data can feed into stock status monitoring in difficult to monitor impounded lowland riverine habitat and also increase our understanding of how potential human induced changes affect fish populations.

Keywords Telemetry · Trout · Dace · Spatial ecology · River fragmentation

Introduction

As the pressures on freshwater resources increase, there is a growing concern for the long-term viability of fish populations (Strayer and Dudgeon 2010; Arthington et al. 2016). Understanding the spatial behaviour of fish, and how they respond to environmental variation is critical to ensure effective management, especially in the time of growing pressures such as climate change (Pletterbauer et al. 2015), invasive species (Toussaint et al. 2016) and altered habitat (e.g. river fragmentation) (Fahrig 2003; Arlinghaus et al. 2016; Jones et al. 2019) all of which can influence native fish behaviour and long term viability in their natural habitats.

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✉ J. Barry
james.barry@fisheriesireland.ie

[1] Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin D24 Y265, Ireland

Riverine habitats in Europe have a long history of exposure to human activity and as a result have become altered (Nilsson et al. 2005), leading to fragmentation, and no longer have a continuous flow from source to sea (Birnie-Gauvin et al. 2018; Barry et al. 2018; Jones et al. 2019). The presence of these weirs, dams and obstructions has negatively affected resident and migratory fish species which inhabit the river. The negative effects of barriers on fish migration are well documented (Doehring et al. 2011; Hall et al. 2011; Gargan et al. 2011). For example they are known to alter the successful completion of lifecycles, thus reducing population viability (Drouineau et al. 2018). There is a paucity of knowledge of fish behaviour in impounded sections (Mann 1988; Quinn and Kwak 2003). The impounded habitat becomes slow-flowing and relatively deep, depending on the barrier height with unknown consequences for resident fish species and how they use such habitat. It is important from a management perspective to gain insight into home range size, movement patterns, population sizes and stock status of fish species present in such impounded sections of river. Given the Europe-wide momentum for barrier removal and/or remediation works (Branco et al. 2017; De Leaniz 2008; Dodd et al. 2017) the impounded sections of river and ecology of resident fish species merit a more thorough investigation.

River discontinuity due to barriers affects resident fish populations by limiting migratory movements both upstream and downstream, and Branco et al. (2017) suggested that fish populations may adjust their life-history strategy to augment residency which may be relevant and important to understand across river systems. Telemetry can be used to quantify area covered by animals and activity patterns which can be associated with basic ecological requirements for resources and refuge and can be regulated by predictable changes in the environment such as river discharge and temperature (Cooke et al. 2012; Barry et al. 2016; Crossin et al. 2017). This monitoring technique has helped to understand the movement behaviour and site fidelity of fish species in lacustrine habitat (Bass et al. 2014; Barry et al. 2016; Hawley et al. 2016; Watson et al. 2019; Bašić et al. 2019) and riverine habitats (Winter et al. 2016). Understanding fundamental movement ecology of fish will aid managers to develop effective conservation and sampling strategies (Crossin et al. 2017).

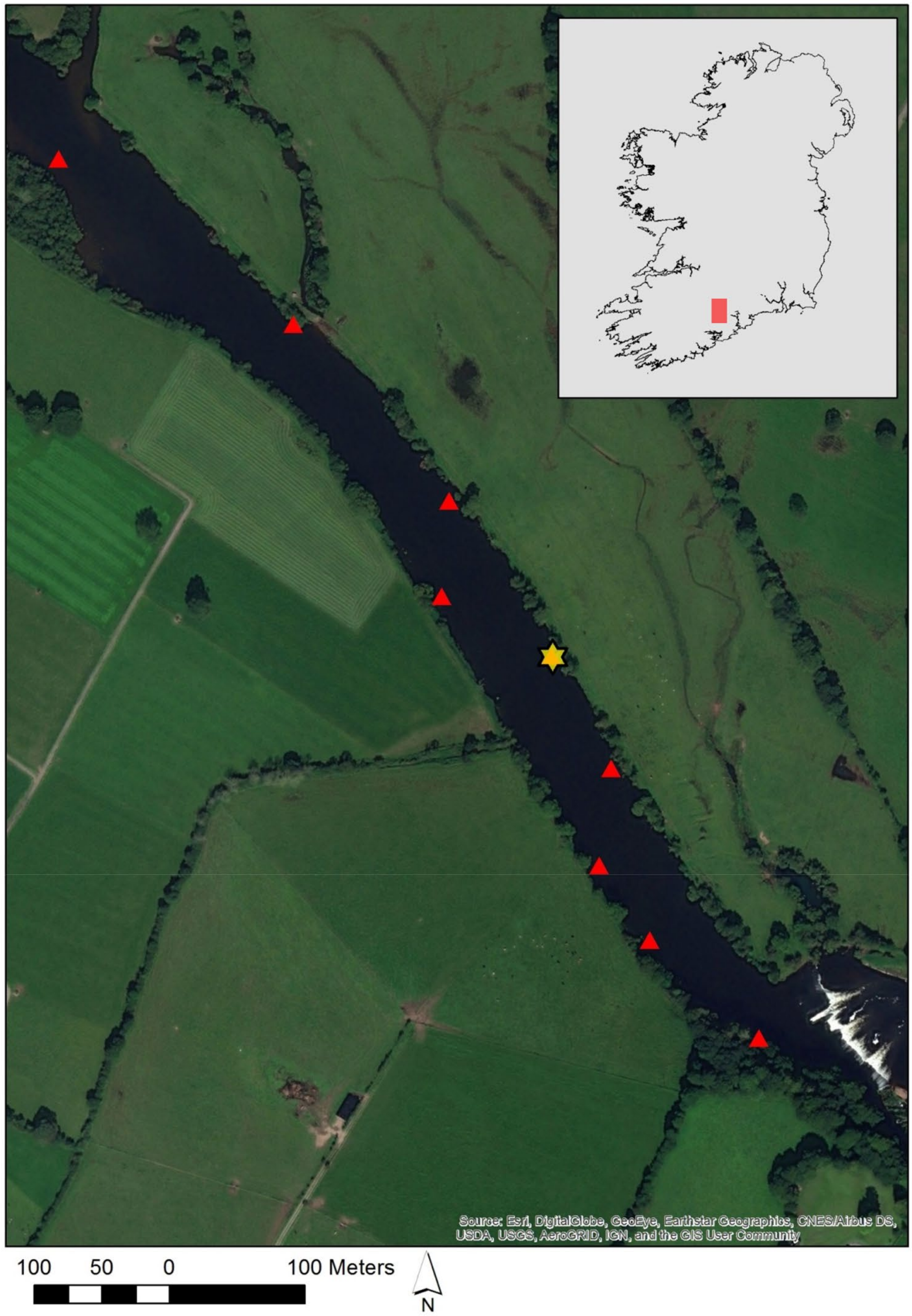
Fish stock assessments in the lower reaches of the Munster Blackwater exhibited that the two most prevalent fish species in study site were the native brown trout (*Salmo trutta* L.) and invasive Dace (*Leuciscus leuciscus* L). Dace were first introduced to Ireland and the Munster Blackwater from Britain in 1889, where it became established but was largely confined (Went 1950). Since the 1990s the species has extended its range significantly. Considered invasive, dace are now present in several catchments, where potential competition with native salmonids for habitat and food has been suggested (Caffrey et al. 2007). Invasive alien species are defined as having being introduced to habitats outside of their native range(s) and where their introduction damages environments, economies or is detrimental to human health (CBD 2009). They are considered a major anthropogenic threat to global biodiversity, prompting efforts to enhance the effectiveness of invasive species management (Caffrey et al. 2014; Piria et al. 2017). Brown trout are ubiquitous in Ireland, found in all catchments where water quality is suitable (Went 1978) and supporting financially and culturally important recreational angling fisheries. Interactions between brown trout and dace are not fully understood (Caffrey et al. 2007; Tierney et al. 2020), thus there is a pressing need to understand spatial ecology of the species and potential interactions with native trout. We hypothesise that dace would exhibit more far ranging movement than that of the native trout given their quick colonisation characteristics seen in other catchments where the species have been introduced. The specific objectives of this study were to; (1) investigate displacement rates and diel activity patterns of trout and dace in relation to biological (e.g. length) and environmental conditions (e.g. time of day, water temperature, water flow); (2) assess home range sizes, core areas (50%) and outer range (95%) sizes to compare dace and trout temporal space use and (3) investigate the residency and site fidelity of tagged individuals over a 4 month period in 2017.

Materials and methods

Study site

The Munster Blackwater is one of Ireland's largest rivers – 170 km in length with a catchment area of 3100 km^2. In its middle and lower reaches, the river has extended lengths of relatively deep water with a low gradient. There is a major man-made weir located approximately 5 km downstream of Fermoy at Clondulane (Fig. 1; Species composition Supplementary Fig. 1). The structure impounds water upstream of its location for lengths of up to 4 km with river width of 40–60 m. The substrate of the site was dominated by gravel/cobble with rare and occasional in-stream vegetation. The land uses adjacent to fished zones are wooded and pasture. The mean depths in the impounded sections of water are 2.2 m $\pm$ 0.55 m (SD). Dissolved oxygen concentration and saturation were 10.4 mgl^{-1} and 107.6%, respectively, with conductivity levels of 570 µS (YSI multi metre) (recorded on day fish were tagged). The acoustic array was installed in the impounded section of river directly upstream of Clondulane weir: (lat 52.150 long $-$8.220). The array covered an impounded area of river approximately 0.01 km^2 (6.30 ha) and 1 km distance. Topographic surveys undertaken show

Fig. 1 Map showing the study site on the Munster Blackwater in Ireland. Red triangles denote Acoustic listening stations, yellow star denote release site



that this 1 km is representative of the entire impounded section (river width and depth for 5 km upstream). Other fish species present in this section of river include Salmon (*Salmo salar*), Roach (*Rutilus rutilus*), Pike (Esox *lucius*), Gudgeon (*Gobio gobio*) and Minnow (*Phoxinus phoxinus*).

Receiver array and fish tagging procedure

A fixed array of seven omnidirectional acoustic receivers (Model: VEMCO VR2W 69 kHz,) was deployed throughout the section of river (Fig. 1). Range tests were undertaken to determine the detection range (Average 328 m ± 15 m) of receivers and transmitter type in the impounded section of river. Receivers were attached (0.25 m above the river bed) to a moored anchor system, in 2–3 m of water. The acoustic array ensured ranges overlap and allowed tagged fish that remained in the study area to be continuously detected.

Trout and dace were captured through boom boat electrofishing in August 2017. Overall 12 individuals were tagged (Trout $n=6$, Dace $n=6$) with V7 acoustic transmitter (Model: VEMCO V7-2L, Length = 20 mm, Diameter = 7 mm, 1.6 g weight in air, 136 dB power output). Each transmitter was programmed to have an average acoustic transmission repeat cycle of 60 s. The mean total length and mass of tagged Trout was 260 ± 30.8 mm and 227 ± 94.3 g (range 183–202 mm, 125–227.4 g). The tag/body weight ratio was 0.87 ± 0.3%. The mean total length and mass of tagged Dace was 194 ± 67 mm and 100 ± 13 g (range 183–202 mm, 80.5–117 g). The mean tag/body weight ratio was 1.6 ± 0.2% (i.e., < 2% Lucas and Baras 2000). The tagging procedure involved fish being anesthetised by immersion in a water MS222 solution (1 mg per litre) until loss of equilibrium. Fish were placed in an u-shaped tagging support and the transmitter was surgically implanted through a small incision (< 10 mm) into the peritoneal cavity, and the incision was closed with independent sterile sutures (3–0 Vicryl W9090—absorbable). Fish were aspirated with 100% river water throughout the procedure. The entire surgical process took less than 3 min. After complete recovery, defined as upright orientation and response to stimuli, fish were released. The tagging was undertaken in accordance with the ethical standards of the Health Products Regulatory Authority of Ireland (HPRA) under the project number AE19118/P010 (https://www.hpra.ie/docs/default-source/vet---non-techincal-project-summaries-folder/q4-2017-october---december/v020_2017q4.pdf?sfvrsn=2).

Data analysis

Detection data

The Animal Tracking Toolbox (ATT) approach was used to standardise telemetry detection data from the study (Udyawer et al. 2018). The ATT is a collection of functions created in the R environment with the "Vtrack" package (Campbell et al. 2012) and calculates standard metrics of dispersal and space use from tagged fish to allow comparisons between animals tracked using passive acoustic telemetry. These data processed in the R statistical computing package (Campbell et al. 2012; Udyawer et al. 2018, R Development Core Team 2019). The ATT package provides a COA() function which estimates short-term Centers of Activity for a user-defined time period (technique described in Simpfendorfer et al. 2002). The optimal time bin was calculated following Villegas-Rios et al. (2013). The resulting value was 60 min.

Modelling

Tagged fish displacement rates, home range size and residency index were analysed using mixed effects models with fish ID code as a random intercept, following Zuur et al. (2009), to allow for correlation between repeated observations for each fish. Probability values (p values) were obtained for effects (fixed and interactions) using the log-likelihood method which compared the models with and without the variable in question to obtain a minimal adequate model. Diagnostic outputs from the final models were assessed graphically by examining the residuals and are shown in the supplementary material. All analyses were conducted using R and modelling packages (R Development Core Team 2019).

Displacement rates

The aim of the fish movement model was to determine what factors were influencing trout and dace movement within the array. Minimum displacement rates were estimated from straight line distances between consecutive centers of activity positions divided by the duration of the observation interval in units of hours. Fish displacement rates were modelled with a Linear Mixed Effects Model (LMM) with the fish ID code as random intercept, following Zuur et al. (2009), to allow for correlation between repeated measures for each tagged fish. Non-zero displacement rate observations were log-transformed and fitted with a LME including a first-order autoregressive ("AR1") error structure to account for temporal dependency between successive observations. This approach was preferred to fitting the data using a Gamma-distributed GLMM because the specification of autocorrelation structures is straightforward in LME models and because such autocorrelation is likely to be important in longitudinal data. It was necessary to the remove the zero displacement observations (approximately 20% of all observations) when representing data using either log-normal or Gamma distributions. Explanatory variables were interrogated for collinearity using pairwise scatterplots and VIF scores (variance inflation factor). Non-zero displacement rates per hour (meters/hour) (continuous response variable) were regressed with respect to fixed effects including; species, individual's physical characteristics (length), month, light category (dawn, day, dusk, night), water temperature, volume discharge (Ballyduff gauging station https://waterlevel.ie) and lunar phase.

Home range analysis

Individual home ranges (HR) were calculated in the ATT toolbox and were determined with an approach using the Brownian Bridge movement model (Bullard 1991; Horne et al. 2007). To identify the factors influencing home range size within the array over the study period we used a linear mixed effects modelling approach. Home ranges (50% values and 95% values) were modelled as lognormal random variables and regressed with respect to three covariates (species, body length and month) and fish ID code as the random effect. Significant fixed effects were identified using model selection based on the log-likelihood method.

Residency Index

Fish residency within the study site was quantified using a Residency Index (RI) (Villegas-Rios et al. 2013). The index of residence is defined as the number of days a fish was detected within the array (any of the seven receivers) divided by the total number of days the full array was deployed (i.e. until end of November 2017). In order to assess the influence of month on fish residency, the RI was calculated on a monthly basis and the total number of days of full array deployment varying by month. A value of 0 indicates no residency within the array, value of 1 indicates permanent residency (Bryars et al. 2012; Villegas-Rios et al. 2013) within the array and a value between 0 and 1 indicates the proportion of all days per month where detections within the array occurred. We used generalised linear models to identify potential factors influencing residency of fish within the array over the study period. The residency index data, with values between 0 and 1, was assumed to follow a beta distribution and was regressed with respect to three covariates (fish species, body length, month). The general linear models also included the tagged fish code as a random intercept.

Results

Fish details

In total 12 fish were tagged (6 brown Trout, 6 Dace) and tracked during the study. Overall an individual fish was picked up on 5.8 ± 0.11 receivers over the study period. The detection period (days where fish were detected) ranged from 36 to 84 days (84 = total possible days) (Table 1). The majority of fish remained within the array for the length of the study period. Mean residency period was 0.9 for Trout and 0.7 for Dace (Supplementary Table 1). One Trout (Fish 49629) was last detected moving upstream shortly after release and was not re detected back in the array during the study period.

Displacement rates

The most parsimonious model for displacement rates determined species, temperature, discharge, light categories, month as the significant single term predictors and both species-light and species-month as significant interactions. The significant interaction between species and light category ($\chi 2 = 10.5$, df = 3, $p < 0.05$) was evident from data exploration where both species exhibited crepuscular activity peaks with higher displacement rates being observed during dawn and dusk light categories (Fig. 2). However, the magnitude of effect was greater for dace over the study period, having higher displacement rates than trout (Fig. 2). There was a negative effect of volume discharge on fish (both dace and trout) displacement rates ($\chi 2 = 7.0$, df = 1, $p < 0.05$). Water temperature had a positive effect on fish displacement over the duration of the study ($\chi 2 = 19.1$, df = 1, $p < 0.05$). Lunar phase had a weakly significant effect ($p > 0.03$) on displacement rates but was omitted for reasons of parsimony. Seasonal effect on displacement rates was investigated, with significant interaction between month and species observed ($\chi 2 = 24.9$, df = 3, $p < 0.0001$). The interaction revealed that trout had higher displacement rates in November whereas dace displacement rates became higher from August to November. Overall, the explanatory power of the displacement rates model was quite low with large daily variations in displacement rates evident for each individual fish. Model diagnostics plots can be seen in the supplementary material (Supplementary Fig. 2) (Fig. 3).

Table 1 Morphometric detection attributes for tagged Dace and Trout

Tag ID	Species	Length (mm)	Weight (g)	Total detections	Detection time (days)
49620	Dace	180	80.5	17,169	55
49621	Dace	190	98.5	22,917	50
49622	Dace	200	101.5	77,357	75
49623	Dace	200	117	48,420	73
49624	Dace	190	92.5	98,306	77
49631	Dace	200	113.5	44,931	57
49627	Trout	230	155	99,410	82
49628	Trout	270	256	134,982	82
49629[a]	Trout	320	384	437	1
49630	Trout	270	263	94,235	84
49632	Trout	230	181.5	102,264	36
49633	Trout	210	125	111,070	75

[a]Fish 49629 was removed from the analysis due to lack of detections

Home range

Home range KUD 50 (core area) and KUD 95 (outer home range area) were calculated per month (km^2) for both trout and dace to examine the temporal stability of estimated home range size. In general over the duration of the study period, dace exhibited a larger home range (mean KUD95: 0.053—$km^2 \pm 0.005$ S.E.) in comparison to trout (mean KUD95: 0.013 $km^2 \pm 0.003$ S.E.) (Table 2). The most parsimonious mixed effect model gave individual length as the only significant predictor for outer home range size ($\chi^2 = 12.81$, df = 1, $p < 0.05$). Specifically, KUD 95 (km^2) decreased with increasing total length for both dace and

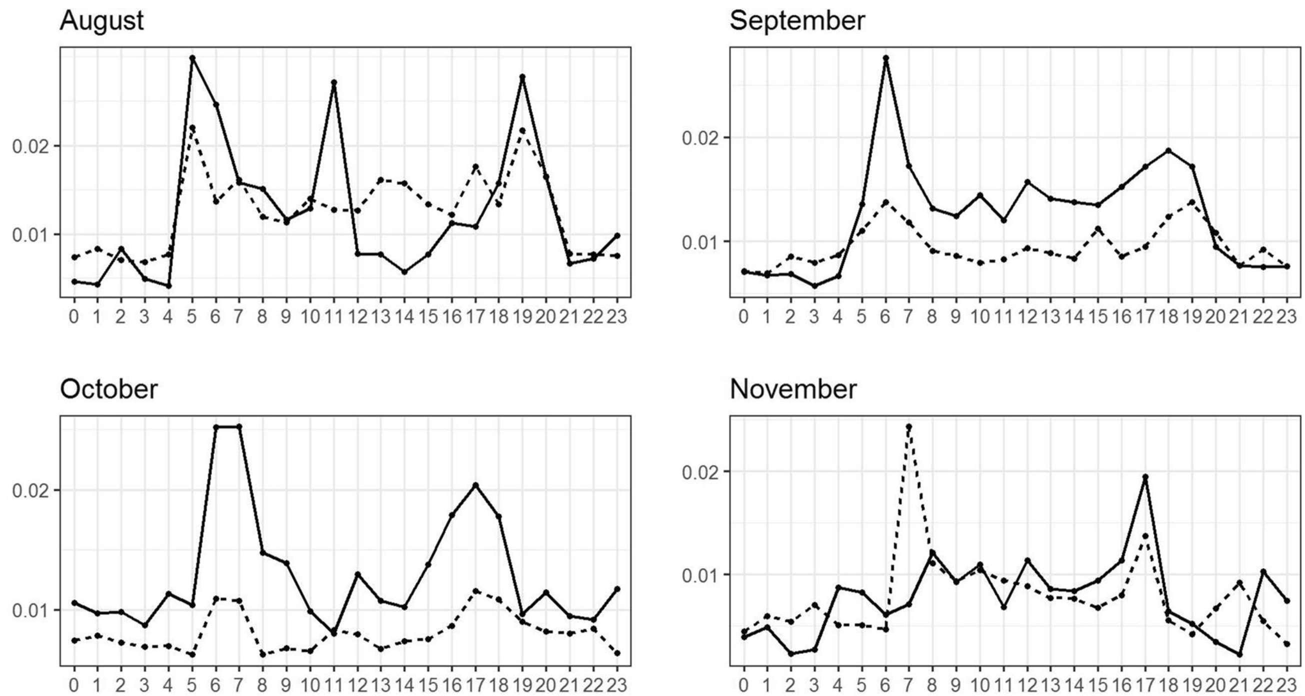


Fig. 2 The displacement rate per hour (facet by month) for Trout (dashed line) and Dace (black line)

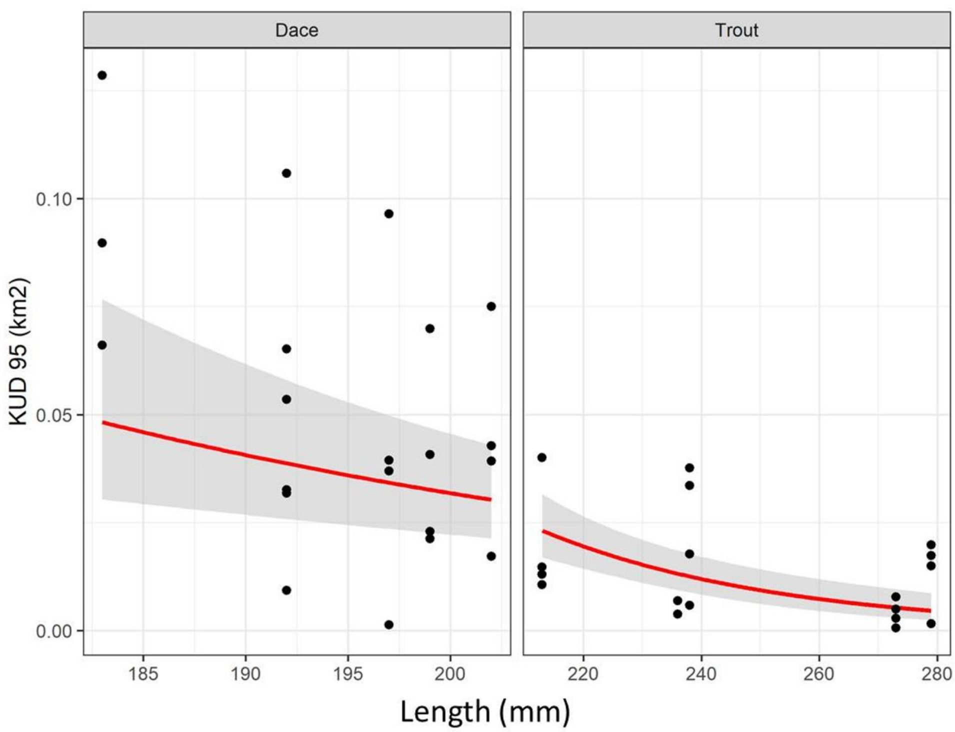


Fig. 3 Model prediction (red line) and 95% confidence intervals (grey) of home range size (KUD95) variation with individual length and associated KUD95 data for dace (length range 183–202 mm) and trout (length range 213–279 mm)

trout (Fig. 4). Neither species nor the length-species interaction terms were found to be significant ($\chi^2 = 0.426$, df = 1, $p > 0.05$ and $\chi^2 = 0.472$, df = 1, $p > 0.05$, respectively). A length-species interaction effect may be difficult to infer from the data because the length ranges of the tagged dace and trout do not overlap. The core area home range model (KUD 50) included a significant negative length and species effect ($\chi^2 = 4.24$, df = 1, $p < 0.05$) and predicted smaller

Table 2 Mean Kernel utilisation distribution 95 and kernel utilisation distribution 50 per month

Month	Dace KUD50	Dace KUD95	Trout KUD50	Trout KUD95
August	0.010	0.0463	0.003	0.016
September	0.008	0.0421	0.002	0.013
October	0.015	0.0605	0.002	0.02
November	0.009	0.063	0.001	0.005

KUD 50 values for all trout compared to dace (Model Diagnostic plot: Supplementary Fig. 3). In fact, the core home range area for trout was predicted to be approximately one half that of dace, irrespective of individual length (Fig. 4). Model diagnostics plots can be seen in the supplementary material (Supplementary Figs. 4 and 5).

Residency Index

The minimal adequate generalised mixed model for fish residency revealed only significant month effect ($\chi2 = 15.9$, df = 3, $p < 0.05$). This is evident from the residency index observations shown [alongside the confidence interval of the model fit] in Fig. 4 for both species which exhibit sharp declines in the month of November. A greater variance in observed RI values across tagged dace in each month compared to trout is also evident from Fig. 4 and Supplementary Table 1. However, fish species was not found to be significant in determining the monthly residency index of the tagged fish according to the model fit ($\chi2$, df = 1, $p > 0.05$). Similarly, length of fish did not have a significant effect on residency index over the duration of the study ($\chi2 = 0.07$, df = 1, $p > 0.05$), model diagnostics plots can be seen in the supplementary material (Supplementary Fig. 6).

Discussion

Knowledge of the distribution of native and non-native fish in riverine habitat provides insights into their ecology and the relationship between fish behaviour and environment. The nature of lowland rivers is that of a homogenous environment (deep and slow flowing) and as a result fish populations can be difficult to sample and quantify without taking into consideration their complex daily and seasonal patterns in movement and distribution. Understanding the space use of these species in a difficult to sample environment will hinder surveys and the management of these species. This study supports findings of extensive activity patterns of riverine brown Trout (Ovidio et al. 2002; Knouft and Spotila 2002; Diana et al. 2004) and Dace (Clough and Ladle 1997; Clough and Beaumont 1998). We add to the current literature by showing the temporal stability of home range

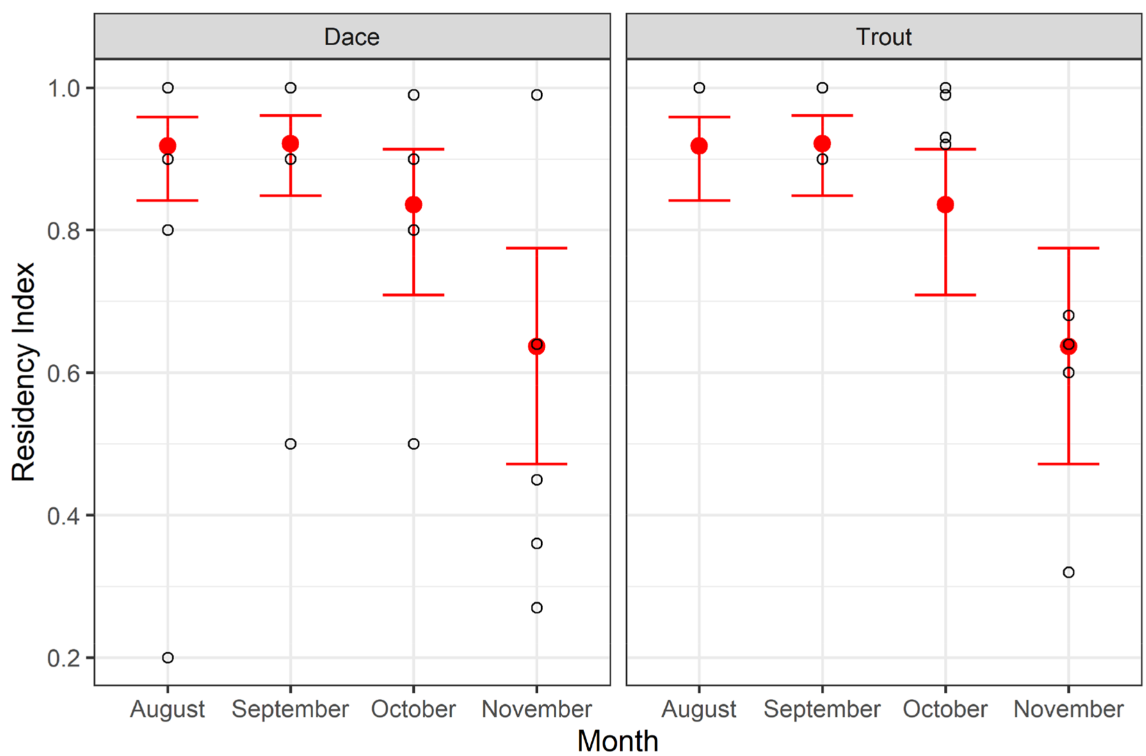


Fig. 4 Model validation plot for Residency Index (± SE) for Dace and Trout over the duration of the study

size and activity patterns of both species within a lowland river. The results from this study show that trout and dace exhibited strong site fidelity within a relatively small area of the 0.1 km^2. During the summer months it is hypothesised that dace feed heavily on the same aerial insects as juvenile salmon and trout (Caffrey et al. 2007). Dace are omnivorous (Cowx 1988) and it is likely that there is dietary overlap with brown trout in Irish rivers (Kennedy and Fitzmaurice 1971). Dace are a shoaling species, typically found in aggregations with con-specifics (Clough et al. 1998). Therefore, due to the high densities in which dace can be found, their greater displacement rates and larger home range, compared to trout demonstrated here, there is the potential for competition for both food and space in sympatric populations of both species, however, this would need further research to investigate potential competitive interactions.

Activity patterns: environmental effects

Dace displayed higher displacement rates than Trout over the duration of the study. Both species exhibited strong crepuscular activity patterns with higher average displacement rates being observed during low light dawn and dusk light periods. In most cases the magnitude of effect was greater for Dace over the duration of the study, having noted higher displacement rates within the array than that of Trout (at all times). It has been noted that fish appear to separate the day into foraging phases and resting phases that are linked with predator evasion (Helfman 1993; Ovidio et al. 2002; Barry et al. 2016; Hawley et al. 2016; Nakayama et al. 2018; Mulder et al. 2019). The daily activity patterns of Dace detailed in this paper may be representative of feeding and safe resting sites noted by previous studies in other freshwater species (Barry et al. 2016; Nakayama et al. 2018). Trout were particularly active in low light periods, with displacement peaks being strongly associated with sunset and sunrise. Crepuscular activity in brown Trout has been noted by several authors (Chaston 1969; Bachman 1984; Ovidio et al. 2002), and activity patterns in brown Trout are linked to light intensity or by changes in light intensity (Bachman 1984). It has been found that trout activity levels correlate with light levels and food availability (Clapp et al. 1990). The dawn and dusk peaks in displacement rates may be related to greater availability of prey at these times. Invertebrate hatches and downstream drifts are known to peak near sunrise and sunset (Jenkins 1969; Elliott 1970) and trout may time their foraging movements in response to invertebrate availability coming in a downstream direction. With regards to other tested environmental variables there was a significant negative effect of discharge on fish displacement for both trout and dace. This may be a result of fish sheltering in high flow events out of main current thus expending less energy. Water temperature had a significant positive effect on fish displacement rates, this has been noted by other authors for various fish species and has been linked to an increase in metabolic rates and thus an increase in activity levels (Garrett and Bennett 1995; Barry et al. 2016). There was a noted change in activity patterns over the duration of the study and was linked to home range (linkages discussed below). The activity change can be explained by trout having displacement rates peaking in November whereas dace displacement became higher from August through to November. The increased displacement rates of trout at this time may be a pre-spawning behaviour, as they are known to reproduce at this time (Campbell 1977).

Home range and residency

The specific area that an animal uses repeatedly throughout its course of activities constitutes a home range. Body size has been shown to be a significant determinant of home range size in mammals, birds, reptiles and fish (Peters 1986). Both trout and dace displayed a temporal stability in range within the array and no significant differences were observed during the tracking time period for either core range or outer home range, for either species. In general dace had a larger home range size than trout, which was consistent over the duration of the study. Dace utilised almost double the amount of "river space" in comparison to trout within the array for both core and home ranges. This is also an important finding from a management perspective, understanding how much river a dace or trout is likely to occupy can feed into population estimates which can be difficult in large lowland rivers (Penczak and Jakubowski 1990; Lyon et al. 2014). Outer home range decreased with increasing total length for both dace and trout. This is a counter intuitive finding and it varies from what has been reported in the literature and is not consistent with the allometric scaling relationship between body size and space requirements (Jetz et al. 2004). The literature suggests that home range size increases with length (Peters 1986). Given the small sample size and size distribution of tagged individuals being small in this study the length/home range observation here may be a result of individual variation and small number of fish tagged in the study. However it must also be noted that barrier at the bottom of this study site may be affecting home range size and reducing the range of tagged individuals. There were significant differences observed between trout and dace core home ranges. In fact, the core home range area for trout was predicted to be approximately one half that of dace, irrespective of individual length. Trout ranges remain relatively stable within a smaller home range, which has also been noted by other authors (Diana et al 2004; Watson et al. 2019). A trend towards a smaller home range was observed from August to November for trout, however, this was not significant. This reduction in space use over the 4 months may be a seasonal effect with onset of winter which has been noted for other trout species (Watson et al. 2019). The difference in home range size between trout and dace may be explained by the amount of foraging and or difference in feeding behaviours exhibited between the species (Swihart et al. 1988; Pearce et al. 2013). Kramer and Chapman (1999) stated that allometric shifts and change of diet decreased the relative cost of swimming and has potential for observed changes in home range size.

Overall both species had high residency within the array. The fact that there is an artificial barrier (affecting downstream migration) at the bottom of the study area may increase the observed residency, barriers can introduce friction to fish migration, promoting residency (Arnekleiv and Rønning 2004; Branco et al. 2017), possibly explaining the high residency within this riverine section. Interestingly, both species exhibited a decline in residency in the month of November. The noted decrease in residency and increase in displacement rate (discussed above) for Trout could be a result of them leaving the array to spawn (Campbell 1977). A greater variance in observed residency values across tagged dace in each month compared to trout was also evident. The decrease in residency and observed lower displacement rates in dace may be a result of them actively seeking winter refuges, a phenomenon reported for other leuciscid species (Horký and Slavík 2017; Horký et al. 2007), and observed in Irish populations of Dace inhabiting navigable rivers. Such behaviour may explain the observed drop off in detections, leading to a decrease in the observed residency index in this study.

Conclusion

While inference of mechanisms influencing the movement for populations (from small sample sizes) with acoustic telemetry alone is limited, we were able to identify some clear daily and seasonal patterns and provide new information on how brown Trout and Dace use an impounded lowland riverine habitat. This work also identifies how barriers to migration may be promoting an artificially high residency or localised movement within the habitat which has been noted for other species (Branco et al. 2017). Given our results, we conclude that the displacement patterns observed are primarily driven by foraging activity, the onset of potential spawning period and change to overwintering behaviour (seasonal changes).

Determining where fish are distributed across days and seasons is valuable for understanding their ecology, evolution and conservation. These data have given novel insight into the patterns affecting fish behaviour in a lowland riverine habitat. It has provided descriptive information on brown Trout and Dace spatial distribution, with important implications for potentially competitive interactions between the native brown trout and non-native, invasive dace. From a fisheries management perspective these data can feed into stock status monitoring. Understanding the interplay between the environment and an animal's behaviour is important from a conservation management perspective with increasing environmental pressures and the predicted climate regime changes.

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