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Common carp aquaculture in Neolithic China dates back 8,000 years

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Despite the growing importance of farmed fish for contemporary economies, the origins of aquaculture are poorly known. Although it is widely assumed that fish domestication began much later than the domestication of land animals, the evidence is largely negative. Here, we use age-mortality and species-selection profiles of fish bones from prehistoric East Asia to show that managed aquaculture of common carp (*Cyprinus carpio*) was present at the Early Neolithic Jiahu site, Henan Province, China, by around 6000 BC.

Aquaculture is the fastest-growing global food production system and now provides half of all fish consumed by humans[1]. Despite its importance, however, the origins of fish farming and domestication remain poorly known. Hominin use of aquatic resources dates back more than one million years but saw a notable expansion with *Homo sapiens*, followed by an exponential increase in the Holocene[2,3]. Although humans began to domesticate several land animals by 10,500 yr BP[4], the domestication of fish is usually thought to have developed much later. Art from Egyptian tombs suggests management of Nile tilapia (*Oreochromis niloticus*) by 1500 BC[5]. In China, common carp (*Cyprinus carpio*) aquaculture can be traced back to the first millennium BC based on historical records. The *Yang Yu Jing*, the oldest written work on aquaculture, was completed about 460 BC. The *Shijing* (Book of Odes) mentions carp being reared in a pond during the period 1142–1135 BC[6]. While documentary and artistic evidence therefore indicates that fish farming had developed in several regions by the second millennium BC, zooarchaeologists have not yet identified fish domestication in earlier prehistory. Estimates of the number of fish species domesticated by humans differ depending on the criteria employed, but higher-end estimates (up to 251 species) are significantly greater than the small number (14) of domesticated land mammal species observed today[7–9]. Fisheries scientists have used levels of human control over aquaculture as a way to classify fish domestication[10]. Here, we argue that this approach can be extended to archaeological collections through the use of age-mortality and species-selection profiles.

Cyprinids (fish of the carp family) have been widely exploited by humans since at least the Upper Palaeolithic[11–13]. Based on historical records, carp were raised in artificial ponds and paddy fields in East Asia by the second millennium BC. Given that rice paddy fields date back to the fifth millennium BC in China[14], it might be expected that carp aquaculture has a similar antiquity. However, no archaeological evidence of carp aquaculture has so far been reported from Neolithic China.

Previous analyses of archaeological remains from East Asia have shown that the mainly mature cyprinids caught by early hunter-fishers had body-length (BL) distributions showing a peak corresponding to size at sexual maturity. This unimodal BL distribution has been identified from Neolithic Tianluoshan, China (circa 5000 BC) and Akanoi Bay (circa 6000–5000 BC) and Irienaiko (circa 6000–2000 BC) in Japan[15,16]. However, a bimodal BL distribution of carp remains was identified at the Iron Age Yayoi culture Asahi site (circa 400 BC–AD 100) in Japan[16]. We hypothesize that this bimodal distribution results from a more managed system of cyprinid use similar to those known from historic and ethnographic examples in East Asia. In such fisheries, a large number of cyprinids were caught during the spawning season and processed as preserved food. At the same time, some carp were kept alive and released into confined, human-regulated waters where they spawned naturally and their offspring grew by feeding on available resources. In autumn, water was drained from the ponds and the fish harvested, with BL distributions showing two peaks due to the presence of both immature and mature individuals.

In order to test this hypothesis that a bimodal BL distribution is associated with carp aquaculture, we first measured the standard BLs of year-class common carp which had been raised over the summer in a paddy field in Matsukawa, Nagano, Japan. We then analysed BL distributions estimated from carp pharyngeal teeth excavated from the Early Neolithic Jiahu site, Henan, China, to determine whether common carp aquaculture was practised there. Jiahu is known for early dates for rice and pigs, fermented beverages, bone flutes and possible early writing[17–20] (see Supplementary Fig. 1 for site locations). Three cultural periods at Jiahu date to 7000–6600 BC (Period I), 6600–6200 BC (Period II) and 6200–5700 BC (Period III)[17]. During its occupation, the climate at Jiahu was warm and humid with high rainfall. Remains of fish, freshwater mussels, turtles, water caltrops and lotus nuts point to the presence of large expanses of water. *Cyprinus carpio* was the most abundant cyprinid found at the site (Supplementary Table 1)[21]. *Cyprinus longzhouensis* is restricted to south China today, but its presence in Period II at Jiahu shows that the climate was warmer at that time, even in winter[17].

The common carp from Matsukawa displayed a mean BL of 95.5 mm (Fig. 1a), a distribution consistent with the first peak at the Asahi site (Fig. 1f). For Jiahu, the number of residual pharyngeal bones/teeth corresponding to each cultural period is shown in Supplementary Table 1. The number of *Cyprinus* A2 teeth measurable for mesio-lateral diameter (MLD) was 47 in Period I, 483 in Period II and 58 in Period III. For the 588 measurable A2 teeth, estimated BL distributions for each period are shown in Fig. 1b–d. During Period I, BL mode was 300–350 mm but 200–250 mm during Period II; the distribution was unimodal during both periods. During Period III, in contrast, two BL peaks were evident, one at 150–200 mm and another at 350–400 mm.

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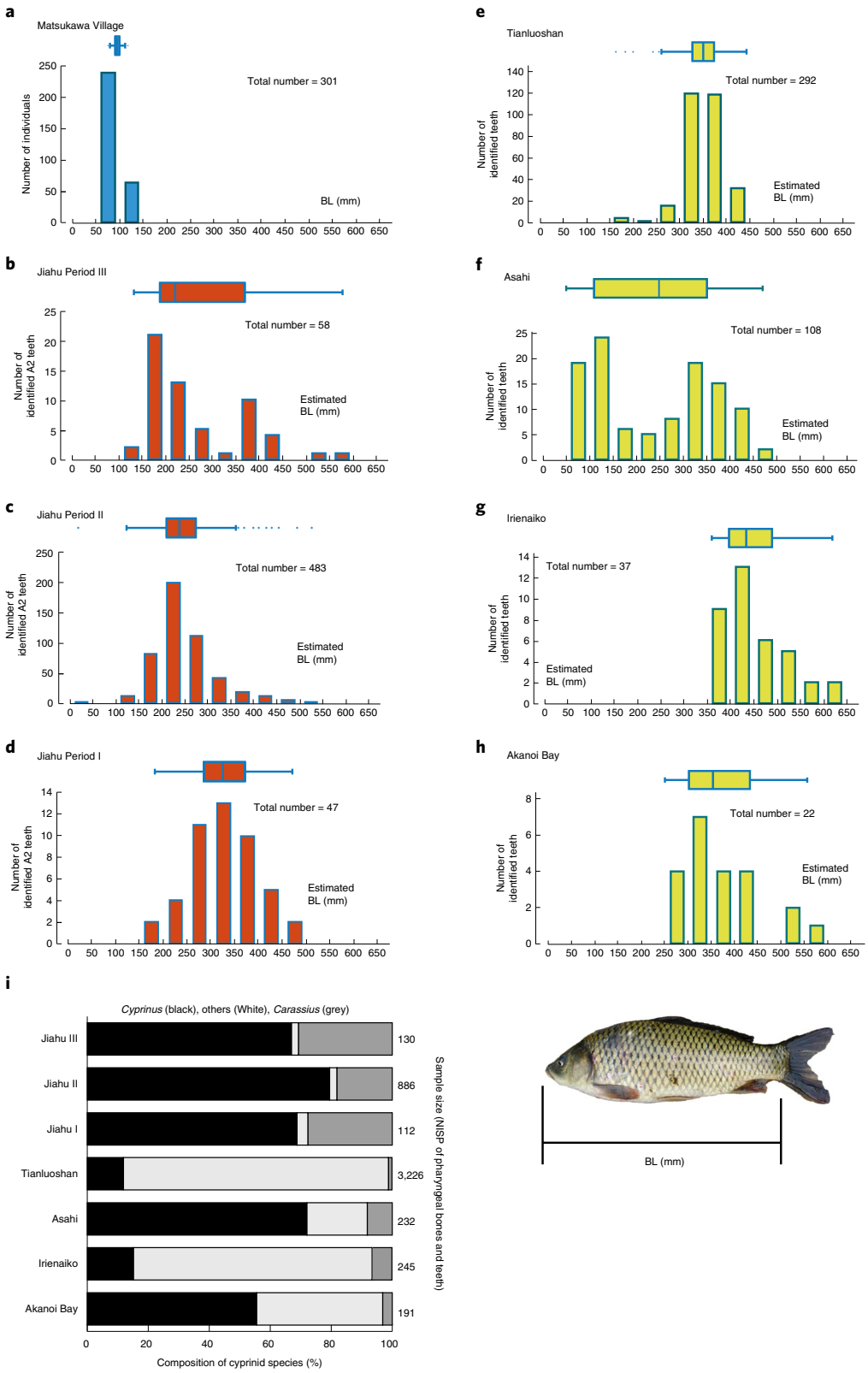

Fig. 1 | Common carp (*Cyprinus carpio*) standard BL distributions and cyprinid species compositions from archaeological sites in China and Japan. **a**, Contemporary year-class sample from Matsukawa, Japan. **b**–**d**, Estimated BL distributions of common carp from three cultural periods at Jiahu (Period III: 6200–5700 BC (**b**); Period II: 6600–6200 BC (**c**); Period I: 7000–6600 BC (**d**)). **e**–**h**, Estimated common carp BL from other sites: Tianluoshan (Middle Neolithic, 4490–4780 cal BC) (**e**), Asahi (Middle Yayoi: 400 BC–AD100) (**f**), Irienaiko (late Initial–early Late Jōmon, circa 6000–2000 BC) (**g**), Akanoi Bay (late Initial Jōmon, circa 6000–5000 BC) (**h**). Box plots shown in **a**–**h** represent quartile values of the data for each group. The lower and upper quartiles, or interquartile ranges (IQRs), are indicated by boxes, and the central bands in the boxes are the second quartiles (that is, medians). The range of lower and upper whiskers are maximum 1.5 × IQR, while the outliers are shown by dots. **i**, Species composition (number of identified specimens (NISP)) of pharyngeal bones/teeth from Japanese and Chinese archaeological sites. *Cyprinus* are shown in black, *Carassius* in white and other species in grey.

BL distributions of common carp from several other archaeological sites in East Asia are shown in Fig. 1e–h. Tianluoshan, Irienaiko and Akanoi Bay had similar unimodal patterns to Period I at Jiahu, showing the characteristics of a carp fishery conducted only during the spawning season. Our results from Tianluoshan are similar to those from a separate study using a larger sample from different archaeological contexts[22]. In contrast to these unimodal patterns, the BL distribution of Period III at Jiahu was similar to that of the Iron Age Asahi site in Japan, suggesting the practice of managed carp aquaculture.

The BL distribution during Period II at Jiahu differs from both Periods I and III, displaying a peak at 200–250 mm (Fig. 1c). The Period II BL distribution appears non-natural and may reflect some degree of selection or artificial manipulation. Under current climatic conditions in Japan, common carp in natural river systems reach sexual maturity in two to three years at a BL of around 300 mm[23]. If the common carp in Period II at Jiahu were mainly caught during the spawning season when they approached waterside settlements, we would expect that BLs over 300 mm would be the most common, as in Period I. However, very few carp over 300 mm in BL have been found in this period. The Period II distribution might be related to the warmer climate during that phase, since carp can attain sexual maturity at a smaller body size under warmer climatic conditions[24].

Management of carp at Jiahu is also supported by species-composition ratios. There are typically more crucian (*Carassius*) than common carp available for human exploitation in natural lake and river systems in East Asia[15]. While young and adult common carp leave lakeshores immediately after the spawning season and are therefore difficult to catch in non-spawning seasons, crucian carp tend to stay closer to river banks or lakeshores throughout the year[23]. At several prehistoric sites in Japan and China where cyprinid fish were an important food item, remains of crucian carp have been found to be more abundant than common carp (Fig. 1i). At Jiahu and Asahi, in contrast, common carp comprised up to 75% of total cyprinid remains. This seems to indicate a cultural preference for common carp, even though these would not have been the most abundant large cyprinids available. Carp aquaculture could have begun in such areas where common carp were utilized in preference to other fish.

The present analysis of cyprinid remains from Jiahu together with previous studies[13,15,16] suggests the following sequence of carp aquaculture in prehistoric East Asia. Stage 1 saw fishing in marshy natural ecotones where carp gather during the spawning season. This stage is known from several sites in both China and Japan, including Tianluoshan, Akanoi Bay and Irienaiko. In Stage 2, marshy ecotones were managed by digging channels and controlling water levels and circulation. Carp will spawn naturally in such environments and juvenile fish can be harvested in the autumn. Archaeological evidence from Jiahu Period III shows that the beginnings of aquaculture can be traced back to this stage. Stage 3 saw constant human inputs including control over reproduction using spawning beds and specialized facilities such as fishponds or paddy fields. Artificial feed may also be provided. Stage 3 aquaculture is described in historical records such as the *Yang Yu Jing* and probable archaeological examples include the Asahi site where rice paddy fields have been found. Stages 2 and 3 may correspond to, respectively, the 'extensive' and 'intensive' aquaculture systems posited for the Roman empire[25,26]. In East Asia, the evolution of carp aquaculture may have been connected with wet rice agriculture. Although rice paddy fields have not yet been identified at Jiahu, the coevolution of carp aquaculture and wet rice cultivation is an important topic for future research.

Methods

Identification and comparative samples. The pharyngeal teeth of cyprinid fish are generally arranged in one to three rows on each side, with the rows referred to as A, B and C from innermost to outermost. Tooth positions are numbered starting from the front of each row, with A2 being the tooth in the second position from the front in the A row (Supplementary Fig. 2). Pharyngeal teeth were identified to the level of subfamily by visual observation. Once subfamily was determined, further identification was made by comparison with reference collections from the Lake Biwa Museum (LBM) and the Institute of Hydrobiology, Chinese Academy of Sciences (IHCAS). The following samples were used for identification. *C. carpio*: LBM 1210046462–46464, 46503–46552; *C. longzhouensis*: IHCAS 50VII165, 50VII966; *Ctenopharyngodon idella*: LBM 1210013612, 13613, 13650–13652, 13655–13657; *Mylopharyngodon piceus*: LBM 1210013645, 13648, 13649, 13668, 13669, 13678–13680; *Carassius auratus*: LBM 1210047577; *Megalobrama amblycephala*: LBM 1210013824, 14585–14587, 17720, IHCAS 570447, 550013; *Megalobrama terminalis*: LBM 1210015022, IHCAS 5469, 5431; *Culter alburnus*: LBM 1210013829–13831, 48360, IHCAS 8990186; *Culter oxycephaloides*: IHCAS 6491904; *Culter recurviceps*: IHCAS 7654978; *Elopichthys bambusa*: LBM 1210011513, IHCAS no number; *Cultrichthys erythropterus*: LBM 1210038429–38441, IHCAS 580906. Species-level identifications were not performed where lack of reference collections made it impossible to compare all species included in a certain genus living in China, such as *Megalobrama* and *Culter*. *Ctenopharyngodon*, *Mylopharyngodon* and *Elopichthys* are cyprinid genera with only one species each. Samples were recorded as 'Gen. et Sp. indet.' when further identification was impossible. *Carassius auratus* includes various subspecies in East Asia, but *Carrasius auratus* samples were not identified to subspecies in this study. On the other hand, we identified all species of genus *Cyprinus*, which includes 18 species and subspecies in total, because each has morphologically characteristic pharyngeal teeth.

Modern samples. Measurement of the carp from Matsukawa Village, Nagano Prefecture, Japan, was conducted on 20 September 2017 after water was drained from a paddy field (circa $30 \times 20\,m^2$) where 6,500 carp fry around 1.5 cm in length had been released on 10 July of the same year. The field had been covered with a net to stop birds from eating the fish. According to local informants, around 20% of the fish usually die, are eaten by birds or escape to other water channels. The 2017 carp were said to be 1–2 cm smaller than previous years, perhaps due to the weather or because around 500 more fry than usual had been used that year. A sample of 301 carp was measured prior to the fish being processed for sale in a local community kitchen. Standard BLs were measured from the tip of the snout to the posterior end of the hypurals using a measuring board.

Archaeological samples. At Jiahu, a Neolithic site located 22 km north of Wuyang, southwestern Henan Province, soil collected from pits and dwellings was wet-sieved through a 0.8 mm mesh to extract residual pharyngeal bones and teeth. The cyprinid remains analysed from Jiahu were derived from a range of archaeological contexts and are unlikely to represent short-term accumulation events. Cyprinid remains from Jiahu included 1,128 pharyngeal bones and teeth (Supplementary Table 1). These were sorted by culture period, and the A2 teeth of common carp were measured. The grinding surface of each A2 tooth was photographed under a microscope (Leica EZ4HD) and the resulting digital images were measured for MLD using Nikon NIS-Elements measuring software (Supplementary Fig. 3). Standard BL was estimated using a regression formula based on the A2 tooth MLD: $BL = 18.2 + 57.6 \times MLD$ (ref. [27]). In previous studies, a regression formula based on the anteroposterior diameter was also used to estimate BL, but the MLD formula was found to be more accurate[16]. A full list of analysed pharyngeal samples from Jiahu with archaeological provenances is given in Supplementary Table 2.

Cyprinid remains from the Tianluoshan site, Yuyao city, Zhejiang Province, China, were from a pit in the K3 area of the site[15]. The Tianluoshan sample analysed here consisted of 400 g of fish bones, 2.18% by dry weight of total fish bones from the K3 pit. Asahi is a large (1.4 km × 800 m) Yayoi-period site spanning Nagoya city and surrounding districts. The cyprinid remains from Asahi analysed here were from excavations conducted in 1960, 1961, 1963, 1995 and 1996. Excavations in the 1960s concentrated on building remains inside the ditch encircling the Middle Yayoi village. Cyprinid bones came from midden deposits in features SD10, SD30 and 60E A shell layers. The 1995–1996 samples came from midden deposits which had accumulated at the bottom of the village moat (ditch) and included features SD101, SD93, SD14, SD106 and SD18. Irienaiko and Akanoi Bay are both wet sites located along the shores of Lake Biwa, Shiga prefecture, Japan. The Irienaiko samples were excavated in 2002–2003, the pharyngeal remains coming from features T91, T92, T93 in the North Area of the site. The cyprinid remains from Akanoi Bay were from pits P8, SK1, SK6, SK10, SK22 and SX1, excavated in 1986–1987. All cyprinid remains analysed here, including those from the 1960–1963 seasons at Asahi, were sampled using wet sieving.

Fig. 1a–d,i are results from this study. The results in graphs Fig. 1e–h have been previously reported[15,16], but all graphs have been redrawn from the original data.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The pharyngeal bone and tooth remains analysed here are curated in the following institutions: Jiahu: Institute of Archaeology, Chinese Academy of Social Sciences,

Beijing; Tianluoshan: Zhejiang Provincial Institute of Archaeology, Hangzhou; Asahi: Aichi Prefectural Centre for Archaeological Operations, Yatomi City, Aichi; Irienaiko and Akanoi: Cultural Property Protection Division, Shiga Prefectural Board of Education, Ōtsu City, Shiga.

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Author contributions

T.N. conceived the initial study and conducted analyses of fish remains from Jiahu with critical input from K.M. and J.Z. M.J.H. and J.U. conducted the fieldwork at Matsukawa. All authors interpreted the results and implications. T.N. and M.J.H. wrote the manuscript with input from J.U. who prepared the figures.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data were collected in the field and added to Excel spreadsheets.
Data analysis	Excel and Nikon NIS-Elements.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
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The pharyngeal bone and tooth remains analysed here are curated in the following institutions: Jiahu: Institute of Archaeology, Chinese Academy of Social Sciences, Beijing; Tianluoshan: Zhejiang Provincial Institute of Archaeology, Hangzhou; Asahi: Aichi Prefectural Centre for Archaeological Operations, Yatomi City, Aichi; Irienaiko and Akanoi: Cultural Property Protection Division, Shiga Prefectural Board of Education, Ōtsu City, Shiga.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Analysis of age-mortality profiles of carp using standard body length measured directly for living samples and estimated by regression analysis of pharyngeal bones for archaeological specimens.
Research sample	Cyprinid remains excavated from the Jiahu archaeological site and live common carp from Matsukawa Village, Nagano, Japan.
Sampling strategy	All relevant remains used from Jiahu. Matsukawa sample (301) was the largest number that could be measured in the alloted time.
Data collection	Jiahu remains were analysed by T. Nakajima, the Matsukawa carp by J. Uchiyama and M. Hudson
Timing and spatial scale	Jiahu analysis conducted in 2011, Matsukawa data collected on September 20, 2017.
Data exclusions	Non-pharyngeal elements from cyprinids at Jiahu were excluded based on the rationale explained in Methods.
Reproducibility	N/A
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Jiahu specimens analysed in the lab, Matsukawa Village specimens in the field in warm, fine weather.
Location	Jiahu site, Henan Province, P.R. China (33-35 N, 113-42 E); Matsukawa Village, Nagano Prefecture, Japan (36-25 N, 137-51 E).
Access and import/export	Samples were analysed with the permission of the relevant authorities in China and Japan.
Disturbance	N/A

Reporting for specific materials, systems and methods

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Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
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☒	☐ Palaeontology
☐	☒ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
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Animals and other organisms

Policy information about studies involving animals; ARRIVE guidelines recommended for reporting animal research

Laboratory animals	The study did not involve laboratory animals.

Wild animals	The study involved carp raised under human control in a paddy field. Our analysis was conducted on the same day the field was drained to process the fish. The carp were caught by hand using nets and transferred to water tanks. A sample of carp was taken from the tanks, measured and then returned to the tanks to be transported to a local kitchen for processing.
Field-collected samples	See explanation under 'Wild animals'
Ethics oversight	Permission was obtained from Matsukawa Village office and from the landowner of the paddy field for the measurement of the carp.

Note that full information on the approval of the study protocol must also be provided in the manuscript.