*The Glasgow Naturalist* (2024) Volume 28, Part 2, 61-71 https://doi.org/10.37208/tgn28224

# The short-term impact of Eurasian beavers (*Castor fiber*) post-reintroduction on amphibian abundance and diversity in a lentic environment

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## ABSTRACT

In 2021, eight Eurasian beavers (*Castor fiber*) were reintroduced into the Idle Valley Nature Reserve (IVNR), Nottinghamshire, England. Amphibian surveys were conducted in four areas within the IVNR prior to the beaver reintroduction to establish baseline data. To investigate the short-term impact of beavers on amphibian abundance and diversity, this study sampled the same four areas post-beaver reintroduction. An additional four areas were also sampled post-beaver reintroduction, to compare areas where beaver activity was present or absent. Furthermore, environmental and beaver-linked variables were analysed to predict adult amphibian abundance. Adult amphibian abundance dramatically increased post-beaver reintroduction. However, there were no significant differences in adult amphibian abundance between areas where beaver activity was present or absent, with only increasing water depth and surveying at night shown to be significantly positively related to adult amphibian abundance. Conversely, there was a significant difference in terms of environmental variables between areas where beaver activity was present or absent. Similarly, beaver active areas were found to have higher young amphibian recruitment. Thus, the reintroduction of the beavers has not had a negative short-term impact on amphibian diversity and abundance, with the findings suggesting that over time the beavers will have a positive impact.

## INTRODUCTION

A species is typically reintroduced to improve the conservation status of that species (Seddon *et al*., 2007), but the reintroduction of some species can be used as a management tool to recover overall species richness of release sites, develop habitat quality or to enhance ecosystem function (Stringer & Gaywood, 2016). Many release sites that could benefit from enhanced ecosystem function are in freshwater ecosystems (Romansic *et al*., 2021), which are increasingly damaged by anthropogenic threats such as pollution, water removal, agricultural runoff, invasive species, and climate change (Naiman & Dudgeon, 2011; Reid *et al*., 2019). To counteract these anthropogenic threats and restore streams, riparian and lentic areas, some environmental managers in the northern hemisphere are using the reintroduction of American beavers (*Castor canadensis*) or Eurasian beavers (*Castor fiber*) as site management tools (Romansic *et al*., 2021).

Historically, Eurasian beavers were distributed throughout much of Europe and large portions of Asia including China and Mongolia (Durka *et al*., 2005). Due to overexploitation in the 17th century, there was a dramatic decline in the beaver populations, with only eight small populations surviving across Europe (Dalbeck *et al*., 2007). Through reintroduction programmes, natural dispersion, and increased protection across Europe, the beaver population has increased from 1,200 individuals a century ago to an estimated 1.5 million currently (Halley *et al*., 2021). In the U.K., beavers were hunted to extinction by the 16th century (Gaywood *et al*., 2015). However, through reintroduction programmes in the last 20 years, the current Scottish beaver population is estimated to be more than 1,000 individuals (Campbell-Palmer *et al*., 2021). The Scottish beaver population originates from the first British beaver trial in Knapdale, Argyll in 2009, where three families were released, along with unofficial beaver release in the River Tay catchment in 2001 (Campbell-Palmer, 2018). Unofficial releases have also been suspected in England: the origin of the River Otter population in Devon is unknown, with the beavers thought to have been released around 2008 (Halley *et al*., 2021). Investigations into the impact of both unlicenced populations concluded with the beavers being allowed to stay, due to evidence of their significant ecological benefits and ecosystem engineering ability (Brazier *et al*., 2020).

A species is considered an ecosystem engineer if it creates, modifies, or maintains habitats (Jones *et al*., 1994). Through tree-felling and browsing, along with the construction of lodges, burrows, canals, and dams, beavers have been shown to shape landscapes, affecting community and ecosystem levels on multiple spatial scales (Rosell *et al*., 2005). In lotic freshwater habitats, stream damming is arguably the most significant beaver activity (Brazier *et al*., 2020). By damming streams, structural heterogeneity increases due to the increase in wetlands and ponds, turning the environment into a lentic habitat (Nummi & Holopainen, 2020). The impact of beavers on existing lentic environments is less studied. However, within these environments, water bodies are connected through the creation of beaver canals (Grudzinski *et al*., 2020). In both environments, beaver activity alters local hydrology, geomorphology, and geochemistry (Brazier *et al*., 2021). Beaver activity also causes shallow areas of water bodies to increase in temperature because formerly shaded areas receive higher light levels due to the felling and drowning of trees (Skelly & Freidenburg, 2000). Increased insolation in shallow sections leads to the growth of submerged and emerging vegetation (Ray *et al*., 2001). The drowned trees and standing deadwood increase the amount of coarse woody debris (CWD) which in turn leads to an increase in macroinvertebrate species richness and abundance (Washko *et al*., 2022). Macroinvertebrates are not the only class of animal found to have increased species richness and abundance in proximity to beaver-modified habitats: mammals, birds, fish, and amphibians also have a positive association with beaver ponds, lodges, and canals (Grudzinski *et al*., 2020; Law *et al*., 2016; Tye *et al*., 2021).

Partly due to their water requirements, amphibians have repeatedly been shown to benefit from beaver activity (Cunningham *et al*., 2007). Beaver canals and ponds have been reported to improve landscape connectivity and habitat heterogeneity for amphibians, leading to increased dispersal and colonisation of new breeding sites (Anderson *et al*., 2015). Beaver-present ponds also have higher young amphibian recruitment than beaver-absent ponds (Stevens *et al*., 2007). Stevens *et al*., (2007) hypothesised that the higher young amphibian recruitment was due to the high stable temperatures in beaver ponds as well as the increased protection provided by beaver activity (Dalbeck *et al*., 2014). In shallow pond edges, the increased CWD and submerged vegetation from beaver activity provide shelter for amphibians, aiding in predator avoidance (Janiszewski *et al*., 2014). Beaver activity may also alter water chemistry and amplify nutrient content, leading to increased food supply for amphibian larvae (Brönmark & Hansson, 2017). However, beaver activity can negatively impact amphibians with flooding of hibernacula as a result of damming or mass death of eggs and larvae when beavers abandon ponds (Bashinskiy, 2014).

The overall positive relationship between amphibians and beaver activity is important due to the global decline and extinction of amphibians since the 1970s (Stevens *et al*., 2007). Between 1970 and 2014, amphibian populations in temperate environments are estimated to have decreased 2.8% per year, which is a greater rate of decline than that shown by any other vertebrate group (Leung *et al*., 2017). Many factors have contributed to the amphibian decline, including habitat loss and alteration, often cited as the foremost causes (Cushman, 2006; Gallant *et al*., 2007). Therefore, with beavers creating and modifying habitats that are suitable for amphibians, it is unsurprising that a meta-analysis of articles investigating the relationship between beavers and biodiversity found that 80% described a positive effect of beaver activity on anurans (Stringer & Gaywood, 2016). Of the 18 articles included in the meta-analysis, only three studied the impact of Eurasian beavers, with the remainder on American beavers (Stringer & Gaywood, 2016). The amphibian fauna in North America comprises many stream-dwelling species (Morrison & Hero, 2003), whereas in Europe amphibians prefer lentic environments (Dalbeck *et al*., 2020). Therefore, despite the similarities between the beaver species, their impact on amphibians may differ due to differences in life-history traits (Stringer & Gaywood, 2016). However, a literature review based purely on studies conducted in Europe reported that all 19 amphibian species known to inhabit central temperate and boreal Europe were found in beaver ponds, despite their diverse ecological needs (Dalbeck *et al*., 2020).

Limited research has been carried out on the relationship between beaver activity and amphibians within the U.K., although both the Scottish and Devon beaver trials have suggested a positive impact (Brazier *et al*., 2020; Downie *et al*., 2019). From mainland European studies, generalists and woodland species, compared to “open country” and pioneer species, benefitted the most from beaver-modified habitats (Dalbeck *et al*., 2020). Therefore, if these results were applied to the British amphibian community, the common frog (*Rana temporaria*), the common toad (*Bufo bufo*), and the palmate newt (*Lissotriton helveticus*) would be expected to benefit the most from beaver activity (Beebee, 2014). For example, Dalbeck *et al*. (2014) demonstrated that beaver ponds are preferred oviposition sites for common frogs in Germany, due to high insolation and a stable hydroperiod causing faster tadpole development. Furthermore, the Devon beaver trial reported an increase in common frog spawning from 10 to 681 over a six-year period after the beaver reintroduction (Brazier *et al*., 2020).

The great crested newt (*Triturus cristatus*) and the smooth newt (*Lissotriton vulgaris*) would also be expected to benefit from beaver activity, but to a lower degree and based on European findings the natterjack toad (*Epidalea calamita*) would not be affected (Beebee, 2014; Dalbeck *et al*., 2020). Although more research is needed to draw firm conclusions, mainland European studies suggest that species with the highest conservation concern in the U.K., the great crested newt (Biggs *et al*., 2015) and the natterjack toad (Buckley & Beebee, 2004) might not benefit significantly from beaver reintroductions (Dalbeck *et al*., 2020). While the common frog and the common toad are not the highest conservation concern in the U.K., since the 1970s their populations have been declining and increased conservation efforts are needed (Beebee, 2014). The common toad, in particular, has declined dramatically in the last 30 years, with a 68% decrease in population (Petrovan & Schmidt, 2016).

One of the main causes of amphibian decline in the U.K. is habitat loss, with many wetlands drained, and rivers canalised over the last two centuries (Oertli, 2018). By draining wetlands and controlling water courses, the natural formation of new ponds has decreased significantly (Oertli *et al*., 2010). On the other hand, many man-made pond systems in modern Britain are former gravel pits (Oertli, 2018). In France, flooded gravel pits have been shown to support a high proportion of amphibian species on a regional scale (Zamora-Marín *et al*., 2021), with a similar relationship suggested to occur in the U.K. (Buckley *et al*., 2014). Former gravel pits have also been found to support high macroinvertebrate diversity and abundance, again supporting the notion of wetland gravel pits being important amphibian habitats (Santoul *et al*., 2004).

A large area of the Idle Valley Nature Reserve (IVNR) in Nottinghamshire, England comprises a former gravel pit that has been transformed into a wetland system. In 2021, eight Eurasian beavers were reintroduced into the enclosed gravel pit wetland system by the Nottinghamshire Wildlife Trust, with the aim of using the beavers as a management tool to benefit wider species recovery plans in Nottinghamshire. One of the objectives of the reintroduction project is to monitor the long-term impact of beavers on amphibian diversity and abundance. Prior to the beaver reintroduction, a baseline amphibian survey was conducted (Woods, 2021). Therefore, the IVNR beaver reintroduction offers an opportunity to investigate both the short-term and long-term impact of beaver activity on amphibians in a man-made lentic environment, with amphibian surveys conducted before and after beaver reintroduction. Previous studies investigating the impact of beaver activity on amphibians have focused on the long-term effect and have been conducted primarily in lotic environments, with no published papers having investigated the short-term impact after reintroduction in an area sampled prior to beaver reintroduction. Furthermore, there has been no published work from the U.K. investigating the impact of beavers on native amphibian species abundance and diversity.

Woods (2021) conducted amphibian surveys in four areas within the IVNR in 2021, prior to the beaver reintroduction. One year later, after the beaver reintroduction, the study reported here sampled the same four areas, plus an additional four areas, to (1) draw comparisons between 2021 and 2022 in terms of amphibian abundance and diversity, and (2) compare amphibian abundance and diversity in areas where beaver activity was present to areas where beaver activity was absent. This paper provides insight into the relationship between amphibians and beavers within the U.K. and highlights the potential short-term impact of beavers, as well as providing a continuation plan for amphibian monitoring within the IVNR beaver enclosure.

## METHODS

### Study site

In November 2021, four adult Eurasian beavers (two males and two females) and four kits (two males and two females) from the Tayside beaver population, were released in a 60 ha enclosed conservation area. The release site is in the northeast of the Idle Valley Nature Reserve (IVNR), Retford, Nottinghamshire (Fig. 1), owned and managed by the Nottinghamshire Wildlife Trust. To keep the beavers within the release site, the area is fenced off and therefore not accessible to the public. The lakes within the site were historically sand and gravel pits. Vegetation within the enclosure is an assortment of successional woodland, scrub, and meadow, maintained by periodic grazing of cattle, wild roe deer (*Capreolus capreolus*), and Reeves' muntjac deer (*Muntiacus reevesi*). The woodlands consist of willow (*Salix* spp.), alder (*Alnus* spp.), and birch (*Betula* spp.) trees (Howard, 2020). Based on Retford amphibian accounts, the highest number of expected native amphibian species within the site is four: common frog, common toad, smooth newt, and great crested newt (Osborne, J., pers. comm.; Woods, 2021).

### Amphibian surveys

Between April and June 2021, prior to the beaver reintroduction, Woods (2021) used visual encounter surveys to assess amphibian abundance and species richness within the study site. In June 2022, post-beaver reintroduction, the amphibian surveys were repeated for this investigation. Six amphibian survey visits were conducted in both 2021 and 2022. A survey visit involved sampling each area once during daylight between 16:00 and 19:30 and once at night between 21:40 and 01:40. Areas 1, 2, 3 and 8 were sampled by Woods in 2021 and by this investigation in 2022 (Fig. 2). Woods (2021) selected these areas using QGIS 3.14, by randomly generating four potential sampling areas within the study site then selecting the closest suitable area in terms of habitat quality and practicality of access. In 2022, from these areas, only area 3 contained signs of beaver activity. To obtain an even number of areas where beaver activity was present and absent, four additional areas were selected to be surveyed in 2022. During the surveys for this investigation, beaver activity was present in Areas 3, 5, 6, and 7 and was absent in areas 1, 2, 4, and 8 (Fig. 2). The presence or absence of beaver activity was determined by signs of beaver activity, including beaver-gnawed trees and branches (Cunningham *et al*., 2007). The location of each area was recorded using a GPS Garmin GpsMap 64.

For both this investigation and the study by Woods (2021), two surveyors spent ten minutes searching for young and adult amphibians along the water's edge and surrounding habitat in each area. For the purpose of this investigation, "young amphibian" refers to froglets, toadlets and juveniles. "Adult amphibian" refers to individuals that are fully formed and a sufficient size, based on the life-stage species size guide obtained from Beebee (2013). The number and species of each observed adult amphibian were recorded. Species were

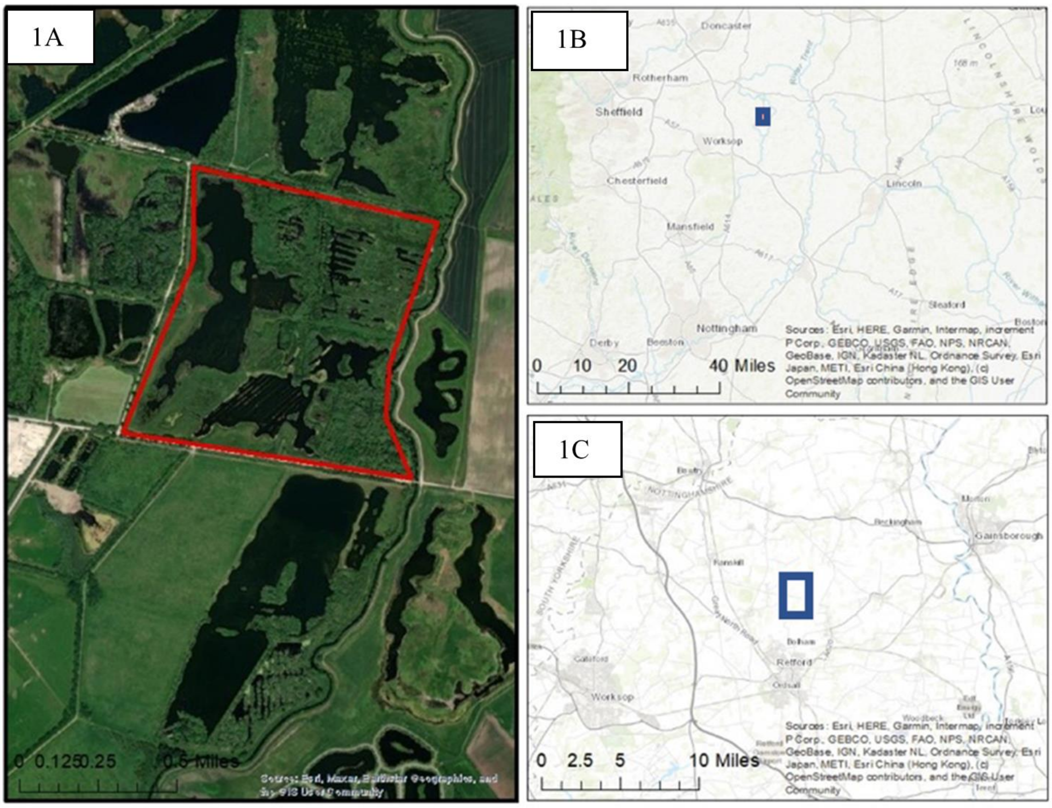

**Fig. 1.** A-C. The location of the Idle Valley Nature Reserve (IVNR) in Nottinghamshire, England. Blue rectangles on maps B and C highlight the location of the IVRN. The red outline in A outlines the fence of the beaver enclosure within the IVNR.

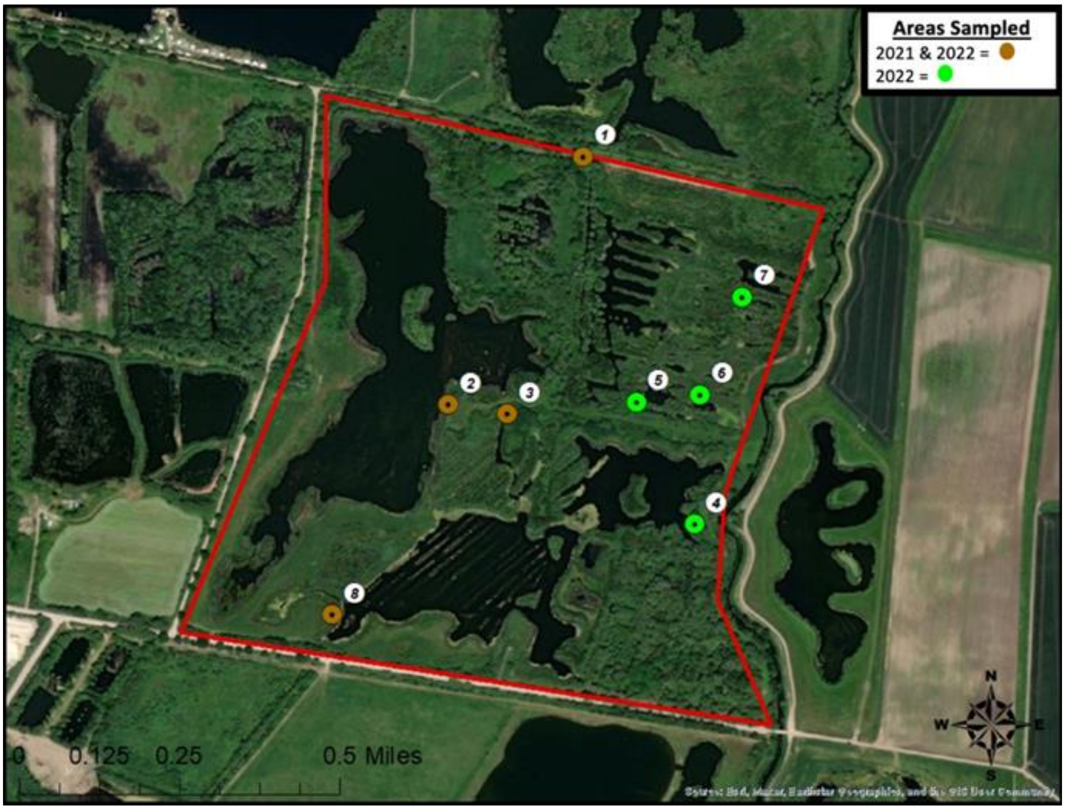

**Fig. 2.** The beaver release site located within the Idle Valley Nature Reserve, Nottinghamshire. The red outline represents the fence of the enclosed site. Each dot is an area where amphibian surveys were carried out along with area number in the white circles. Areas 1 (53.37103, -0.933473), 2 (53.367648, -0.936508), 3 (53.367518, -0.935176) and 8 (53.364781, -0.939126) (orange) were sampled by Woods in 2021 (Woods, 2021) and by this investigation in 2022. Areas 4 (53.366015, -0.930965), 5 (53.367683, -0.932267), 6 (53.367784, -0.930834) and 7 (53.369116, -0.929883) (green) were sampled in 2022. In 2022, beaver activity was present in areas 3, 5, 6 and 7 and beaver activity was absent in areas 1, 2, 4 and 8.

identified using the key from Beebee (2013). The number of young amphibians encountered was recorded in three categories: 0, 1-24 and 25+, as it was difficult to accurately count more than 25 mobile young amphibians. For the same reason, young amphibians were not identified to species level. During night visits, a million-candle power torchlight was used. The protocol and procedures employed in this study were approved by the Nottingham Trent University School of ARES Ethical Review Committee.

### Area characterisation

Environmental variables and variables linked to beaver activity were recorded based on the variables collected in similar studies (Table 1). During each visit to an area, water temperature, water pH and water Total Dissolved Solids (TDS) were recorded using a Hanna Combo device, model HI 98129 from the closest body of water (Bashinskiy & Osipov, 2016) and signs of beaver activity were recorded as present or absent. The average canopy cover and average water depth 1 m from shore were recorded once for each area (Romansic *et al*., 2021). Signs of beaver activity included beaver-gnawed trees and branches (Cunningham et al., 2007). Canopy cover was recorded using the iOS %Cover application (Public Interest Enterprises) on an iPhone 7 (Model A1778). At the start and end of each survey, air temperature was recorded using a weather gauge (Cunningham *et al*., 2007). Beaver presence was not included as a variable as no beavers were seen during the surveys.

### Data analysis

Abundance was expressed as the number of individuals encountered in an area per visit (Romansic *et al*., 2021). Species richness was expressed as the number of species occupying an area per visit (Romansic *et al*., 2021). The data analysis was carried out using the software R (Version 4.2.0). To validate the underlying assumptions of the chosen statistical tests, a data exploration process was performed for each objective, following the guidelines of Uzal *et al*. (2020). To compare the adult amphibian abundance between the 2021 amphibian surveys and the 2022 surveys a Wilcoxon test was used because the data were paired and not normally distributed. A Wilcoxon test was also used to compare adult amphibian abundance in area 3 between the 2021 and 2022 surveys. A Mann-Whitney test was performed to compare the adult amphibian abundance in 2022 between areas with beaver activity present to areas with beaver activity absent in 2022, as the data were unpaired and not normally distributed. To compare the environmental variables of water temperature, pH, total dissolved solids (TDS), and average water depth in areas where beaver activity was present to areas where beaver activity was absent, a Mann-Whitney test was also performed.

To investigate the relationship between adult amphibian abundance and environmental variables and variables related to beaver activity in 2022, a Poisson GLMM was performed. A Poisson GLMM was selected as the data were not normally distributed and had a high proportion of zeros. Collinearity issues were identified using a correlation matrix with corresponding pairplots and were confirmed using the variance inflation factor (VIF). The covariate with the highest VIF value was removed until all the VIF values were below 3 (Craney & Surles, 2002). This process resulted in the covariates

| Variable | Description and inclusion justification | Data type | Units/categories |
|---|---|---|---|
| Air temperature | The average air temperature throughout the survey (Woods, 2021; Cunningham *et al*., 2007). | Continuous | ºC |
| Water temperature | Temperature of nearest water body (Woods, 2021; Bashinskiy & Osipov, 2016). | Continuous | ºC |
| Water pH | The pH of the nearest water body (Woods, 2021; Bashinskiy & Osipov, 2016). | Continuous | Logarithmic |
| Water TDS | The TDS of the nearest water body (Woods, 2021; Bashinskiy & Osipov, 2016). | Continuous | Parts per million (ppm) |
| Average water depth 1 m | The average water depth 1 m from the shoreline with 5 samples taken at each area (Romansic *et al*., 2021). | Continuous | cm |
| Average canopy cover | The average canopy cover 1 m in from the shoreline with 5 samples taken at each area (Romansic *et al*., 2021). | Categorical | Dense/mid-dense/sparse/very sparse |
| Beaver activity | Signs of beaver activity such as gnawed trees or branches (Romansic *et al*., 2021). | Categorical | Present/absent |

**Table 1.** Description and scale of environmental and beaver related variables recorded from eight amphibian survey sites within the Idle Valley Nature Reserve, Nottinghamshire, England.

air temperature, TDS, and canopy cover not being included in the final model. Sample area was included in the final model as a random factor to account for the dependency in the data. Based on AIC values, the GLMM was shown to fit the data better than a model that did not include sample area or a model that included sample area as a fixed term. The GLMM was not over-dispersed. To investigate model misfit due to a potential excess of zeros, simulations of the fitted model were generated. The number of zeros in the simulated datasets was shown to correspond well to the raw data. To investigate the association between the categorical variables of young amphibian abundance and beaver activity in 2022, a chi-square test was performed.

## RESULTS

Six surveys were conducted between 14/06/22 and 29/06/22, each comprising visiting the eight selected areas twice. Therefore, in total, there were 96 observations in the 2022 data. The average air temperature during the amphibian surveys was 20°C.

### Amphibian abundance and species richness: comparison of 2021 and 2022

In 2021, across areas 1, 2, 3 and 8, 11 adult amphibians were encountered: 10 (91%) common frog and 1 (9%) common toad (Woods, 2021). In 2022 in the same areas, 71 adult amphibians were encountered, with 57 (80%) common frogs, 13 (18%) common toads, and 1 (2%) smooth newt. The abundance of adult amphibians encountered in the areas sampled by Woods (2021) was significantly higher in 2022 (Wilcoxon test, W = 52, n = 48, $P < 0.001$). The species richness also increased from two species to three species. Area 3 was the only area to be sampled in both years that showed signs of beaver activity after beaver reintroduction. In area 3, one adult amphibian was encountered in 2021 and 31 adult amphibians in 2022, a significant increase in adult amphibian abundance (Wilcoxon test, W = 2, n = 12, $P < 0.05$). The species richness also increased from 1 to 3 in area 3.

### Comparison between adult amphibians in beaver activity present/absent areas

In 2022 there were 108 adult amphibian encounters across the 12 visits to the eight sample areas, with 86 (80%) common frogs, 20 (18%) common toads and 2 (2%) smooth newts. In areas where beaver activity was present (areas 3, 5, 6, and 7), 64 adult amphibians were encountered: 52 (81%) common frogs, 11 (17%) common toads, and 1 (2%) smooth newt. In areas where beaver activity was absent (areas 1, 2, 4 and 8), 44 adult amphibians were encountered: 34 (77%) common frogs, 9 (21%) common toads, and 1 (2%) smooth newt. Adult amphibian abundance was not significantly higher in areas where beaver activity was present compared to areas where beaver activity was absent (Mann-Whitney test, W = 981, n =48, $P = 0.2$).

### Relationship between environmental variables and beaver activity

Median water temperature was significantly higher in areas where beaver activity was absent (21°C) compared with areas where beaver activity was present (19.8°C) (Mann-Whitney test, W = 1474, n =48, $P = 0.02$). The temperature range in areas where beaver activity was absent was 29.6-10.7°C. The range where beaver activity was present was 26.7-17.2°C. The median water pH of 8.86 in areas where beaver activity was absent was significantly higher than in areas where beaver activity was present (7.68) (Mann-Whitney test, W = 1994, n =48, $P < 0.001$). Total dissolved solids (TDS) and water depth were significantly higher in areas where beaver activity was present compared to areas where beaver activity was absent (Mann-Whitney test, W = 564, n =48, $P < 0.001$; Mann-Whitney test, W = 442, n =48, $P < 0.001$).

### Relationship between adult amphibian abundance and environmental and beaver linked variables

A Poisson GLMM was fitted to the 2022 data to predict adult amphibian abundance within Idle Valley Nature Reserve beaver enclosure, with sample area fitted as a random term. Observed Adult amphibian abundance was significantly higher at night ($P < 0.001$). There was also a significant positive relationship between amphibian abundance and average water depth ($P = 0.023$). There was no significant relationship between adult amphibian abundance and water temperature, pH, or beaver activity.

### Young amphibian recruitment in areas where beaver activity is present and areas where beaver activity is absent

Across the 12 visits to each area, young amphibians were present 48% of the time. When young amphibians were encountered, 68% of the encounters were during the daylight sampling periods. Young amphibian presence was recorded 58% of the time in areas where beaver activity was present. One to 24 young amphibians were encountered 33 times, with 48% in areas where beaver activity was present. The category of "25+ young amphibians" was recorded on 13 occasions, with 85% of these encounters in areas where beaver activity was present (Fig. 3). The association between the number of young amphibians per area visit and the presence or absence of beaver activity was significant ($X^2(2, N = 96) = 8$, $P = 0.02$).

## DISCUSSION

Adult amphibian abundance was found to have increased substantially post-beaver reintroduction, with the species richness remaining the same. However, the increase in adult amphibian abundance between 2021 and 2022 could be due to several factors such as natural amphibian population fluctuations and hotter temperatures in 2022. Moreover, there were no significant differences in adult amphibian abundance between areas where beaver activity was present and areas where beaver activity was absent, with only increasing water depth and surveying at night significantly positively related to adult amphibian abundance. There was a significant difference between areas where beaver activity was present and areas where beaver activity was absent in terms of environmental variables, which could partly explain the significant

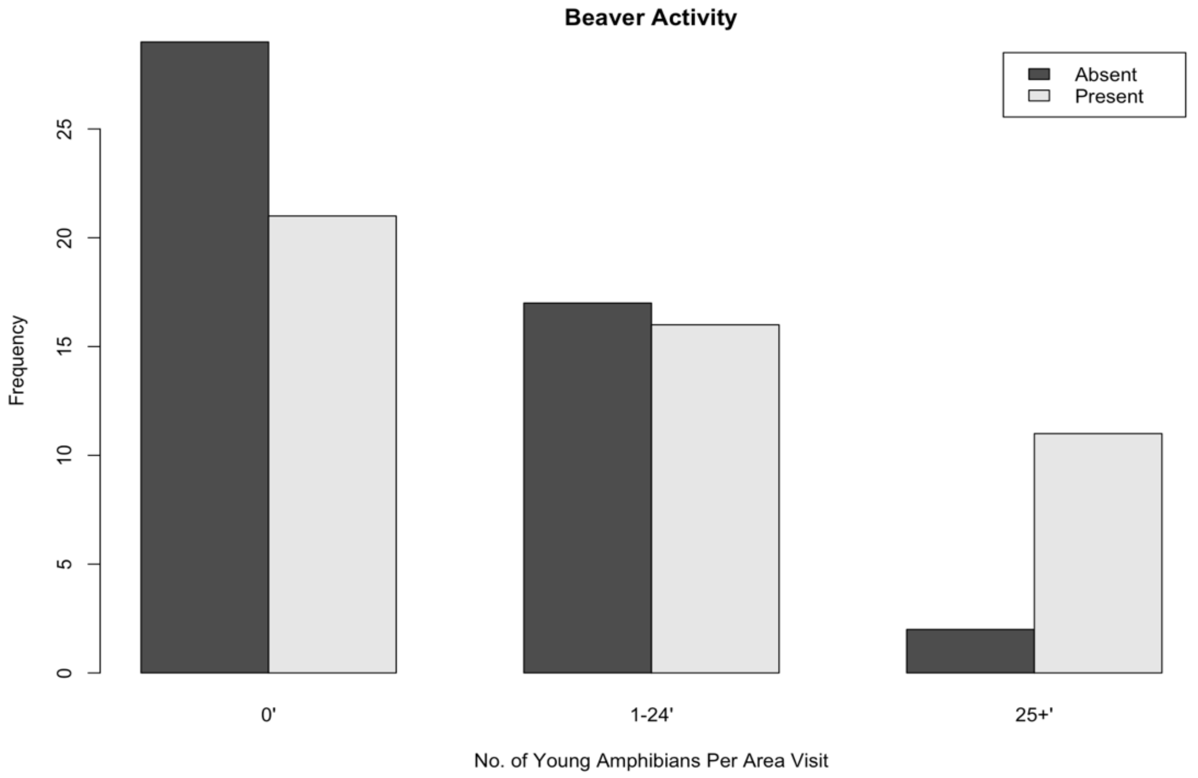

**Fig. 3.** Frequency of young amphibian abundance with three categories: 0 young amphibians, 1-24 young amphibians and over 25 young amphibians, encountered per area visit in areas where beaver activity was present (grey) and areas where beaver activity was absent (black)

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association between beaver activity and young amphibian abundance, with the vast majority of 25+ young amphibian encounters occurring in areas where beaver activity was present.

Amphibian population fluctuations mostly follow an episodic recruitment pattern, with populations found to naturally decrease in most years and then increase exponentially in favourable years (Alford & Richards, 1999). Therefore, 2022 could be a favourable year, explaining the dramatic increase in both adult common frogs and common toads in 2022 compared to 2021 (Woods, 2021). Furthermore, favourable years for common frogs and common toads have been linked to increased air temperature, with higher growth rates and rapid metamorphosis in warmer conditions (Laugen *et al*., 2003; Merilä *et al*., 2000). For example, Sewell *et al*. (2010) conducted amphibian surveys in two contrasting British landscapes over two years. In both landscapes, occupancy rates were significantly lower for common frogs and common toads during 2008 which was notably cooler than 2007. The average air temperature during Woods (2021) surveys was 11°C, while the average temperature during this investigation was 20°C. The difference in temperature could be due to the surveys of this investigation taking place slightly later in the year than Woods (2021). However, the average monthly temperature across England was hotter from January to June in 2022 than in 2021 suggesting favourable conditions for amphibian populations.

The increase in adult amphibian abundance between 2021 and 2022 could also be partly attributed to the reintroduction of beavers. In area three, the only area sampled by both this investigation and Woods (2021) where beaver activity was present, amphibian abundance significantly increased, and species richness increased from one species to three. The positive impact of beaver activity on amphibians in other countries has been well documented. However, previous investigations sampled areas where beavers have been for several years (Dalbeck *et al*., 2007; Dalbeck *et al*., 2014; Romansic *et al*., 2021) whereas this study investigated the short-term impact post-reintroduction. The difference in timescale may explain why there was no significant difference in adult amphibian abundance between areas where beaver activity was present and areas where beaver activity was absent, although areas where beaver activity was present had slightly higher abundance. Therefore, it can be concluded that amphibians are, at the least, continuing to occupy areas that have been altered by beavers at the same rate as unmodified areas, demonstrating that the beavers have not had a negative short-term impact on amphibian abundance and diversity. By continuing amphibian surveys as part of the monitoring plans in the Idle Valley Nature Reserve (IVNR), it will become clearer whether beavers are having a positive impact or if the increases seen in 2022 were due to a favourable year, allowing for an accurate assessment of amphibian demographic trends (Salvidio, 2009).

Unlike amphibian abundance, water temperature was significantly different between areas where beaver activity was present compared to areas where beaver activity was absent. The beaver activity of felling trees increases water temperature, both through increasing sunlight from lower canopy cover and insolation (Ray *et al*., 2001; Skelly & Freidenburg, 2000). In contrast, for this investigation, the median water temperature was slightly higher in areas where beaver activity was absent. Beaver activity could still have increased water temperatures in the areas where beaver activity was present, but due to a lack of before and after water temperature readings, the true effect is unknown. In areas where beaver activity was absent, the range of temperature was much larger than in areas where beaver activity was present. Increased insolation and drowning vegetation have been suggested to maintain water temperatures within beaver ponds (Dalbeck *et al*., 2014). Water bodies with less fluctuating temperatures have also been linked to rapid tadpole emergence (Stevens *et al*., 2007). However, water temperature was not significantly related to adult amphibian abundance. The positive association between amphibian abundance and water temperature has previously been recorded through counting egg masses and not adult occupancy rates, with the differences in methodology potentially explaining the lack of significance for this study (Gollmann *et al*., 2002; Stevens *et al*., 2007). Therefore, to investigate the impact of beavers on amphibian abundance and diversity within the IVNR, egg mass counting should be included in the future monitoring programme along with the continuation of recording water temperature.

As with water temperature, beavers have also been shown to alter water pH (Vehkaoja *et al*., 2015) and amphibians are sensitive to changes in pH (Azizishirazi *et al*., 2021). The water pH was significantly lower in areas where beaver activity was present compared to areas where beaver activity was absent. Accordingly, Puttock *et al*. (2017) also found beaver ponds to be more acidic than ponds without beavers. All British amphibians prefer a neutral pH of 6-9 (Beebee, 1983). However, water pH was not found to significantly predict adult amphibian abundance, although adult amphibian abundance decreased as the pH increased and became more alkaline. It is likely that if the beavers become active in the areas where they are currently absent, they will make the water more acidic and closer to neutral, benefitting amphibians. However, in some cases, beaver activity has been found to make the water more alkaline, with the effects of beaver activity on water pH seemingly site-dependent (Margolis *et al*., 2001). To investigate the relationship further and the impact on amphibians, it is essential that water pH is recorded within the beaver enclosure as part of the monitoring plan, especially due to the uniqueness of the study site.

Contrasting with the other environmental variables, increasing water depth was shown to be significantly positively related to adult amphibian abundance. Water depth was also significantly different in areas where beaver activity was present and absent, with beaver activity areas shown to have higher water depth. Other studies have demonstrated that beavers increase water depth through damming creating new wetlands and ponds (Gollmann *et al*., 2002; Swinnen *et al*., 2019). However, literature reporting that beavers increase water depth usually refers to lotic environments where the beavers make the habitat lentic (Hood & Larson, 2015). As the IVNR is already a lentic environment with the water source primarily being groundwater, beaver activity will most likely have limited impact on water depth, with only minor fluctuations caused through the increase or decrease of areas of underwater vegetation. Therefore, the results from this investigation would suggest that beavers and amphibians have similar habitat selection preferences in terms of pond shore depth within the IVNR, with both selecting deeper water edges.

Significantly more adult amphibians were also encountered at night. This is to be expected, as adult common frogs, common toads, and smooth newts are more active at night (Vences *et al*., 2000). However, day surveys should continue within the IVNR Nottinghamshire Wildlife Trust (NWT) amphibian monitoring plan, as young amphibian detection rates were notably higher during daylight. The continuation of both day and night visual encounter surveys is supported by Sewell *et al*. (2010), with their investigation also finding that alternative surveying times allow multiple amphibian life-stages to be recorded.

There was a significant association between young amphibian abundance and beaver activity, with areas where beaver activity was present shown to have the highest frequency of 25+ young amphibians encountered per visit. A high level of young amphibian recruitment has been linked to beaver-modified habitats due to increased levels of CWD leading to high nutrient content (Brönmark & Hansson, 2017; Stevens *et al*., 2007). Total dissolved solids (TDS) are the metric usually used to measure nutrient content (Boyd, 2020). There was a significant difference in TDS between areas where beaver activity was present and areas where beaver activity was absent, with beaver-active areas having a higher TDS content. Higher levels of CWD have also been shown to increase protection for tadpoles and young amphibians due to a greater number of hiding places (Janiszewski *et al*., 2014). Therefore, the higher TDS content caused by beaver activity could explain why beaver-active areas had higher young amphibian abundance than areas where beaver activity was absent.

Due to the uniqueness of this investigation, both in terms of timescale and study site, the findings should be interpreted with caution. The slight variation in time of year and use of different surveyors must be considered when comparing this investigation with that of Woods (2021). Furthermore, the difference in environmental variables between areas where beaver activity was present and areas where beaver activity was absent could be due to habitat characteristics that were there before the beavers were reintroduced and not due to beaver activity. However, this short-term investigation is part of a wider project in which amphibian abundance and diversity within the study site will be monitored for many years, which will diminish these limitations. The future monitoring plan should continue to use the same methodology as this investigation along with other amphibian sampling techniques. Sewell *et al*. (2010) found that adding bottle-trapping to their amphibian surveys led to greater detection of all three British newt species. With only two smooth newts sampled by this investigation using visual encounter surveys, the ongoing monitoring programme should include bottle trapping to effectively monitor the newt population. Moreover, beaver projects at lotic sites within the U.K. have found a dramatic increase in egg spawn counts each year from when the beavers were reintroduced (Brazier *et al*., 2020). Therefore, egg counting should also be included as standard in the monitoring plan with surveys starting earlier in the year.

## CONCLUSION

With amphibians declining across the U.K., there is a need for alternative management strategies to counteract population declines. As ecosystem engineers, beaver reintroduction has been shown not just to benefit beaver conservation but also other species, including amphibians. Therefore, the Idle Valley Nature Reserve offers a unique opportunity to investigate the relationship between amphibians and beaver activity within a lentic habitat, allowing further understanding of beavers as management tools. The intention of this study was to investigate the short-term impact of beavers on amphibian abundance and diversity post-reintroduction, and to pave the way for the future amphibian monitoring programme within the Idle Valley Nature Reserve. This investigation demonstrated that the reintroduction of beavers has not had a negative short-term impact on adult amphibians, and may have positively impacted recruitment levels, with significantly higher abundance of juvenile amphibians observed in beaver-active areas. The results suggest that over time the beavers will have a wider positive impact on amphibian diversity and abundance as seen in other beaver trials. Therefore, continuation of the monitoring programme is essential and will most likely provide further evidence for the support of beaver reintroductions and help amphibian conservation.

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