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Spatial distribution and seasonal movement patterns of reintroduced Chinese giant salamanders

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Abstract

Background: Very little is known about the temporal or spatial movement patterns of Chinese giant salamanders (*Andrias davidianus*) due to their rarity, remote habitat and secretive nature. Commercial breeding farms provide a unique opportunity as a source of animals for reintroduction and spatial ecology studies, which will help inform conservation management efforts for this threatened species. We surgically implanted radio transmitters into the body cavity of 31 juvenile giant salamanders, and these salamanders were subsequently released into two small river systems (Donghe and Heihe Rivers) located in the Qinling Mountains of central China and were monitored daily from May 2013 to August 2014.

Results: Only two salamanders survived through the end of the project at the Heihe River compared with 12 at the Donghe River, thus movement data for salamanders released at the Heihe river are described individually. The overall sedentariness (ratio of no movement to all observations) for the two salamanders at the Heihe River was 0.29 and 0.28 compared to the average sedentariness of 0.26 ± 0.01 for the 12 salamanders at the Donghe River. Mean daily movement was 15.4 m ± 0.7 at the Heihe River compared to 9.3 m ± 0.3 at the Donghe River. Overall linear home range (LHR) was 246 m and 392 m for the two salamanders at the Heihe River, compared with a mean LHR of 227.2 m ± 70.5 at the Donghe River. The Donghe salamanders exhibited different movement patterns across seasons, having higher sedentariness, shorter daily movement, and smaller LHR in winter than in summer. Up-stream dispersal and fidelity to release site were recorded at both rivers. The mean dispersal distance for the Donghe River salamanders was 145.3 m ± 61.9, while the two surviving salamanders at the Heihe River had a dispersal distance of 211 m and 205 m.

Conclusions: This project provides important insights on the movement ecology of a large aquatic salamander species, and in particular, our results may assist with reintroduction efforts by developing best management practices on when and where to release animals as a conservation strategy.

Keywords: *Andrias davidianus*, Aquatic salamander, Daily movement, Dispersal, Home range, Radio-telemetry, Reintroduction

Background

Around the world, amphibian declines and local extinctions are accelerating at an alarming rate, with > 40% of all amphibians listed as threatened on the IUCN Red List [1]. This percentage is higher than in birds (14%) and mammals (25%), raising global concerns about the loss of amphibian biodiversity. The various factors contributing to the decline of amphibians include habitat loss, over-utilization, disease, pollution, and climate change [2–5]. Among amphibians, species with a larger body mass or that live in aquatic habitats may have a higher risk of decline [6, 7]. Both risk factors are exemplified by species in the Cryptobranchidae family, which have the largest body size among living amphibians and exhibit totally aquatic life histories. There are three cryptobranchid species including the hellbenders (*Cryptobranchus*

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alleganiensis) in North America, the Japanese giant salamanders (JGS, *Andrias japonicus*) and Chinese giant salamanders (CGS, *Andrias davidianus*) in Asia. According to the IUCN Red List, the hellbender and the JGS are listed as Near Threatened, while the CGS as Critically Endangered [8–10]. Furthermore, the two subspecies of hellbender are listed differently under the US federal Endangered Species Act (ESA), with *C. a. bishopi* classified as Endangered, and *C. a. alleganiensis* as Threatened. Conservation efforts are needed for these giant salamanders, especially for the Critically Endangered CGS.

Translocation and reintroduction are increasingly implemented in restoration efforts of threatened amphibian species [11]. Thus, having an understanding of the target species' movement ecology is crucial to designing reintroduction projects; for example, with aquatic species, choosing a long enough stretch of river for released animals to diversify is important for the establishment of a reintroduced population. These three giant salamander species are reported to be highly sedentary [12–14]. This trait may be beneficial for establishing populations in the wild, as moving away from release site is one of the most common reported causes to reintroduction failure [11], and penning prior to release would reduce post-release dispersal thus contribute to population establishment [15, 16]. Unfortunately, very little is known regarding other aspects of movement for CGS and JGS, although there are a number of studies on movement ecology for hellbenders [14, 17–19] that can be used for comparison.

As an endemic species, CGS were once found widely in the mountain tributaries of the three major river systems–Pearl, Yellow and Yangtze Rivers–in central and southern China [20]. However, since the 1950s CGS populations have declined dramatically, largely due to over-exploitation for human consumption, water pollution, and habitat destruction such that they are now almost extinct in the wild [10, 21–23]. Unlike hellbenders, no published studies have radio tracked wild CGS and their spatial ecology remains largely unknown. The only available telemetry study monitored 4 captive-reared CGS (two adult males and two adult females) reintroduced to the wild over a 6 month period [13]. This study found that all 4 of their released animals moved upstream, settled in one location within 10 days post-release and had an average home range of 34.75 m^2 [13]. Although this initial publication studying CGS movement revealed some interesting aspects on the species movement and habitat selection, more animals tracked over a longer period of time would be a valuable addition to understanding the species' movement ecology across seasons.

Due to CGS's rarity and associated challenges with telemetry approval for wild animals in China, captive populations may be a better sink for studying movement, especially given these populations will be used for future reintroduction efforts. Critical information on movement ecology under a controlled design is possible with captive-bred individuals and has been demonstrated in the high profile recovery efforts of the California condor (*Gymnogyps californianus*, [24]). Although captive breeding for the purpose of CGS conservation has not been reported, commercial breeding in *Andrias* farms has been highly prosperous over the past decade in China [25]. In these farms, hundreds of thousands of animals each year are produced for human consumption, as they are considered a delicacy in the Chinese food market. The farms might also provide animals for restoration efforts, which relieves pressure on wild populations at risk of poaching. The release of farm-bred animals also provides an ideal opportunity to examine CGS movement ecology that can be used to optimize reintroduction projects.

We reintroduced 31 juvenile CGSs at two sites in the Qinling Mountains in central China and monitored their movements through radio-telemetry. We have previously reported survivorship [26] and habitat use [27] but describe here the post-release movement of the salamanders over an extended period of 16 months, from May 2013 to August 2014. Our specific objectives were to: 1) assess activity patterns including sedentariness (ratio of no movement to all observations) and daily movement; 2) determine home range sizes and overlap of home ranges with conspecifics; 3) compare seasonal movement patterns; and 4) assess dispersal distances and variables that may affect dispersal patterns. We hypothesized that the released CGSs would make short-distance movements of a comparable magnitude to the movements observed by hellbenders [18, 19], and have an up-stream biased dispersal similar to other aquatic salamanders [28, 29]. Results from this study will help to fill in knowledge gaps in movement ecology of CGS, and may provide suggestions for future reintroduction projects on better monitoring design.

Results

Sedentariness and daily movement

A total of 5939 salamander locations were recorded during the study, of which 4441 were from the Donghe River. The overall sedentariness ranged from 0.09 to 0.53 at the Heihe River, and 0.18 to 0.32 at the Donghe River (Table 1). Only two salamanders in the Heihe cohort survived at least four seasons, and for each an overall sedentariness of 0.29 and 0.28 was determined. At the Donghe River, 12 salamanders survived at least four seasons, with an average overall sedentariness of 0.26 ± 0.01. The mean daily movement was 15.4 ± 0.7 m (*n* = 979, 4–298 m) at the Heihe River, and 9.3 ± 0.3 m (*n* = 3185, 4–880 m) at the Donghe River. Although our

Table 1 Parameters describing the post-release movement and home ranges of individual Chinese giant salamanders reintroduced to the Heihe (3 year old animals) and Donghe (5 year old animals) rivers in central China

Animal ID	n[a]	Sedentariness	Daily movement (m)[b]	LHR (m)[c]	MCP (m^2)[d]	Status[e]
Heihe						
202	2	-	17 (n = 1)	10	-	M*
235	403	0.29	9 (*n* = 274) [4–107]	246	18,876	A
251	47	0.29	12 (*n* = 29) [4–100]	194	5534	M$^{\blacklozenge}$
273[f]	126	0.38	9 (*n* = 73) [4–262]	2364	302,433	U
291	4	-	6 (n = 3) [4–77]	80	210	M$^{\blacksquare}$
351	5	-	10.5 (n = 2) [9–12]	16	78	M*
392	12	0.09	10.5 (*n* = 10) [5–89]	176	2588	M*
412	180	0.22	7 (*n* = 131) [4–70]	64	3571	U
431[f]	121	0.25	10 (*n* = 84) [4–132]	1083	24,726,132	U
472[f]	46	0.53	20 (*n* = 19) [4–85]	9524	959,773	U
531	397	0.28	8 (*n* = 271) [4–298]	392	25,625	A
571	51	0.30	11 (*n* = 30) [4–60]	91	4301	U
610	46	0.40	6 (*n* = 24) [4–215]	401	17,182	U
710	3	-	7 (n = 2) [6–8]	12	1	M*
730[f]	55	0.41	10.5 (*n* = 26) [4–113]	3865	574,909	U
Donghe						
101	385	0.29	6 (*n* = 267) [4–64]	389	11,149	A
211	326	0.31	6 (*n* = 216) [4–77]	156	3868	A
312	155	0.32	6 (*n* = 98) [4–44]	118	2630	M$^{\blacksquare}$
332	332	0.20	8 (*n* = 257) [4–32]	46	1156	A
371	339	0.24	6 (*n* = 247) [4–49]	76	2086	A
450	364	0.22	7 (n = 274) [4–34]	41	828	A
490 [f]	327	0.27	6.5 (*n* = 225) [4–48]	722	44,955	A
511	401	0.19	7 (*n* = 316) [4–37]	84	1733	A
550	76	0.32	6 (*n* = 44) [4–93]	261	6099	M$^{\blacksquare}$
591[f]	262	0.18	9 (*n* = 207) [4–880]	1730	159,357	U
630 [f]	332	0.29	6 (*n* = 217) [4–21]	762	52,728	U
651	59	0.27	7 (*n* = 36) [4–30]	41	634	U
671	335	0.21	8 (*n* = 254) [4–54]	151	3610	A
751	345	0.22	7 (n = 254) [4–100]	560	20,390	A
770	77	0.29	8 (*n* = 45) [4–18]	93	1227	M$^{\blacksquare}$
790	326	0.30	7 (*n* = 221) [4–79]	542	22,367	A

[a] Total number of observations collected

[b] Median of distances between sequential daily locations that were > 3 m. Numbers in parentheses indicate sample size and numbers within brackets represent the range of observed values (minimum cut-off of 4 m to represent a daily movement)

[c] Linear Home Range: length of river section occupied by the salamander during the period it was monitored

[d] Minimum convex polygons

[e] Salamander status: A = Alive, U=Undetermined, M = Mortality, with superscripts explaining causes of mortality, where * = dehisced sutures,
◆ = flood, ■ = unknown

[f] Salamanders moved downstream during floods

data indicated that salamanders can move large distances (up to 880 m), their mean daily movement was relatively short, with 74% of daily movements ≤10 m at the Donghe River and 58% at the Heihe River.

Home range and overlap of home ranges

Linear home range (LHR) during the entire study period differed considerably among salamanders, ranging from 10 to 9524 m at the Heihe River, and 41 to 1730 m at the Donghe River (Table 1). Minimum convex polygons (MCP) showed the same variations. Not surprisingly, the largest home ranges were from salamanders that moved downstream during floods, while the smallest home ranges were from salamanders that died soon after release. Excluding salamanders that were swept downstream during floods and those that did not survive at least four seasons, each of the two salamanders surviving at the Heihe River had an overall LHR of 246 m and 392 m, and an overall MCP of 18,876 m^2 and 25,625 m^2. The Donghe salamanders had a mean LHR of 227.2 ± 70.5 m ($n = 9$, range: 41–560 m), and a mean MCP of 7465.2 ± 2828.8 m^2 ($n = 9$, range: 828–22,367 m^2). LHRs of these 11 salamanders were strongly correlated with their MCPs (*Spearman rho* = 0.945, $p < 0.001$).

For each salamander at the Donghe River, the number of neighbors with a weekly overlapping LHR decreased quickly post-release and remained relatively stable in the following weeks (Fig. 1a). Similarly, the percentage of overlap also rapidly decreased in the first 10 weeks and then became relatively stable, with an average overlap of 39.4% (range: 0–99.1%, Fig. 1b). After the 50th week, we started to lose signal due to battery depletion, thus the 0 overlap in Weeks 50–52 might be biased (i.e., the overlapping neighbor's data may be missing because we could not locate it anymore, when in fact it could have remained in the river) and were presented here for reference only. Despite this general overlap of home ranges, we never found two salamanders under a single boulder simultaneously.

Seasonal variation in movements of the Donghe salamanders

Salamanders at the Donghe River had different sedentariness (Fig. 2a), mean daily movement (Fig. 2b), and LHR among seasons (Fig. 2c). Specifically, salamanders had a higher sedentariness (*Friedman chi-squared* = 11.045, $p = 0.026$), shorter daily movement (*Friedman chi-squared* = 12.447, $p = 0.014$), and shorter LHR (*Friedman chi-squared* = 9.542, $p = 0.049$) in winter than in summer. Measurements in spring and autumn were usually between those of winter and summer and did not differ significantly. The only exception was sedentariness in summer 2013 (Fig. 2a), which was higher than sedentariness in summer 2014 ($p = 0.007$) and did not differ from that in winter 2014 ($p = 0.939$).

Dispersal patterns

Released salamanders showed all three types of dispersal patterns – moving upstream, moving downstream, and fidelity to release site (Figs. 3, 4). All downstream dispersals were associated with flood events. Among salamanders with different types of dispersal at both rivers, no difference was found on their initial body mass (Donghe: $H = 1.000$, $p = 0.607$; Heihe: $H = 2.786$, $p = 0.248$) or body condition (Donghe: $H = 1.250$, $p = 0.535$; Heihe: $H = 1.071$, $p = 0.585$). Regardless of direction, the dispersal distance (distance from release site to the centroid of the last weekly LHR) of salamanders ranged from 1 to 572 m at the Donghe River (Fig. 3a-d) and 1 to 6130 m at the Heihe River (Fig. 4 a-d). Similar to home ranges, the largest dispersal distances were from salamanders that moved downstream during floods, while the smallest dispersal distance was from salamanders that died or disappeared at an early stage post-release. Excluding salamanders that moved downstream during floods and those that did not survive at least four seasons, the mean dispersal distance was 145.3 ± 61.9 m ($n = 8$, range: 4–451 m) at the Donghe River, and 211 m

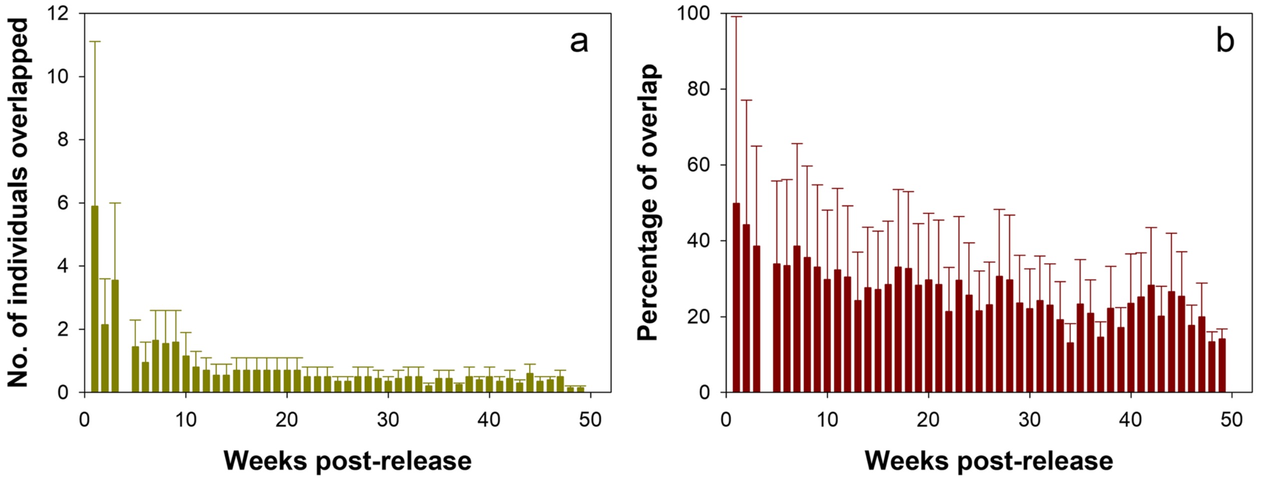

Fig. 1 Mean number of individual Chinese giant salamanders at the Donghe River that overlapped with each other from July 2013 – August 2014 (**a**), as well as the mean percentage of overlap (**b**). From the 50th week forward we started to lose radio signal due to battery depletion, thus 0 overlap in Weeks 50–52 may be biased and are only presented for reference

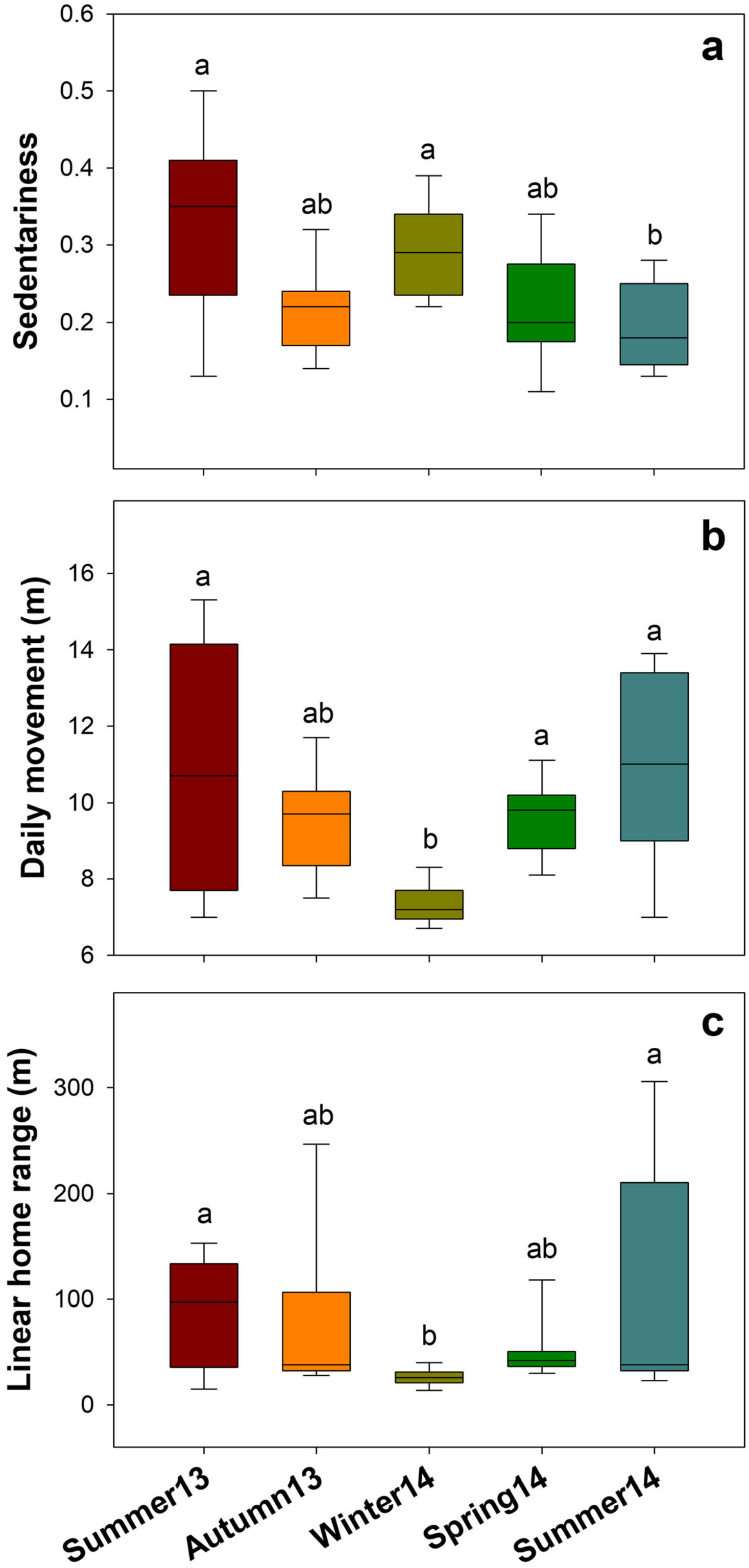

Fig. 2 Seasonal sedentariness (**a**), daily movement (**b**), and liner home range (LHR, **c**) of salamanders (n = 9) at the Donghe River following release. Seasons with the same lowercase letters indicate there is no difference between the two. The upper whiskers represent the 90th of the percentile while the lower whiskers represent the 10th of the percentile of the data

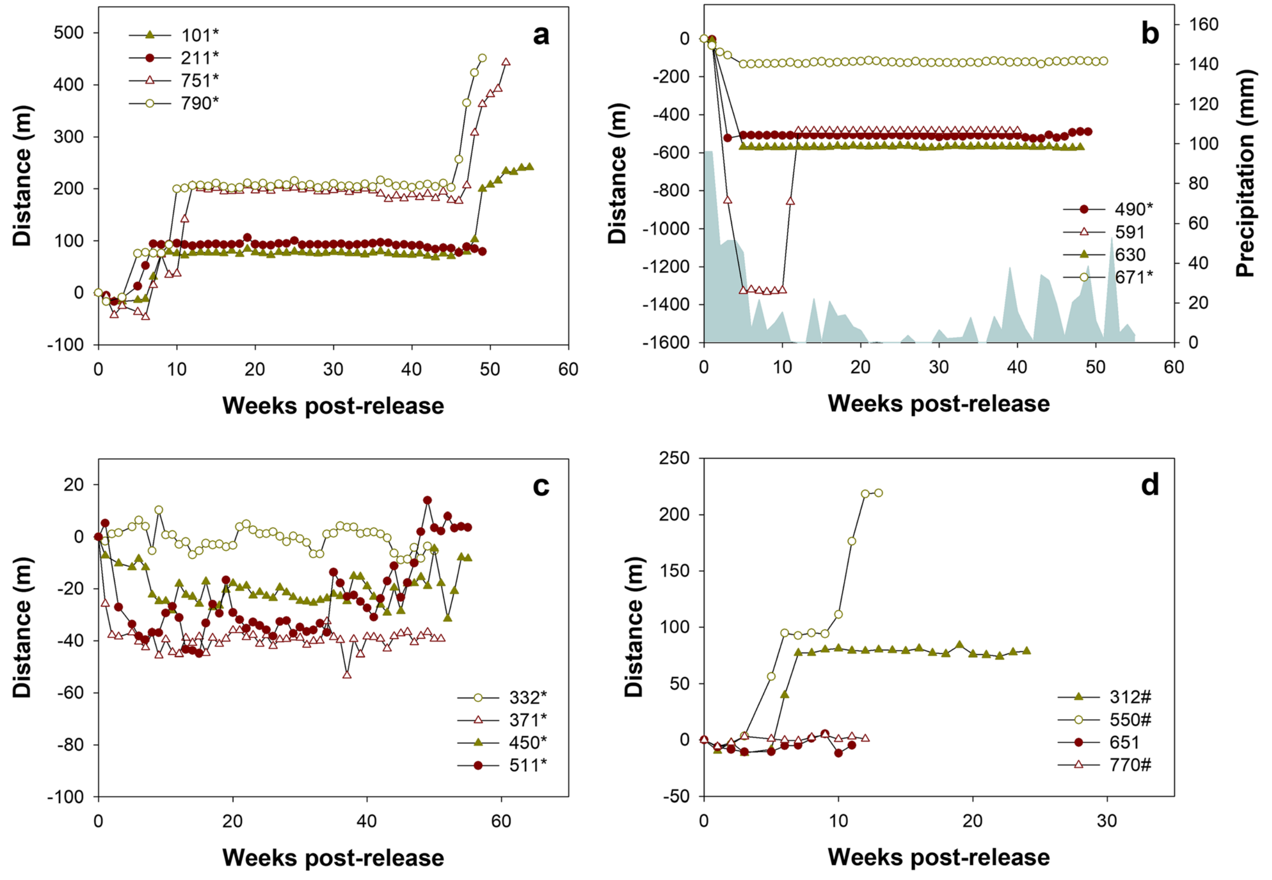

Fig. 3 Dispersal distance from the release site for every Chinese giant salamander reintroduced at the Donghe River (July 2013 – August 2014), including those that moved upstream (**a**), downstream (**b**), showed fidelity to their release sites (**c**), and those that died shortly post-release (**d**). Salamander identities were listed in figure legends, with * indicating the animal was confirmed alive at the end of the project, and # indicating the animal was confirmed dead. Shaded area in (**b**) indicates the amount of weekly precipitation in millimeter

and 205 m for the two surviving salamanders at the Heihe River.

The 4 up-stream dispersing salamanders at the Donghe River found a suitable refuge within 12 weeks and remained at those sites for almost an entire year. Three of the four salamanders displayed a second round of movement and dispersal between the 46th–48th week post-release (Fig. 3a). Upstream dispersal of these three animals continued until the transmitters ran out of battery power.

Discussion

Although giant salamanders are generally considered as highly sedentary and having limited mobility, our study revealed that reintroduced CGSs moved quite frequently throughout the year. The year-round sedentariness for our salamanders was under 0.31, indicating these animals moved ~ 70% of the days during our study period. The previous telemetry study on this species [13] does not report an overall sedentariness for their salamanders during their monitoring period. Instead, they indicate that their animals moved upstream within 3–10 days post-release and had a second round of upstream movement after their dens were destroyed by a flood. Thus, we could not directly compare our results with their findings and make meaningful predictions. However, there are several studies on the movement ecology of hellbenders, which we can compare our study against. Burgmeier et al. [14] indicated that wild hellbenders moved during ~ 25% of their observations, and Bodinof et al. [18] reported captive-reared hellbenders moved < 50% of their observations post-release. Compared to these results, we found that CGSs moved more frequently than the hellbenders. Lacking movement data from wild CGSs, we cannot determine whether the high frequency of movement of our animals was because they were captive-reared, continuously seeking a suitable refuge or if it was a biological trait of this species. More studies on the movement of captive-reared vs. wild aquatic salamander species, may help to answer this specific question.

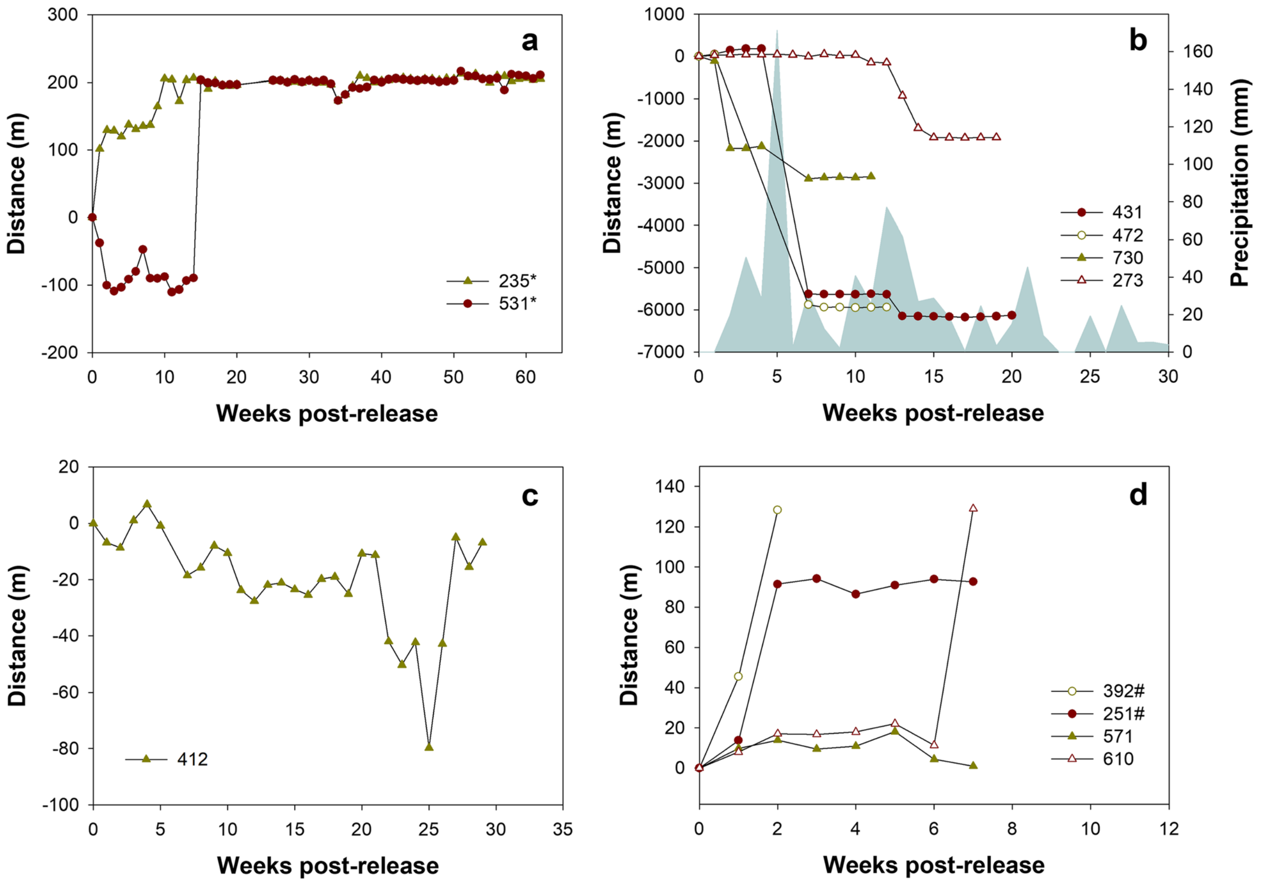

Fig. 4 Dispersal distance from the release site for every Chinese giant salamander reintroduced at the Heihe River (May 2013 – July 2014), including those that moved upstream (**a**), downstream (**b**), showed fidelity to their release sites (**c**), and those died shortly post-release (**d**). Salamander identities were listed in figure legends, with * indicating the animal was confirmed alive at the end of the project, and # indicating the animal was confirmed dead. Shaded area in (**b**) indicates the amount of weekly precipitation in millimeter

We found that reintroduced CGSs generally move short distances, with a mean daily movement of 9–15 m, although they were able to move long distances, up to 880 m within a single day. These results were comparable to reports on hellbenders, which found that hellbenders travel on average 3 m daily [18], 4 m weekly [19] or 28 m for less regular movements [14]. Similarly, long-distance movements have been reported on hellbenders with a range from 347 to 990 m [14, 17, 18]. Our findings were in line with conclusions from studies on hellbenders [14, 18] and other amphibians [30, 31], in that we found giant salamanders are capable of moving relatively long-distance over a short period of time, but that their tendency is to limit their movements to short distances.

The average overall LHR for the Donghe salamanders was 227 ± 70 m (range: 41–560 m), while those of the two salamanders that survived at the Heihe River were 246 m and 392 m. These measurements were comparable to results from the previous study on CGSs [13], which indicated that the distance from salamanders' initial locations to their settlement locations were 204–554 m, but probably larger than those reported for hellbenders, e.g., 144 ± 58 m [14] and 23–110 m [32]. When comparing MCPs, salamanders in our study also had larger home ranges (7465.2 ± 2828.8 m^2) than hellbenders (2211.9 ± 990.3 m^2, [14]). However, these home ranges were still relatively small considering that salamanders can move up to 880 m within a single day. Together, with results of sedentariness and daily movement, we may infer that reintroduced CGSs made frequent short-distance and non-directional movements, post-release. We may conclude that similar to hellbenders [18], reintroduced CGSs had a relatively high site fidelity to their release site, at least in their first year in the wild. These traits may be beneficial for the establishment of new populations in the wild [11, 16, 33]. However, these traits, together with the small initial population size, may result in limited gene flow and reduced effective population size, which impede the persistence of populations. Therefore, several rounds of reintroduction efforts may be needed before a self-sustaining population could be established in the wild.

The overlapping LHR of the Donghe salamanders for most of the study period indicated that reintroduced juvenile salamanders had a high tolerance of other individuals, at least in their first year in the wild. This tolerance and overlap of home ranges may reflect that they were raised in larger groups in captivity, in accordance with predictions from the mechanism called natal habitat preference induction (NHPI, [34]). However, this mechanism remains to be further tested since NHPI was not found to be supported on several pond-breeding salamanders [35]. Burgmeier et al. [14] reported that overlapping home ranges of adult hellbenders only occur in summer, and they had once located a male and a female under the same shelter during the breeding season. However, in our study salamanders had overlapping home ranges throughout all four seasons in the wild. One possible explanation for this overlap was that our salamanders were still juveniles and juveniles may not be as territorial as adults. Moreover, because they were juveniles, we never found two or more giant salamanders under the same shelter due to breeding. Hence, for monitoring and management convenience, future reintroduction projects could release juvenile CGSs relatively close to each other at the beginning (in rivers with plenty of food resources) without significant injury or mortality due to territorial battles.

We found that salamanders moved less frequently and shorter distances in winter than in summer, which is similar to the movement observed by hellbenders [14]. As an ectotherm, this movement pattern may largely be related to temperature since CGSs are found to increase their metabolic rate and food intake as temperature increases, as long as the temperature is below their upper tolerance limits [36]. Many amphibian and reptile species hibernate during winter to cope with low temperatures (e.g., [37, 38]). Salamanders in our study showed reduced movement (both frequency and distance) in winter; however, they did not seem to hibernate during this cold period as their average sedentariness was still around 0.3 in winter. Interestingly, salamanders had a high sedentariness in their first summer in the wild, as high as that in winter, which was much higher than in the second summer. Reintroduced/translocated animals may exhibit exploratory movement after release, and would move more frequently with longer distances to search for suitable habitat (e.g., [39–41]). Our observed movement patterns were contrary to these findings. Salamanders moved less frequently in the first summer than in the second summer, although when they did move, they moved long distances as seen in the second summer. This may be explained by an alternative theory, that naive animals reintroduced to a novel environment usually move very little shortly after release because their fear of predators would reduce their mobility to avoid predator encounter rates [42]. Yet, when they did move, their moving ability was more affected by seasons (temperature). Additional studies are needed before we can make any accurate predictions related to this movement pattern.

In contrast to our hypothesis that salamanders would primarily disperse upstream, we found almost an equal number of salamanders showed fidelity to release site as upstream dispersal (6 vs. 6 at Donghe, 1 vs. 2 at Heihe, respectively). Furthermore, 4 animals were pushed downstream during floods at each river. We did not find any difference based on body mass or body condition between salamanders with different dispersal patterns, probably due to a relative equivalent body condition of individuals within the same age grous from the same breeding farm. We propose that the age of the animals may have an effect on their dispersal directions. For example, Bodinof et al. [18] reported that 20 out of 26 juvenile hellbenders dispersed downstream post-release, whereas Cecala et al. [29] found that large larval salamanders exhibit upstream movement, but not small larvae. Zheng and Wang [13] reported that all four of their older study animals moved upstream and none of them were pushed downstream by floods, although floods destroyed their dens and triggered a second round of upstream movement. The four salamanders in Zheng and Wang's study were adults and may have been more resilient to floods than the juveniles in our study. In support of this proposal, the Heihe salamanders, which were 2 years younger than the Donghe animals, were more affected by floods such that they were pushed further downstream and all disappeared with status undetermined. In contrast, salamanders that were pushed downstream during floods at the Donghe River went shorter distances and half of them were confirmed alive and continued to be monitored. These results provide supporting evidence that younger giant salamanders may be more affected by floods and are more likely to disperse downstream (passively). However, different characteristics of the rivers in our study may confound this explanation. For example, the Heihe salamanders were possibly impacted by the larger floods occurring at this river compared to Donghe river flooding (physical observation). Future studies may need to release salamanders of different ages at one site to clarify the effect of age on their dispersal patterns.

Three of the Donghe salamanders started a second round of upstream movement in June 2014. Since these animals were still juveniles (1–2 years from sexual maturity), we would not consider these movements related to breeding migration as in other amphibians [12, 43]. Rather, we propose this behavior to be dispersal of juveniles away from their natal population [44] and the timing may be related more to seasonal changes in temperature. Unfortunately, we could not determine the individuals' sex at the time of release, and thus cannot determine whether there was a sex-biased dispersal pattern. A longer monitoring project may help to elucidate more on the dispersal behavior of reintroduced or translocated CGSs, although this would require additional transmitters be attached once battery life of the original transmitters approached its end.

Conclusions

Our study revealed that although more active than the hellbenders, captive-reared CGSs had a short-distance average daily movement, small home range, and a relatively high site fidelity to their release site, considering their ability to move long distances. These traits may contribute to the establishment of new populations in the wild. Reintroduction of this large aquatic salamander provides a good opportunity to study movement ecology of this critically endangered species in detail, which in turn may help to design more successful reintroduction projects.

Methods

Study area

Our study occurred at two headwater sites within the Qinling Mountains located in central China. The Heihe River in Zhouzhi County, Shaanxi Province (33°53′N, 108°00′E, datum = WGS84) is on the north slope of the Qinling Mountains and is a tributary in the Yellow River watershed. The Heihe River site is at an elevation of ~ 930 m and surrounded by deciduous broad-leaf forest along the river banks. The Donghe River in Ningshan County, Shaanxi Province (33°21′N, 108°16′E, datum = WGS84) is on the south slope of the Qinling Mountains and belongs to the Yangtze River watershed. This headwaters site is at an elevation of ~ 1230 m and the river banks are lined with a mixture of evergreen and deciduous broad-leaf forest. The mean width of the river stretches where we released salamanders were 15 m at the Heihe River and 9 m at the Donghe River [27]. These two sites were selected because the founder and parent stock originated in these rivers, and the wild CGSs are still found occasionally in them (according to local Fisheries Bureaus), indicating that these rivers continue to represent suitable habitat for this species.

Study animals

Our study involved 32 captive-reared juvenile salamanders from two age groups (3 and 5 years old; $n = 16$ animals/age group). All weights (kg), lengths (cm) and distances (m) are reported as the mean ± standard error (SE) of the mean. The younger cohort of animals had a mean body mass of 0.5 ± 0.2 kg and a mean total length of 44.00 ± 3.24 cm; whereas, the older cohort of animals had a mean body mass of 1.6 ± 0.4 kg and a total length of 63.97 ± 4.86 cm. Both cohorts were juveniles and could not be sexed. Radio transmitters (F1035, Advanced Telemetry Systems, Inc., Isanti, USA) were surgically implanted into the abdomen of all salamanders by a veterinarian on 13–16 March, 2013 [45]. One salamander from the younger cohort died before release due to post-surgical complications, hence a total of 31 salamanders were released to the wild. The younger cohort was released at the Heihe River site between 28 April – 2 May, 2013, whereas the older cohort was released at the Donghe River site on 12 July, 2013 [26]. The younger cohort was originally collected from the Heihe River as larvae by local Fisheries Bureau and head started in a commercial breeding farm. The older cohort was born in captivity; however, their parents were collected from the Donghe River. At both sites, all salamanders were released along a 50 m stretch, with a mean initial spacing of 1.9 ± 0.6 m. Boulders were located throughout both rivers and each animal was released beside a rock large enough to provide shelter.

Radio-telemetry and data collection

We measured the body mass and total length for each salamander prior to release. Salamanders were monitored every day post-release using a radio-receiver with a 3-element Yagi antenna (R410, Advanced Telemetry Systems, Inc., Isanti, Minnesota, USA), until the depletion of the transmitter battery (radio signals disappeared gradually 16 months after activation in March 2013). Coordinates of salamander locations were recorded by handheld GPS units (60CSx, Garmin, Ltd., New Taipei City, Taiwan). We trained local field assistants at both sites to help with tracking and monitoring of released salamanders throughout the year. Salamanders were located and monitored every day except for a few days when floods occurred in the summer and early autumn (~ 15 days at the Donghe River and ~ 5 days at the Heihe River). Since boulders selected by the animals as shelter were usually too large to turn over manually, we determined the presence of salamanders using an underwater inspection camera (M12, Milwaukee Electric Tool, Brookfield, WI, USA).

Statistical analyses

Daily movements were calculated in ArcGIS (Version 10) as the straight-line distance (m) between locations collected across sequential days for each animal. This parameter describes the net displacement within a single day, rather than the accumulated distance a salamander moved, and is similar to many studies describing movement ecology of hellbenders (e.g., [18]). Long-distance displacements downstream during floods were excluded from our analyses. Since the accuracy of the GPS units that we used for this project usually varied from 3 to 5 m (depending on weather condition), consecutive locations with ≤3 m distance were treated as stationary movements. Thus, sedentariness was calculated as the proportion of stationary movements (≤ 3 m distances) across all daily movements observed. Mean daily movement of salamanders was calculated as the mean of all movements > 3 m.

Following Burgmeier et al. [14], we calculated both linear home range (LHR), which refers to the length of river used by an individual, and minimum convex polygons (MCP) to facilitate comparison with other giant salamander species. The overall LHR and MCP during the entire monitoring period was calculated for each salamander. We then tested the correlation between their LHRs and MCPs using Spearman's rank-order correlation test. We divided our data into weeks and generated weekly LHR for each salamander when more than four locations were recorded within a week. We determined the centroid of each weekly LHR in ArcGIS, and calculated the distance from release site to the centroids. These distances were plotted against time to show the salamanders' dispersal patterns throughout the study period. Distance to the centroid of the last weekly LHR was calculated as the dispersal distance for each salamander. Based on weekly LHR, we counted the number of individuals that overlapped with other salamanders and calculated the percentage of overlap for each week. Data from the Heihe salamanders were not used for this analysis since too many individuals died or were lost within the first couple of weeks [26].

We compared initial body mass and body condition before release for salamanders with different dispersal patterns (i.e., up-stream, down-stream, and fidelity to release site) using a non-parametric Kruskal-Wallis test. Salamanders that had a dispersal distance shorter than 100 m were categorized as fidelity to release site, whereas other salamanders were categorized as up-stream or down-stream dispersers, depending on their dispersal directions. We did not include salamanders that did not survive 10 weeks post-release in this comparison. Body condition was shown as the residual to the regression line of the cubed root of mass and total length constructed by all 31 salamanders before release [46]. We also compared sedentariness, mean daily movement, and LHR of salamanders at the Donghe River among seasons, using a Friedman rank sum test with a post-hoc Conover test. We defined seasons as: spring – March to May, summer – June to August, autumn – September to November, and winter – December to February. The two summers (2013 and 2014) were treated separately. We excluded salamanders that did not survive at least four seasons, as well as those that moved long distances downstream during floods. Only two salamanders at the Heihe River were eligible under these criteria. We did not conduct seasonal comparison for these two animals due to the small sample size, nor did we add them into the Donghe group for comparison since they were from a different system. All statistics were conducted in R (version 3.3.3, [47]), using the package PMCMR [48] and differences were considered significant at $p < 0.05$.

Abbreviations

CGS: Chinese giant salamander; IUCN: International Union for Conservation of Nature and Natural Resources; JGS: Japanese giant salamander; LHR: Linear home range;; MCP: Minimum convex polygons

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Authors' contributions

AJK, SW, and HXZ conceived the original idea and procured funding. LZ, AJK, and HXZ designed the study. LZ, HZ, QW, and WJ conducted field work and collected data. LZ and AJK analyzed data and wrote the manuscript, and all other authors provided editorial advice for the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Ethical treatment, handling and tracking of giant salamanders were approved by the Shaanxi Institute of Zoology animal research committee. The Fisheries Bureau of Shaanxi Province provided a permit for reintroduction of giant salamanders at both streams.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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